2.0 Assessment Approach: Building On Existing Knowledge

2.1 Introduction

This chapter provides a review of previous assessments of the impacts of climate change on US agriculture. We also describe the methods and approaches used in the Agricultural Sector Assessment. As part of the National Assessment, some aspects of the approach were dictated by the need for consistency across the various Assessment activities. For example, with regard to future climate scenarios our guidance was to focus on using the Canadian Climate Center and Hadley Center climate scenarios as well as to consider both future climate change and historic climate variability. The National Assessment also provided some guidance on future socio-economic scenarios. We did not develop numerical agro-economy scenarios “consistent” with the economic scenarios and instead imposed climate change on the agricultural economy as it exists today. We discuss some of the reasoning for this decision, beyond simply the lack of time and resources.

We begin with a brief review of climate change impact studies, focusing on those efforts that have sought a comprehensive assessment or relatively comprehensive review of the literature. Our goal is to summarize the main findings, identify as extensively as possible where some of the climate-agriculture links exist, and as a result be able to indicate which links have not been explored. We then describe the method and approaches we have used to fill some of these gaps. The purpose is to help the reader who may be unacquainted with past assessments to understand the context for our findings, what is new, and what reinforces previous work.

2.2 Past Assessments: General Findings

Several assessments of agriculture that include the US or cover major parts of the US have been conducted over the past 20 years. As the bibliographies of these reviews and assessments attest, there are many detailed studies on various aspects of climate change with numerous papers reporting experimental results of, for example, the impact of elevated ambient levels of CO_2 on crops. This fundamental research is absolutely critical for developing and improving assessment models, assessment research, and ultimately assessments of this type. There are two aspects of this type of research for assessment research that are critical to understand:

(1) Inevitably assessment involves scaling up results of bench, site, or field level experiments to a farm, a region, the entire country or world markets. There are two very broad concerns in doing this. First, will a mix of independently conducted site studies be representative of the scaled up area and are they based on consistent assumptions and approaches? Second, are there “fallacies of composition” that occur in simply adding together effects? The most obvious example is that a farm-level model of the impact of climate change on farm profits is irrelevant by itself; production changes across the country and the world

will result in changes in market prices. These changes can be far more important for farm profitability than the direct effect of climate on farm yields.

(2) Assessment usually involves translating results obtained under controlled, experimental conditions to conditions observed on the farm. The concerns here involve at least three issues: First, are the environmental controls in these experiments a reasonable approximation of open-field conditions and if not are the responses estimated relevant to real-world conditions? Second, do these experiments consider complex interactions with the environment (e.g. changes in pests, soils, and other environmental factors)—if not, is there some validity in considering just one element at a time? Can one, for example, consider response to CO_2 independent of temperature, moisture, nutrients, salinity, tropospheric ozone and other factors?

Broader assessments, those that attempt to simulate impacts of climate change on the agricultural economy, address the above issues in a variety of ways. Sometimes they do so by making simplifying assumptions (e.g. that an average CO_2 response independent of other factors can be used). In other cases, the effects are simply ignored (e.g. changes in the distribution of pests, in soils, or in variability) either because there are quantitative methods for assessing the problem or on the assumption that effects are small. In other cases, the method used may implicitly capture the effect under some conditions. For example, statistical evidence drawn from cross-section data can embody all the effects associated with climatic conditions that vary across regions. Also, implicit, however, is that climate change will involve the wholesale shift of climatic regimes with these associations intact. For example, would imply that pests, soil conditions, and farming practices would all change at the same rate as climate. Another approach is to use expert judgment. Experts also likely weigh a variety of evidence, perhaps including the potential effects of pests and diseases, for example, to come up with a judgment about crop yields under a changing climate.

2.2.1 Conclusions from Previous Assessments

We do not attempt to review here much of the detailed scientific literature that is the background for these assessments. Excellent reviews on crops and livestock effects, pests, and soils as well as discussion of global and regional impacts are included in a forthcoming special edition of the journal, *Climatic Change*, Climate Change: Impacts On Agriculture (J. Reilly and S. Schneider, eds.). The 5 articles included in the edition contain over 500 citations, providing a detailed guide to the literature for readers so inclined. Instead, we provide a short summary of the major assessments below by approximate date over which the assessment occurred.

1976-1983: National Defense University.

A National Defense University (D. Gale Johnson, 1983) project produced a series of reports with the 1983 report providing the final report on agriculture, integrating yield and economic effects. It focused on the world grain economy in the year 2000, considering both warming and cooling of up to approximately 1ºC for large warming or cooling and 0.5ºC for moderate changes for the US, with associated precipitation changes on the order of +/- 0-2 percent. These estimates varied somewhat by region. The base year for comparison purposes was 1975. It relied on an expert opinion survey for yield effects, using these to create a model of crop-yield response to temperature and precipitation for major world grain regions. There was not explicit account of potential interactions of pests, changes in soils, or of livestock or crops such as fruits and vegetables. No direct effects of CO_2 on plant growth were considered as the study remained agnostic about the source of the climate change (e.g. whether due to natural variability or human-induced). Economic effects were assessed using a model of world grain markets. Crop yields in the US were estimated to fall by 1.6 to 2.3 percent due to moderate and large warming and to increase by very small amounts (less than 0.3 percent) with large cooling and even smaller amounts with moderate cooling. Warming was estimated to increase crop yields in the (then) USSR, China, Canada, and Eastern Europe, with cooling decreasing crop production in these areas. Most other regions were estimated to gain from cooling and suffer yield losses from warming. The net effect was a very small change in world production and on world prices. The study assigned subjective probabilities to the scenarios, attempted to project ranges of crop yield improvement in the absence of climate change, and compared climate-induced changes to normal variability in crop yields and uncertainty in future projections of yield. A summary point highlighted the likely difficulty in ultimately detecting any changes due to climate given the year-to-year variability and the difficulty in disentangling climate effects from the effects of new varieties and other changing technology that would inevitably be introduced over the 25-year period.

1988-1989: US EPA

US EPA (J. B. Smith and D. Tirpak, 1989;) evaluated the impacts of climate change on US agriculture as part of an overall assessment of climate impacts on the US. The agricultural results were published in Adams, et al. 1990. The study evaluated warming and changes in precipitation based on doubled CO_2 equilibrium climate scenarios from 3 widely known General Circulation Models (GCMs), with increased average global surface warming of 4.0 to 5.2º C. In many ways the most comprehensive assessment yet to date, it included studies of possible changes in pests, and in a case study of California, interactions with irrigation water. The main study on crop yields used site studies and a set of crop models to estimate crop yield impacts. These were simulated through an economic model. Economic results were based on imposition of climate change on agricultural economy in 1985. Grain crops were studied in most detail, with a simpler approach for simulating impacts on other crops. Impacts on other parts of the world were not considered. The basic conclusions summarized in the Smith and Tirpak report were:

- Yields could be reduced, although the combined effects of climate and CO_2 would depend on the severity of climate change.
- Productivity may shift northward.
- The national supply of agricultural commodities may be sufficient to meet domestic needs, but exports may be reduced.
- Farmers would likely change many of their practices.
- Ranges of agricultural pests may extend northward.
- Shifts in agriculture may harm the environment in some area.

1988-1990: Intergovernmental Panel on Climate Change (IPCC), first assessment report.

In the first assessment report of the Intergovernmental Panel on Climate Change (IPCC), (M.L. Parry 1990a and in greater detail, M.L. Parry, 1990b) North American agriculture was briefly addressed. The assessment was based mainly on literature review and, for regional effects, expert judgement. North American/US results mainly summarized the earlier EPA study. Some of the main contributions of the report were to identify the multiple pathways of effects on agriculture including effects of elevated CO_2, shifts of climatic extremes, reduced soil water availability, changes in precipitation patterns such as the monsoons, and sea-level rise. It also identified various consequences for farming including changes in trade, farmed area, irrigation, fertilizer use, control of pests and diseases, soil drainage and control of erosion, farming infrastructure, and interaction with farm policies. The overall conclusion of the report was that "on balance, the evidence suggests that in the face of estimated changes of climate, food production at the global level could be maintained at essentially the same level as would have occurred without climate change; however, the cost of achieving this was unclear." As an offshoot of this effort, the Economic Research Service of USDA (S. Kane, J. Tobey, J. Reilly, 1991 and subsequently, as Kane, Reilly, and Tobey, 1992 and Tobey, Reilly, and Kane, 1992) published an assessment of impacts on world production and trade, including specifically the US. The study was based on sensitivity to broad generalizations about the global pattern of climate change as portrayed in doubled CO_2 equilibrium climate scenarios, illustrating the importance of trade effects. A "moderate impacts scenario" brought together a variety of crop model study results based on doubled CO_2 equilibrium climate scenarios and the expert judgements for other regions that were the basis for the IPCC. In this scenario, the world impacts were very small (a gain of $1.5 billion 1986 $US). The US, was a very small net gainer ($.2 billion) with China, Russia, Australia, and Argentina also benefiting while other regions lost. On average, commodity prices were estimated to fall by 4 percent although corn and soybean prices rose by 9-10%.

1990-1992: US DOE, Missouri, Iowa, Nebraska, Kansas (MINK) study.

In the Missouri, Iowa, Nebraska, Kansas (MINK) (Rosenberg (ed.) 1993; Easterling, et al., 1993) study, the dust bowl of the 1930's was used as a surrogate climate change for the four-state region. Climate change in the rest of the world was not considered. Unique aspects of the study included consideration of water, agriculture, forestry, and energy impacts and projection of regional economy and crop variety development to the year 2030. Crop response was modeled using crop models; river flow using historical records; economic impacts using an input-output model of the region. Despite the fact that the region was "highly dependent" on agriculture compared with many areas of the country, the simulated impacts had relatively small effects on the regional economy. Climate change losses in terms of yields were on the order of 10 to 15%. With CO_2 fertilization effects, most of the losses were eliminated. Climate impacts were simulated for current crops as well as "enhanced" varieties with improved harvest index, photosynthetic efficiency, pest management, leaf area, and harvest efficiency. These enhanced varieties were intended to represent possible productivity changes from 1990 to 2030 and increased yield on the order of 70%. The percentage losses due to climate change did not differ substantially between the "enhanced" and current varieties. Despite relatively mild effects on the agriculture sector of the region as a whole, locally severe displacements could occur. For example, irrigation in western Kansas and Nebraska would be untenable and would move to the eastern ends of these states.

1992: Council on Agricultural Science and Technology (CAST) Report

The Council on Agricultural Science and Technology (CAST, 1992) report, commissioned by the US Department of Agriculture did not attempt any specific quantitative assessments of climate change impacts, focusing instead on approaches for preparing US agriculture for climate change. It focused on a portfolio approach to responding to climate change recognizing that prediction with certainty was not possible. Attention was directed to reform of agricultural policy, improving energy and irrigation efficiency, maintaining input supply and export delivery infrastructure, preserving genetic diversity, maintaining research capability, developing alternative cropping systems, enhancing information systems, attending to develop human resources, harmonizing agricultural institutions, and promoting freer trade. Although the study did not provide quantitative assessments, it did conclude with a relatively optimistic view of US agriculture's ability to cope. The study also addressed opportunities to mitigate agricultural greenhouse gas emissions.

1992: National Research Council

The National Research Council/National Academy of Sciences undertook a broad assessment of the policy implications of greenhouse warming, both mitigation and adaptation. The report included a discussion of climate change impacts on agriculture and the effect of elevated CO2 on crops (NRC, 1992).

1992-1993: Office of Technology Assessment study.

The Office of Technology Assessment (OTA, 1993) study, similar to the CAST study for agriculture, focused on steps that could prepare the US for climate change rather than estimates of the impact. The study's overall conclusions for agriculture were that the long-term productivity and competitiveness of the US agriculture were at risk and that market-driven responses may alter the regional distribution and intensity of farming. It found institutional impediments to adaptation, recognized that uncertainty made it hard for farmers to respond and saw potential environmental restrictions and water shortages, technical limits to adaptation, and declining Federal interest in agricultural research and education. The study recommended removal of institutional impediments to adaptation (in commodity programs, disaster assistance, water-marketing restrictions), improvement of knowledge and responsiveness of farmers to speed adaptation, support for both general agricultural research and that targeted toward specific constraints and risks that might be related to climate change (e.g. drought, heat stress).

1992-1994: US EPA Global Assessment

A global assessment (C. Rosenzweig and M. Parry, 1994; Rosenzweig, et al., 1995) of climate impacts on world food prospects expanded the method used in the US EPA study for the United States to the entire world. It was based on the same suite of crop and climate models and applied these to many sites around the world. It used a global model of world agriculture and the world economy that simulate the evolving economy through to 2060, assumed to be the period when the doubled CO_2-equilibrium climates applied. The global temperature changes were +4.0 to +5.2º C. Scenarios with the CO_2 fertilization effect and modest adaptation showed global cereal production losses of 0-5.2%. In these scenarios, developed countries showed cereal production increases of 3.8 to 14.2% while the developing countries showed losses of 9.2-12.5%. The study concluded that there was a significant increase in the number of people at risk of hunger in developing countries because of climate change. The study also considered different assumptions about yield increases due to technology improvement, trade policy, and economic growth. These different assumptions and scenarios had equally or more important consequences for the number of people at risk of hunger.

Other researchers simulated yield effects estimated in this study through economic models, focusing on implications for the US (Adams, et al., 1995) and world trade (Reilly, et al. 1993; 1994). Adams et al. (1995) estimated economic welfare gains for the US of approximately $4 and $11 billion (1990 U.S.$) for 2 climate scenarios and a loss of $16 billion for the other scenario, under conditions reflecting increased export demands and a CO_2 fertilizer effect (550 ppm CO_2). The study found that increased exports from the U.S., in response to high commodity prices resulting from decreased global agricultural production, led to benefits to U.S. producers of approximately the same magnitude as the welfare losses to U.S. consumers from high prices. Reilly, et al. (1993; 1994) found welfare gains to the US of $0.3 billion (1990 U.S. $) under one GCM scenario and $0.6 to $0.8 billion losses in the other scenarios when simulating production changes for all regions of the world through a trade model. They also found widely varying effects on producers and consumers, with producers effects ranging from a $5 billion loss to a $16 billion gain, echoing the general findings of Adams, et al., that consumer and producer effects could differ in direction and as a result, net out to a small effect on the total economy. In particular, Reilly, et al.1994 showed that in many cases, more severe yield effects produced economic gain to producers when world prices rose.

1994-1995: IPCC, second assessment report.

The second assessment report of the IPCC included an assessment of the impacts of climate change on agriculture (Reilly, et al. 1995). As an assessment based on existing literature, it summarized most of the studies listed above. The overall conclusions included a summary of the direct and indirect effects of climate and increased ambient CO_2, regional and global production effects, and vulnerability and adaptation. With regard to direct and indirect effects:

- The results of a large number of experiments to resolve the effect of elevated CO_2 concentrations on crops have confirmed a beneficial effect. The mean value yield response of C_3 crops (most crops except maize, sugar cane, millet, and sorghum) to doubled CO_2 is +30% although measured response ranges from -10% to +80%.

- Changes in soils, e.g., loss of soil organic matter, leaching of soil nutrients and salinization and erosion, are a likely consequence of climate change for some soils in some climatic zones. Cropping practices including crop rotation, conservation tillage and improved nutrient management are, technically, quite effective in combating or reversing deleterious effects.
- Changes in grain prices, changes in the prevalence and distribution of livestock pests, and changes in grazing and pasture productivity, as well as the direct effects of weather will affect livestock production.

- The risk of losses due to weeds, insects and diseases is likely to increase.

With regard to regional and global production effects:

- Crop yields and productivity changes will vary considerably across regions. Thus, the pattern of agricultural production is likely to change in a number of regions.

- Global agricultural production can be maintained relative to base production under climate change as expressed by GCMs under doubled CO_2 equilibrium climate scenarios.

- Based on global agricultural studies using $2xCO_2$ equilibrium GCM scenarios, lower latitude and lower income countries have been shown to be more negatively affected.

With regard to vulnerability and adaptation:

- Vulnerability to climate change depends not only on physical and biological response but also on socioeconomic characteristics. Low income populations depending on isolated agricultural systems, particularly dryland systems in semi-arid and arid regions are particularly vulnerable to hunger and severe hardship. Many of these at-risk populations are found in Sub-Saharan Africa, South and Southeast Asia as well as some Pacific Island Countries and tropical Latin America.

- Historically, farming systems have responded to a growing population and have adapted to changing economic conditions, technology, and resource availabilities. It is uncertain whether the rate of change of climate and required adaptation would add significantly to the disruption likely due to future changes in economic conditions, population, technology and resource availabilities.

- Adaptation to climate change is likely; the extent depends on the affordability of adaptive measures, access to technology, and biophysical constraints such as water resource availability, soil characteristics, genetic diversity for crop breeding, and topography. Many current agricultural and resource policies are likely to discourage effective adaptation and are a source of current land degradation and resource misuse.

- National studies have shown incremental additional costs of agricultural production under climate change that could create a serious burden for some developing countries.

Material in the 1995 IPPC Working Group II report was reorganized by region with some updated material in a subsequent special report. Included among the chapters was a report on North America (Shriner and Street, 1998).

1995-1996. The Economic Research Service of the USDA.

The Economic Research Service of the USDA (Schimmelpfennig, et al. 1996) provided a review and comparison of studies that it had conducted and/or funded, contrasting them with previous estimates. The assessment used the same doubled CO_2 equilibrium scenarios of many previous studies (global average surface temperature increases of 2.5 to 5.2^o C. Two of the main new analyses reviewed in the study used cross-section evidence to evaluation climate impacts on production. One approach was a direct statistical estimate of the impacts on land values for the US (Mendelsohn, et al. 1994) while the other (Darwin, et al, 1994) used evidence on crop production and growing season length in a model of world agriculture and the world economy. Both imposed climate change on the agricultural sector as it existed in the base year of the studies (e.g. mid-1980s; 1990). A major result of the approaches based on cross-section evidence was that impacts of climate were far less negative for the US and world than had previously been estimated with crop modeling studies. While the studies showed similar economic effects as previous studies, they included no direct effect of CO_2 on crops, which in previous studies had been a major factor behind relatively small economic effects. Hence, if the direct effect of CO_2 on crop yields were to have been included, the expected result would have been significant benefits. The more positive results were attributed to the adaptation implicit in cross-section evidence that had not been completely factored into previous analyses. The assessment also reported a crop modeling study (Kaiser, et. al., 1993) with a complete farm-level economic model that more completely simulated adaptation response. It, too, showed more adaptation than previous studies. A summary of this review was subsequently published as Schimmelpfennig and Lewandrowski, (1998).

1996-1998: Electric Power Research Institute Assessment.

The Electric Power Research Institute (EPRI) funded a study of the impacts of climate change on all market sectors in the continental United States. Three different approaches were used to analyze agriculture. All three explored a range of hypothetical climate scenarios combining 1.5, 2.5, and 5.0 C warming with 0%, 8%, and 15% precipitation increases. The studies explored both a 1990 economy and a 2060 economy. Carbon dioxide levels were assumed to be 550 ppmv. Overall the studies found substantial benefits for the US resulting from climate impacts on US agriculture. Adams et al. 1998 used a crop production approach in conjunction with a linear programming model to predict effects across major crops in the US. The study adapted the agricultural model constructed for the USEPA (Adams et al., 1990) to include a more complete accounting of farmer adaptation, livestock, and warm-loving crops. The Adams et al study found substantial benefits with 1.5 and 2.5C warming of between 32 and 54 billion dollars in 2060. These benefits were reduced with a 5C warming to between 9 and 32 billion dollars. The study was unique in finding significant net economic benefits across the range of scenarios examined. When climate change was imposed on a 1990 economy, the magnitude of benefits was similar to the magnitude of benefits found in earlier studies for at least some scenarios. The relatively large benefits for 2060 reflects the fact that the underlying agricultural economy was considerably larger due to assumptions about growth in productivity.

Segerson and Dixon (1998) used cross-sectional data from the Midwest Plains to analyze grain crops. They relied on a production function model to estimate crop climate sensitivity. The authors found that crop sensitivity was slightly less than what Adams et al had assumed. These lower sensitivities were then introduced into the Adams et al model and generated slightly higher benefits from warming.

Mendelsohn, Nordhaus, and Shaw explored cross sectional analysis across all counties in the continental US that had agriculture. The model accounted for both farm value per acre and the fraction of land used for farming. The model also accounted for both climate normals and climate variation. The study found that including variation changed the measured sensitivity of crops to warming. With variation in the model, warming is more beneficial. Climate variation itself, however, was highly damaging. The Ricardian study suggested net benefits from warming that were similar to the Adams et al 1998 study for the United States.

EPRI has also funded two Ricardian studies in Brazil and India; the World Bank also supported the latter. The India study (Dinar et al, 1998) and the Brazilian study (Sanghi and Mendelsohn, 1999) reveal that the Ricardian model works well in developing countries. Warmer winters and summers are harmful in both of these countries as they are in the United States. Both Brazil and India, however, appear to be more sensitive to warming than the United States. Even adjusting for their different initial temperatures, the developing countries appear to be more temperature sensitive (Mendelsohn, Dinar and Sanghi, 1999). The results suggest that empirical studies of climate sensitivity will have to be completed in more developing countries in order to get an accurate picture concerning climate effects around the world. Specifically, there is currently very little information about Africa even though it is likely to be one of the most sensitive areas to warming in the world.

1998-1999: Pew Center Assessment

As part of a series on various aspects of climate change aimed at increasing public understanding, the Pew Center on Global Climate Change completed a report on agriculture (Adams, Hurd, and Reilly, 1999). The report series is based on reviews and synthesis of the existing literature. The major conclusions were:

- Crops and livestock are sensitive to climate changes in both positive and negative ways.

- The emerging consensus from modeling studies is that the net effects on U.S. agriculture associated with doubling of CO_2 may be small; however, regional changes may be significant (i.e. there will be some regions that gain and some that lose.) Beyond a doubling, the negative effects are more pronounced both in the U.S. and globally.

- Consideration of adaptation and human response is critical to an accurate and credible assessment.

- Better climate change forecasts are a key to improved assessments.

- Agriculture is a sector that can adapt but changes in the incidence and severity of pests, diseases, soil erosion, tropospheric ozone, variability and extreme events have not been factored in to most of the existing assessments.

2.2.2 General Results and Conclusions from Past Assessments

Several general results and conclusions are common among past assessments and, for those who have been involved in the research, have become common wisdom or consensus conclusions. There are, however, important caveats and limitations of existing assessments. These limitations exist not because researchers have not recognized them but because it has, for one reason or another, proved difficult or impossible to overcome these limitations in ways that have been convincing to most other researchers. Until more convincing evidence is marshaled on one side or the other, these limitations introduce uncertainty in the conclusions. We list first the major conclusions and then the major limitations of assessments to date.

Major agreement and consensus:

- *Over the next 100 years and probably beyond, human-induced climate change as currently modeled will not seriously imperil aggregate food and fiber production in the US*, nor will it greatly increase the aggregate cost of agricultural production. Most assessments have looked at multiple climate scenarios. About _ of the scenarios in any given assessment have shown small losses for the US (increased cost of production) and about _ have shown gains for the US (decreased cost of production).[1]

- *There are likely to be strong regional production effects* within the US with some areas suffering significant loss of comparative advantage (if not absolutely) to other regions of the country. With very competitive economic markets, it matters little if a particular region gains or loses absolutely in terms of yield but rather how it fares relatively to other regions. The south and southeastern US are persistently found to lose both relative to other regions and absolutely. The effects on other regions within the US are less certain. While warming can lengthen the growing seasons in the northern half of the country, the full effect depends on precipitation, notoriously poorly predicted by climate models.

- *Global market effects and trade dominate in terms of net economic effect on the US economy*. Just as climate's effects on regional *comparative* advantage is important, the relevant concern is the overall effect on global production and prices and how US producers fare *relative to their global competitors* or potential competitors. The worst outcome for the US would be severe climate effects on production in most areas of the world and with particularly severe effects on US producers. Consumers would suffer from high food prices, producers would have little to sell, and agricultural exports would dwindle. While unlikely based on newer climate scenarios, some early scenarios that featured particularly severe drying in the mid-continental US with milder conditions in Russia, Canada, and the Northern half of Europe produced a moderate version of this scenario. The US and the world could gain most if climate change was generally beneficial to production worldwide but particularly beneficial to US producing areas. Consumers in the US and around the world would benefit from falling prices and US producers would also gain because the improving climate would lower their production costs even more than prices fell, thus increasing their export competitiveness. In fact, most scenarios come close to the middle with relatively modest effects on world prices. The larger gainers in terms of production are the more Northern areas of Canada, Russia, and Northern Europe. Tropical areas more likely suffer production losses. The US as a whole straddles a set of climate

[1] Assessments have used a number of different "yardsticks" for measuring effects. These include such measures as total grain production in tons or value of production, commodity prices, and economic welfare. The latter concept is generally favored among economists as showing the true economic cost. While there are many differences among these measures, the basic conclusion stated here is not particularly sensitive to which measure is used.

zones that include gainers (the northern areas) and losers (south and southeast).

- Effects on producers and consumers often are in opposite directions and this is often responsible for the small net effect on the economy. This result is a near certainty without trade and reflects the fact that demand is not very responsive to price so that anything that restricts supply (e.g. acreage reduction programs, environmental constraints, climate change) leads to price increases that more than make up for the reduced output. Once trade is factored in this result depends on what happens to production abroad as discussed above.

- *US agriculture is a competitive, adaptive, and responsive industry and will adapt to climate change; all assessments reviewed above have factored adaptation into the assessment.* The final effect on producers and the economy after adaptation is considered may be either negative or positive as discussed above. The evidence for adaptation is drawn from analogous situations such as the response of production to changes in commodity and input prices, regional shifts in production as economic conditions change, and the adoption of new technologies and farming practices.

- The relatively small net effect on the US agricultural economy across assessments is the combination of a variety of negative and positive effects. In many of the earlier assessments, the direct effect of carbon dioxide on plant growth offset fairly large yield declines related to changes in temperature and precipitation. Some later assessments have not included the carbon dioxide effect at all but have estimated a much larger adaptation response and have found small negative and even positive effects despite the omission.

- The agriculture and resource policy environment can affect adaptation. Lack of water markets, agricultural commodity programs, crop insurance, and disaster assistance can encourage the continuation of practices that are no longer economic on a regular basis. The FAIR act of 1996 eliminated farm program payments tied to base acreage (failure to maintain base acreage in a crop could mean loss of payments and so this encouraged continued production of the same crop). More effective water markets could transfer water to the highest value uses and encourage greater irrigation efficiency but establishment of markets is hampered by water laws dating to the 1800's that granted water rights in the Far West and open access to subsurface resources in the Plains states. The pressure of increasing competition for these resources is leading to some progress in this regard. Crop insurance and disaster assistance can have the perverse effect of encouraging continued cropping in areas that are prone to crop disasters, essentially subsidizing production in areas that are no longer competitive. There is growing awareness of the perverse effect these programs can have and some interest in managing them in ways that minimize or eliminate the effect. It appears hard, however, for Congress and the Administration to resist pressure to come to the aid of those in a time of need regardless of whether those in need have, themselves, prepared well for the inevitable vagaries of weather and the variability of crop prices.

There have been a number of assessments of agricultural impacts of climate change and the consensus and agreement among the studies is strengthened by the fact that the assessments were conducted by different teams of researchers, using different methods, and sponsored by different organizations. All of these research teams have labored under the same set of constraints, some quite severe, and thus many of the results are conditioned on these limits. They include:

- *The climate scenarios on which these results depend have been very unrealistic representations of what climate might really be like over the next several decades to 100 years*. Most climate scenarios are based on doubled CO_2 equilibrium scenarios. There is no particular future year to which these scenarios apply and other factors that affect climate such as sulfate aerosols have not been included. One assessment assumed the climates were realized 2060, most others apply the conditions to today's agriculture and are silent about when the effects might be realized. As a result, there are no estimates of climate impacts for the next several decades based on actual results of climate models and no estimates of potential consequences in the far distant future—beyond a doubled CO_2 environment.

- *The detailed predictions of climate models are particularly uncertain, with most climate modelers placing little or no confidence in the details because the processes that control these details are not well represented.* Clouds and precipitation are key concerns. The big climate models do a poor job of representing current variability and do not simulate events such as ENSO, hurricanes, and typhoons, nor do they have any ability to represent changes in small scale, convective storms.

- *The climate scenarios that were used represent atmospheric physics as currently understood, almost exclusively constructed for research rather than assessment purposes*. They had limited or no interaction with oceans and terrestrial systems and excluded other climate forcings. For assessment purposes, it would be far more preferable to try to roughly take into account as many things as are thought to be important rather than to be very precise about the things we know well while leaving out completely things we suspect but have not proved. It would also be preferable to have a range of scenarios that bounded our uncertainty about these many features rather than everyone's version of a central estimate (central, conditioned on (recognizing that) some things were left out completely). Scenarios that could happen with great consequence but with low probability need to be assessed, appropriately discounted for the fact that there might only be a 1 in 100 or 1 in 1000 chance of occurrence.

- *The CO_2 fertilization effect will likely increase yields but the magnitude of the effect remains uncertain*. The experimental evidence shows an average yield increase of 30 percent for many crops but more like 7 percent for corn, sorghum and sugar cane[2] under doubled levels (from ~ 300ppm to ~600ppm) and improvements in water use efficiency. The range of experimental results of doubled CO_2 is from –10 to +80% and some would fasten on the low end of this range. A wide variety of factors that could considerably reduce the anticipated gain. Only about 2/3's of the increase in greenhouse gas forcing may be due to CO_2, other gases would cause warming but not have beneficial effects. Most of this experimental evidence is from single plants grown under glass (highly artificial conditions) and the effects could be quite different under open-field conditions, with pessimists imagining necessarily less effect. The CO_2 effect depends on and interacts with many other factors, probably explaining, in part, the wide range of experimental results. Grain quality and forage quality may be reduced (less protein) for crops grown under elevated CO_2. Not all of these interactions necessarily would lead to a lower fertilization effect. For example, the evidence indicates a stronger effect when crops are under stresses such as water, heat, and salinity, conditions more likely to be observed under commercial than experimental conditions. Most of the crop models used in assessments apply a very simple multiplier to represent elevated CO_2 rather than model the complex interactions explicitly.
- *Many broader agro-ecological (system-wide) effects have not been included in assessments*. The dominant "crop model methodology" simulates only the short-term and local effects of essentially different weather on crop growth. Persistent changes in weather (i.e. climate) may lead to changes in soils, pest prevalence, irrigation water availability, the concentrations of other pollutants such as tropospheric ozone, and changes in the ability of farmers to conduct field operations. For the most part, these have not been explicitly incorporated into assessments.

- *The extent, ease, and cost of the adaptation response are controversial and unresolved*. While some amount of adaptation is inevitable some analysts question whether the analogous situations that are used as evidence of adaptability are good analogies for climate change. Gradual climate change may be difficult to detect and hence the producer may not know that climate has changed, interpreting a string of odd weather as normal variability, and thus experience losses for some time before (s)he recognizes that climate has changed. There is also debate about adjustment costs—whether climate will change so gradually that any adaptation can be handled as a part of normal replacement of capital or whether adaptation will require disruptive and costly replacement of equipment made obsolete by changing climate. For

[2] The distinction here is between C3 and C4 crops, referring to the pathways through which carbon is utilized. The C4 crops of corn, sorghum and sugar cane experience much less gain. Virtually all other crops of commercial importance are C3 crops.

adjustment to be costly, it would likely be the case that local climates would have to experience some type of punctuated change as the global average change in temperature is quite slow relative to the normal rate of capital turnover in agriculture. There is, however, little confidence that climate models would capture such types of change, if indeed, they were a possibility.

- *Regional and local predictions remain, at best, vaguely probabilistic in nature.* For example, the finding that the South and Southeast has usually been found to be negatively affected may not apply to every corner of the region nor every crop grown there nor in every climate scenario. The predictability of detail at the small geographic levels for many key dimensions of climate is nearly zero. The climate models themselves are only coarsely resolved. Better downscaling methods are being applied but have not been broadly used in the assessments discussed above.

2.3 Approach of the Current Assessment

As evident from the review of past efforts, there are two broad methods of assessment. These are (1) Review and synthesize existing literature, (2) Conduct a broad scale modeling/analysis effort centered on a consistent set of scenarios. The IPCC and PEW center efforts are examples of the first. The US EPA and EPRI efforts are examples of the latter. There are also two broad objectives of assessments. These are (1) Estimate the impact (measured in a variety of ways) of climate change on agriculture. (2) Provide some guidance about what to do about climate change to limit or avoid negative consequences or take advantage of opportunities. The CAST and OTA assessments were examples of the latter while the USDA and EPRI are examples of the former. The second IPPC assessment, using literature review, included both an evaluation of impacts and the potential responses that could limit impacts. Assessments also vary in their attempts to provide quantitative information and those that provide qualitative conclusions.

This assessment tackles several of the caveats and limitations but not all. We use quite recent transient climate scenarios and thus are able to consider impacts relevant to specific years, the 2030-2040 period and the 2090-2100 period. This is a substantial improvement compared with previous analyses; whether and what types of actions might be taken over the next 5 to 10 years depend on when the climate impacts are expected. We evaluated and include in our assessment the potential implications of changes in pesticide expenditures due to climate change. The issue of pests and climate remain uncertain but this inclusion adds another dimension to the complex climate agro-ecosystem interactions we might ultimately expect. We have evaluated a broad group of crops including the major grains (wheat, corn, sorghum) and soybeans, forage crops (alfalfa and range) and some of the more important fruits and vegetables (tomatoes, citrus, and potatoes). By including vegetables and fruits, and other crops that are heat loving, we help remove a potential bias in some previous work that considered only the major grains; the concern with some of these studies was that heat-loving crops that may have benefited from warming could have overestimated damages. We have also considered more completely, the effects of climate change on irrigation water supply. We were able to use results of the water sector assessment to evaluate more realistic changes in water supply to agriculture. We begin with a brief discussion of the scenarios used for the various analyses. Then we provide a summary and overview of models used in the analysis. Finally, we provide a brief discussion of surprise, uncertainty, and the scope of climate-agroecosystem-economic interactions. The ability to assess the complete system in all its complexity does not yet exist; it is useful, none-the-less, to convey a sense of these complexities.

2.3.1 Scenarios

The National Assessment recommended and provided socioeconomic and climate scenarios. We used the Canadian Climate Center and Hadley Center climate scenarios. We did not make use of the socioeconomic scenarios.

2.3.1.1 Socioeconomic Scenarios and Assumptions

Following the pattern of many past assessments of climate change impacts, we applied climate change to the cropping and economic system as it existed today (circa 1990). This approach appears, to many, to go against common sense. Crop yields are likely to be higher in the future, agricultural prices will be different, land use patterns will change, the global trade picture will change, and the entire set of technological options available to farming will change. Indeed, our steering committee suggested that we must necessarily consider climate change operating in a future world. Paraphrasing one member, the historical response and even the response of today's agricultural system is irrelevant as agriculture is changing so fast.

Why did we ignore this advice? The simple answer was that developing interesting scenarios of the future that differed in ways that are important in terms of climate response would have required resources beyond those we had. There is not a widely developed set of long-term forecasts for agriculture. The Economic Research Service of USDA produces a 10-year ahead baseline for the US. We require scenarios for 30 and 90 years in the future. There are several forecasts of world agriculture that try to look out 30 years (for a review, see Reilly and Fuglie, 1998), however, these types of scenarios do not necessarily change the sensitivity of agriculture to climate change.

The EPA global study and the DOE MINK study developed future scenarios of world agriculture and agriculture for the Missouri, Iowa, Nebraska, Kansas region, respectively. The lessons from these studies and from other future forecasts are that: (1) Future prices and other measures of agricultural shortfall or excess depend almost completely on the rate of yield growth relative to population growth. (2) Any extrapolation of yield growth at rates like those experienced over the past few decades will result in yields at least 70 percent above today's yields by 2030; it is hard to imagine or conceive of crops that maintained such yield growth through 2090. (3) Factors other than climate change are more important for the agricultural economy in the future and these factors are uncertain; changing underlying assumptions within a range most experts would accept as bracketing what might happen in the future can lead to vastly different and larger effects than climate change. (4) When different future assumptions about these other factors have been incorporated in climate assessment they have not changed the climate response that much. For example, after adjusting crop response to generate higher yields, the MINK study still found about the same percentage effect of climate change on crops. The EPA global study found that for measures of those at risk of hunger, the absolute number increased with population increase and, because hunger risk depended directly on income and food prices, scenarios with higher income or more rapid yield growth produced smaller numbers of at risk people. One analysis used crop yield results from the EPA global study imposed on the current (1990) agricultural economy. It came to similar broad conclusions as the original study in terms of areas that win and lose as a result of climate change and in terms of the net effect on the world food system. As a first approximation measuring economic response in terms of producer and consumer surplus is likely to be relatively insensitive, in percentage terms, to the scale of activity (more or less production) and even to whether prices have fallen or risen, unless the demand and supply responses are highly non-linear.

The “non-effect” on climate response to forecasted futures of other variables is hardly, however, an absolute finding or certainty. It likely reflects instead our inability to foresee or create scenarios that would substantially change the climate response. If there were much more irrigation, or much less, the response to precipitation would change. If future US agriculture concentrated in particular areas that were then either much more beneficially or negatively affected by climate change than other areas, the response would change. By 2090, the crops and production practices may be unrecognizable to us today; perhaps any fast-growing, highly productive crop will be a feedstock for manufactured food and feed products, eliminating or nearly so, the need to produce grain and other specialized crops. Suitable biomass crops might be grown under many conditions including freshwater and marine environments.

One problem with trying to assess what these different scenarios might mean for climate change is that such dramatic changes may represent, in part, a response to a gradually changing climate. If technological change itself is highly responsive to relative scarcity of land (and the climatic conditions that go with it) then the variety of dramatically different scenarios would develop only under some climate scenarios but not others. Considerable evidence has been collected by some researchers (Hyami and Ruttan, dates) showing strong endogenous response of technology to relative input prices. In this framework, broadly worsening climate conditions would increase the price of land in the few remaining good areas and these price increases would spur technical change to reduce the need for good climate. For example, the response might be to generate the production system outlined above as a possibility for 2090, where almost any type of biomass crop could be used as a feedstock for food production. On the other hand, improving climate conditions could turn many areas into potentially prime producing areas. This could greatly reduce the need for yield-enhancing research; improving climate and higher levels of ambient CO_2 would produce yield increase without any research effort. Research dollars would be invested more profitably elsewhere rather than spur even greater yield increases that caused commodity prices to plummet. The ability to quantify and forecast this endogenous response over long periods of time is almost non-existent at present and presents a formidable challenge for research. For the above reasons we, therefore, chose to impose climate on agricultural markets as they exist today, supplementing this modeling work with a discussion of possible future changes and how they could alter climate sensitivity of agriculture.

With regard to the future, our stakeholder meeting identified several important changes for agriculture. Given their importance, it is worthwhile to speculate on how these changes might interact with climate sensitivity. The first of these is the technological change. Precision agriculture and biotechnology are the two main technological forces behind agricultural research at the moment.

- Precision agriculture allows farmers to precisely and differentially manage (in terms of water, nutrients, pesticides, etc. applications) small areas of a field using computer monitoring and global position systems. The idea is that much more efficient use of inputs and higher yields are possible by directing the right amount of input to each area rather than use an average amount of input where it is too much in some areas and too little elsewhere. While precision agriculture may have such effects, it is not clear that it would reduce climate sensitivity. A crop growing with ideal levels of nutrients, water, and pest control would still be subject to losses from climate. Indeed, the current practice tends to be relatively high levels of applications of inputs to get high yield over most of the field. More careful monitoring and faster response to changing conditions could however reduce adjustment costs if farmers are able to detect and respond to changing climate conditions more rapidly. Clear detection of climate change based on pure data analysis of historic weather, is fundamentally limited by the ability to separate trend from a very noisy record.

- Biotechnology offers the possibility to modify crops and livestock well beyond the limits imposed by the genetic diversity within varieties that can be interbred. Biotechnology appears capable of dramatically changing the technological response. There remain some broad biological limits. Without water, for instance, high levels of biomass production per hectare are probably not possible. But, the genetic diversity across species could allow much response to many different environmental conditions. If anything, biotechnology increases the potential for endogenous technological change to minimize climate effects.

Globalization of markets and industrialization of agriculture were two additional forces. A major force behind globalization is to ensure supply to markets under current weather variability. Along these lines, globalization will almost certainly reduce any negative impacts of climate change on commodity and food markets, minimizing the impact of climate on those who obtain their food from these markets. It is likely, however, to amplify regional effects on producers and could further marginalize the poor in developing countries. Already, the global market places considerable pressure on producing areas that have difficulty competing with more productive, lower cost producing areas. With a strong network of interwoven international markets, crop failures in a region need not increase market prices if balanced by gains elsewhere. In contrast, in a world with regional differentiated markets, producers in the failing area would benefit from higher regional prices. Food consumers in the region would obviously pay more. An interesting example of the attempt to shield regional producers from competitors in other regions is the milk marketing system that is gradually being dismantled in the US. Regional consumers paid higher prices but these supported a dairy industry in the Northeast against competition from Wisconsin. Also at risk are subsistence farmers and consumers around the world. Governments and markets have not been particularly kind to traditional and tribal populations when they have had the unfortunate luck of being located on a resource that became valuable. If climate change caused world commodity prices to rise, it is a near certainty that wealthy consumers in the developed countries could bid away any remaining production from poorer regions.

Industrialization of agriculture is a broad idea, incorporating many different changes in the structure of the agriculture sector. In part, it includes the increasing technological sophistication and precision management of production that allows production of commodities to meet processing specifications. It also includes the increasing horizontal (across the producing entities and regions) and vertical (with input and processing industries) integration of production. One feature of this structural change is contract production whereby many smaller farms produce under contract with a processor with some form of price guarantee and with greater specification for inputs and production practices used to assure uniformity and timely delivery of the product. One feature of this form of production is that the large processor pools risks across many farmers and areas, creating greater assurance of return for farmers under contract. This broad scale integration is likely to reduce further the chance that a local or regional crop failure will disrupt supply in the region. Integration will also pool income risks for producers. Contract production could have similar effects but the relative risk to the producer and contractor depends on the specific terms of the contract.

The other major trend in US agriculture is the drive toward improved environmental performance. We examine many of these issues in more detail in Chapter 5. There are three broad issues. One is competition between agriculture and environment for resources, mainly land and water. In the Western US, the desire to improve fish habitat (e.g. salmon spawning areas on rivers) is leading to a rethinking of the allocation of water and pressure to remove dams that supply water. There is continuing debate and discussion about grazing on Federal land and its implications for wildlife habitat. Other concerns about endangered species habitat, wetland preservation, and further demands for parkland and open space will likely increasingly bid for land now in agriculture. We investigate competition for groundwater in the Edwards Aquifer in the area including San Antonio, Texas. We also examine overall agricultural resource use implications in Chapter 3. A second issue involves interactions of agriculture and urban/suburban in the landscape. There are positive and negative aspects of this interaction. Farmland can provide greenspace in the midst of urban development. Such farmland can provide unique services and products for the local urban area, from fresh produce for farmers markets to farm experiences for urban dwellers. On the negative side, intensive production, particularly large livestock operations, have created large concerns about odor and pollution. The positive aspects of this interaction have led many states to develop programs to preserve farmland. The negative aspects have led to regulations and prohibitions on farming practices. A third aspect is the production practices that lead to pollution, to now mainly water pollution but with recent concerns about air pollution effects. Soil erosion runoff into lakes and rivers carries with it nutrients and agricultural chemicals. Irrigation drainage water similar also concentrates chemicals and salts in water bodies. Leaching of chemicals applied to crops can lead to groundwater contamination. Climate change has the potential to greatly affect these interactions by changing land use, irrigation water use, as well as the intensity of rain and wind that is responsible for erosion. We consider the impact on land and water use in Chapter 3 and soils, nutrient runoff into the Cheasapeake Bay, and implications for pesticide expenditures in Chapter 4. As our case studies in Chapter 4 illustrate, the drive to improve environmental performance of agriculture could, by itself, significantly change farming practices and this can greatly affect how climate change will affect agriculture and the environment.

2.3.2 Climate Scenarios

We used the Hadley Center and Canadian Climate Center model simulations to develop climate scenarios for the crop modeling work. In this regard, we followed previous agricultural assessments and applied the monthly mean changes in climate between the greenhouse gas-forced scenarios and the control runs to a 30-year actual record of weather for the sites at which we ran the climate models. This approach has been used in the past because, while climate model output broadly agrees with observed seasonal and spatial patterns of climate, the agreement with actual weather at a specific site is very poor. Applying the differences (additive for temperature and as a ratio for precipitation) means, for example, that all days are warmer but the pattern of warm and cool days (i.e. the variance) remains the same. This means that any change in variance predicted by the GCMs is averaged out. We discuss later in more detail what the climate models indicate about variance of weather and climate and some results using changes in variability.

Broadly, the Hadley and Canadian Climate Center scenarios represent scenarios that fall in the middle and at the high end, respectively, of IPCC projections of warming by the year 2100. Both scenarios have increased precipitation at the global level, consistent with the speeded up hydrological cycle accompanying warming. For the US as a whole, the Canadian model predicts a 2.1º C average temperature change by 2030 and a 5.8º C warming by 2095 with a four percent decline and 17 percent increase in precipitation, respectively. The Hadley Center scenario produces a 1.4º C (2030) and 3.3º C (2095) increase in temperature with precipitation increases of six and 23 percent. Both indicate more warming in the winter and relatively less in the summer. The Mountain States and the Great Plains tend to show more warming than other regions in both scenarios. The Hadley scenario also shows greater warming in the Northwest. More detail on the climate scenarios is available at http://www.cgd.ucar.edu/naco/vemap/vemtab.html.

2.4 Agricultural Models

Climatic and other factors strongly interact to affect crop yields. Models have provided an important means for integrating many different factors that affect crop yield over the season (Rötter, 1993). Scaling up results from detailed understanding of leaf and plant response to climate and other environmental stresses to estimate yield changes for whole farms and regions can, however, present many difficulties (e.g., Woodward, 1993).

Higher level, integrated models typically accommodate only first-order effects and reflect more complicated processes with technical coefficients. Mechanistic crop growth models take into account (mostly) local limitations in resource availability (e.g., water, nutrients) but not other considerations that depend on social and economic response such as soil preparation and field operations, management of pests, and irrigation.

Models require interpretation and calibration when applied to estimate commercial crop production under current or changed climate conditions (see, Easterling *et al.*, 1992; Rosenzweig and Iglesias, 1994); in cases of severe stress, reliability and accuracy to predict low yields or crop failure may be poor. With regard to the CO_2 response, recent comparisons of wheat models have shown that even though basic responses were correctly represented, the quantitative outcome between models varied greatly. Validation of models has been an important goal (Rosenberg., et al., 1992; Olesen and Grevsen, 1993; Semenov *et al.*, 1993a,b; Wolf, 1993a, b; Delecolle, 1994; Iglesias and Minguez, 1994; Minguez and Iglesias, 1994).

To generate results at the national and global level, results from crop models are then used in an economic model (e.g. Adams, et al., 1995; Reilly, et al., 1994). There are two basic types of economic models. (1) Those that include costs of many different activities (e.g. crops, cropping practices, rotations, etc.) (e.g. Adams, et al., 1995). With changed conditions, such as changed productivity due to climate changes, such models find the least cost way to satisfy demand. (2) Those based on statistical estimates of supply and demand for individual crops (e.g. Reilly, et al., 1994). Changes in climate can then be represented as shifts in supply. The activity type of model tends to have much more spatial and cropping practice detail. We apply the activity type model in this assessment because of the spatial and crop detail.

There have been efforts to further integrate crop yield, phenology, and water use with geographic-scale agroclimatic models of crop distribution (Brown and Rosenberg, 1999; Kenny *et al.*, 1993; Rötter and van Diepen, 1994; Kenny *et al.*, 1995) thus providing greater representation of diverse conditions across a large geographic scale. There have also been efforts to integrate crop models and farm-level economic response (e.g. Kaiser *et al*., 1993). Simplified representations of crop response have been used with climate and soil data that are available on a global basis (Leemans and Solomon, 1993). More aggregated statistical models have been used to estimate the combined physical and socioeconomic response of the farm sector (Mendelsohn *et al.*, 1994; Darwin *et al.*, 1995).

Incorporation of the multiple effects of CO_2 in models has generally been incomplete. Some do not include any CO_2 effects and thus may overestimate negative consequences of CO_2-induced changes in climate. Other models consider only a crude yield effect. More detailed models consider CO_2 effects on water use efficiency, e.g., Wang *et al.* (1992), Leuning, *et al.* (1993). With few exceptions, most models fail to consider CO_2 interactions with temperature and effects on reproductive growth (Wang and Gifford, 1995). The EPIC model incorporates the CO_2 effect in a relatively simplified fashion (Stockle et al., 1992a,b).

We use the site-level models for our basic analysis, following the approach used in many previous assessments. To examine the sensitivity of our results to this modeling approach we also have applied the Brown and Rosenberg (1999) model. It has fewer crops and is expensive to use so we simulated it only with the Hadley center scenario. The results are reported in detail in Izaurralde, Brown, and Rosenberg (1999). The model projects corn, winter wheat, soybeans, and alfalfa under dryland and irrigated conditions. This allowed us to investigate to what extent the projections of this crop modeling approach differ from the site approach. The reduced form statistical approach of Mendelsohn et al. is relatively simple to apply, once the response is estimated. It, however, does not include a CO_2 fertilization effect and captures all response as change in land value. Thus, there is not detail on specific crops. The case for this approach is that it takes better account of farm-level response, at least under long-run equilibrium conditions, and includes (implicitly though not explicitly) all crops that contribute to agricultural land value.

Broadly our approach has been to try to use several different approaches and to test results with sensitivity analysis. This has allowed us to consider to what extent the results depend on the particular method used.

2.5 Vulnerability, Surprise, Uncertainty

Quantitative analysis of climate change impacts faces many difficult challenges. The great value of quantitative analysis is that it enforces considerable rigor to our thinking about effects. The limitations are that potential interactions are only partly or poorly quantified and often not incorporated in assessment models, climate scenarios are uncertain, we have only a vague idea of what agriculture may look like in the future when climate change is expected to occur, and with something as far-reaching as global climate change there are likely to be things that happen that we never foresaw or imagined. These set of concerns have caused analysts to approach assessment in ways other than the linear approach typically used (e.g. from climate scenario, to crop impact, to economic impact).

Vulnerability and sensitivity analysis has been one alternative approach. The idea here is that climate scenarios are so uncertain that instead one should investigate a wide range of climatic conditions. Such analysis identifies the climate conditions that are particularly damaging. Applied to agriculture, analysts might then identify things that could be done to reduce or eliminate these damages. Such an approach is one way to avoid the narrow range of climate conditions simulated by GCMs. The difficulty, however, is that it is not hard to imagine disastrous weather and it would not make sense to spend large amounts of money to protect oneself against an outcome that was extremely unlikely to occur. The usefulness of this approach rests in finding things that are simple, cheap, and easy to do that could insulate one against things that one had not anticipated.

If a probabilistic scenario analysis can be completed, then one can include both the probability and damage associated with each scenario in an uncertainty/vulnerability analysis. In principle, one can estimate the expected cost associated with climate and undertake only those actions whose cost were less than *expected* reduction in damages (for a more formal discussion, see Reilly and Schimmelpfennig, 1999). For example, it would be worth only $100 to avoid a $10,000 dollar damage that had only a 1 in 100 chance of occurring. Unfortunately, climate modeling is unable at this time to generate such probabilistic scenarios.

The other concern is surprise—climate interactions with agriculture that we never anticipated. By there very nature, once we have thought of the interaction it is no longer a complete surprise. It is, however, easy to make the mistake of applying existing assessment approaches and models, implicitly assuming they contain all the important interactions. The antidote to falling into this trap is to rethink fundamental relationships and interactions, consider broader connections, and to conduct targeted research to investigate some of links where little is known.

What are possible surprises? The most significant surprise for agriculture would be significantly different climate scenarios than are now projected by the major climate prediction centers. Significant increases in variability could greatly disrupt agriculture. We consider this issue in detail in Chapter 4. As already discussed, the climate predictions used thus far are mainly central tendency estimates and do not exhibit major non-linearities or state changes. Describing the likelihood or the character of such scenarios is well beyond the scope of the Agricultural Assessment, but the impacts on agriculture of such climatic consequences of warming would be far different than any scenarios evaluated to date, including those in this assessment. It is under such scenarios that rapid change, at least at a regional level, could occur and with it significant adjustment costs.

Within the agricultural system, the development of new pests and/or expanded range and greater resistance to control methods are certainly possible but difficult to foresee. We know that weather and climatic factors are one critical element of the range of pests but are poorly equipped to evaluate the full set of habitat interactions. We will observe climate change as a change in extreme events (more hot days and less cold days; more heavy rain or longer droughts) rather than changes in the means. Once in 100 or 1000 year events will always be a surprise. Our ability to identify whether the occurrence of such an event signals a change or is simply chance will at least partly determine whether we go back to doing the same or adapt. In this regard, institutional preparedness and response is nearly impossible to predict. An unwillingness to adapt and change, rigidities in policy, or counterproductive policy responses could increase costs. Face with loss of comparative advantage and threats to its local farming community, a region might seek Federal money to subsidize farming, to create protectionist trade policy, or to build huge water projects only to maintain regional production. Such programs could at huge economic and environmental cost and might ultimately fail as climatic conditions continue to worsen.

Finally, we know very little about how a regional and local economy responds to multiple changes. The local tax base, recreation, agriculture, water, forests would be affected simultaneously. History has many cases of regions and communities declining and depopulating when a critical resource is exhausted, a industry on which a community is based fails or fails to keep pace with competitors, or other areas are deemed more livable or more fashionable. On the other hand, many areas have diversified, shifted, and reoriented themselves to take advantage of new conditions.

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