3.0 Impacts of Climate Change on Production Agriculture and the US Economy

3.1 Introduction

Climate change affects farmers and the US economy by way of a number of different effects. Analysis of various effects such as impacts on crop yields, water demand, water supply, and livestock using biophysical models can tell us much with regard to why a particular climate scenario causes yields to rise or fall. This analysis also can suggest directions for adaptation at the farm-level. All of these changes occurring together and across the entire US and the entire world mean that national and global markets can be affected. Thus, to consider economic viability of farming and impacts on consumers and the US economy requires that the full effect of changes in crop yield, water demand, water supply, pests, and livestock as they vary across the country and the world must be considered. As reviewed in chapter 2, many studies have demonstrated that farmers can suffer economic losses even if crop yields improve because commodity prices fall. The net effect on the US economy can be positive in this situation because consumers gain from lower food prices but these results are also sensitive to how climate change affects agriculture production in the rest of the world.

The techniques and approaches used build upon a number of previous efforts, the most recent of which was sponsored by the Electric Power Research Institute and is reported in Adams et al(1999). The other notable direct ancestor of this work is Adams et al (1990).

In this analysis, eight principal direct effects of climate change were considered. These involve the effects of climate change on

1) crop yields and irrigated crop water use,
2) irrigation water supply,
3) livestock performance and grazing/pasture supply,
4) pesticide use, and
5) international trade

This chapter combines these biophysical effects of climate change in an economic model that determines the new set of price, consumption, regional production, and resource use levels that clear markets.

The focus of the analysis was to estimate the consequences for the agriculture sector of climate-induced changes via each of the mechanisms listed above in terms of the overall level of producer income and the welfare of agricultural consumption by consumers. We also estimate changes in the location of production and the utilization of resources as influenced by climate change. These changes were estimated using a U.S. national agricultural sector model (ASM) that is linked to a global trade model. In particular the basic analytical approach was to introduce estimates of climate change induced alterations in the eight data items listed above and examine how the model solution differs from the solution realized under base, without climate change, conditions. The most important aspect of this analysis was generating changes in necessary inputs into the economic model such as crop yields and water demands for irrigation. Several teams of crop modelers simulated changes in yields and water demand to provide these changes.

The results were simulated for transient scenarios of the Canadian Climate Center model and the Hadley Center model. The impact analysis, while based on these transient scenarios, used average climate conditions for the 2030-2040 and 2090-2100 periods from the model to develop estimates representative of these decades.

The underlying yield and water demand changes were simulated for crops like those that exist today. Similarly, changes in pesticide use, water supply, livestock changes, and trade scenarios are based on patterns that exist today. The economic results were produced by simulating the impact of climate change on the agricultural economy as it existed in the year 2000, however, we also considered the impacts of climate change on a scenario of the agricultural economy projected forward to the years 2030 and 2090. These scenarios took advantage of scenarios generated under the Forest Sector Assessment. The ASM model used in this analysis is part of the combined Forest-Agriculture sector model that was used in the Forest Sector Assessment. We were thus able to simulate the combined effects of forest and agriculture changes on the US economy and consider the implications for land use.

We considered the effects of climate change via the five mechanisms above in such a way that these changes could be introduced into the economic model. The economic model used in the analysis does not use climate data directly. It uses changes in crop yields, water demand, water supply, and other factors as they are affected by climate. The changes are then introduced into the ASM model alone or in combination to evaluate their effect on the agricultural economy and resource use. This section reviews the basis for these changes and discusses the additional assumptions needed to introduce them into the economic model. Section 3.2 describes the basic methods and findings from the crop studies. Section 3.3 describes the approaches and additional assumptions needed to use these site level results in a national level economic model. Section 3.4 provides details on the estimation of livestock effects. Section 3.5 briefly describes the process by which pesticide use was included in the economic estimates, with greater detail provided in Chapter 6. Section 3.6 describes the basis for considering the effect of changes in production elsewhere in the world that affect US agriculture through international trade. Section 3.7 reports the economic and resource use results estimated using the economic model.

3.2 Simulations of Crop Yields and Crop Irrigation Demand

It is widely recognized that agricultural crop production might be significantly affected by the predicted changes in climate and atmospheric CO_2 (Rosenzweig and Hillel, 1998). While elevated CO_2 increases plant photosynthesis and thus crop yields (Kimball, 1983), the GCM-predicted changes in temperature and precipitation have the potential to reduce crop yields by hastening plant development and by modifying the water and nutrient budgets in the field, thereby increasing plant stress (Long, 1991). The net effects of increased CO_2 and climate change on crop yields will ultimately depend on local conditions. For example, warmer spring-summer air temperatures might be beneficial to crop production at northern temperate latitude sites, where the length of the growing season would increase. However, warmer temperatures might be negative during crop maturity in those regions where summer temperature and water stress already limit crop production (Rosenzweig and Tubiello, 1997). These various mechanisms and effects of climate on crops means that effects at a specific site depend highly on the specific details of a climate scenario.

The response of agricultural systems to future climate change will additionally depend on management practices, such as the type and levels of water and nutrient applied. Water limitation tends to enhance the positive crop response to elevated CO_2, compared to well-watered conditions (Chaudhuri et al., 1990; Kimball et al., 1995). The contrary is true for nitrogen limitation: well-fertilized crops respond more positively to CO_2 than less fertilized ones (Sionit et al., 1981; Mitchell et al., 1993).

Within cropping systems, a wide range of adaptations may exist, to help maintain or even increase crop yields under climate change, compared to current conditions. After all, farmers are able to respond to environmental change today, by choosing the most favorable crops, cultivars, and rotations. Assessment studies help to highlight which adaptation strategies might succeed in the future, and to identify climate and management thresholds beyond which crop yields could not be maintained at present levels.

Because many interacting factors determine the response of crops to changes in climate conditions and to elevated CO_2 concentration, computer simulations are used to analyze crop response and adaptation strategies to future climate change (e.g., Rosenberg, 1993; Rosenzweig and Parry, 1994).

The crop yield and irrigation water use impacts developed here were based on the crop studies conducted as part of the agriculture sector assessment. Coordinated site studies were conducted by GISS, University of Florida, and the National Resource Ecology Laboratory provide the core set of yield and irrigation water use estimates for economic analysis. The PNNL crop yield results were conducted only for the Hadley Center climate scenarios, and did not include as many crops as covered by the coordinated site level studies, or consider adaptation. The advantage of the PNNL work, however, is that it estimated impacts for each of over 250 representative regions whereas the detailed site studies were based on at most 46 sites. The PNNL analysis also used a different crop model, the Erosion Productivity Index Calculator (EPIC), to estimate yield and irrigation water demand effects. The PNNL results allow us to consider the sensitivity of the results to the specific design of the coordinated site level studies. We also adapted results from a Southeastern U.S. project being conducted at the National Center for Atmospheric Research (NCAR) in Colorado and led by Dr. Linda Mearns to provide estimates of impacts on cotton, an important crop for which we were unable to conduct new yield estimates. We describe very briefly here the basic approach and summarize the principal findings from the core site-level crop studies conducted here. We review very briefly other related crop studies. Details on each of the studies conducted under the auspices of the Agricultural

Sector Assessment are included in reports available at the National Assessment WEB site (http://www.nacc.usgcrp.gov).

3.2.1 Crop Models and Methods

We chose 45 sites across the US to assess potential impacts of climate change on the production of several major crops: wheat, maize, soybean, potato, citrus, tomato, sorghum, rice, and hay. The sites were chosen using USDA national and state-level statistics. Necessarily, they do not span the US homogeneously, but rather focus on areas of major production, of importance to the National output. At each site we collected observed time series of daily temperatures (minima and maxima), precipitation, and solar radiation, spanning the period 1951-1990, representing the “baseline” climate for this study. Scenarios of climate change were produced according to transient simulations performed with two general circulation models (GCMs), as distributed by the US National Assessment: the Canadian Center Climate Model (CC) and the Hadley Centre model. Two time periods were considered in this analysis: “2030” and “2090”, representing changes in climate predicted by each GCM, and calculated using twenty-year averages centered around the years 2030, and 2090, respectively. Atmospheric CO_2 concentrations, to be used for the crop model simulations, were calculated using the “business as usual” IPPC scenario. These were: 350 ppm for the baseline; 445 ppm for “2030”; and 660 ppm for “2090”.

GCM output was downscaled to each of the study sites by linear interpolation, using the four grid-points closest to each location. Mean monthly changes in temperature and precipitation were then applied to the observed baseline meteorological series, to produce representative weather for the future scenarios. A total of 5 scenarios were used in this study: 1) baseline, representing current conditions; HAD-2030 and CCCM-2030, representing climate and CO_2 levels averaged over 2020-2039 according to Hadley and Canadian Center predictions, respectively; HAD-2090 and CCCM-2090, representing conditions averaged over the period 2080-2099.

A suite of crop models was used to simulate growth and yield of the study crops under the current and climate change scenarios. The DSSAT family of models was used extensively in this study, to simulate wheat, corn, potato, soybean, sorghum, rice, citrus, and tomato (Tsuji et al., 1994). The CENTURY model was used to simulate grassland and hay production (Parson et al., 1994).

All models employed have been used extensively to assess crop yields across the US under current conditions as well as under climate change (Rosenzweig et al., 1995; Parton et al., 1994, Tubiello et al., 1999). Apart from CENTURY, which was run in monthly time-steps, all other models use daily inputs of solar radiation; minimum and maximum temperature; and precipitation, to calculate plant phenological development from planting to harvest; photosynthesis and growth; and carbon allocation to grain or fruit. All models use a soil component to calculate water and nitrogen movement, and are thus able to assess the effects of different management practices on crop growth.

The simulations performed for this study considered: 1) rainfed production; and 2) optimal irrigation, defined as re-filling of the soil water profile whenever water levels fall below 50% of capacity at 30 cm depth. Fertilizer applications were assumed to be optimal at all sites.

The climate change scenarios used in this study are more realistic than those previously available. Because they include the effects of sulfate aerosols on future climate change, they result in predicted changes in temperature and precipitation than are smaller than in previous "equilibrium" and transient climate change simulations, particularly in the first half of 2100. In fact, the temperature increases considered here in 2090 become substantial at all sites considered, as the "masking" effect of aerosols on climate warming becomes small, compared to the magnitude of greenhouse forcing.

Additional analyses, independent from the above site studies reported above, were developed by other groups in the US as part of the assessment effort or in ongoing research with using the same or similar climate models. There are some important differences in the assumptions used in these analyses that make them not directly comparable to the core studies reported above.

Researchers at the Pacific Northwest National Laboratories (PNNL) developed national-level analyses for corn, winter wheat, alfalfa, and soybean, using climate projections from the Hadley GCM (Izaurralde et al., 1999). In the PNNL study, the baseline climate data were obtained from national records for the period 1961 – 1990. The scenario runs were constructed for two future periods (2025 – 2034; 2090 – 2099). The Erosion Productivity Impact Calculator (EPIC) was used to simulate the behavior of 204 "representative farms" (i.e., soil-climate-management combinations) under the baseline climate, the two future periods, and their combinations with two levels of atmospheric CO_2 concentrations (365 and 560 ppm). This differed from the core studies that used 2030 and 2090 CO_2 levels. However, the CO_2 effect was fairly linear and independent of climate effects in the PNNL work, allowing interpolation. The results of the PNNL study were used in the economic model to compare the approach with that used in the coordinated site studies.

Another group, coordinated at Indiana University, focused only on corn, developing a regional analysis for the Corn Belt region, using Hadley model projections (Southward et al., 1999, in preparation). Baseline climate was defined using the period 1961-1990. Several future scenarios were analyzed for the decade of 2050, with atmospheric CO_2 concentration set at 555 ppm. Corn yields were simulated with the DSSAT model at 10 representative farms. Adaptations studied included change of planting dates, as well as the use of cultivars with different maturity groups. This work was not conducted with funding from the Agricultural Sector Assessment but offers some additional site-level information for corn.

Although specific differences in time horizons, CO_2 concentrations, and simulation methodologies complicate the comparison of these additional analyses to the work discussed herein, model findings were overall in general agreement with ours. They are briefly discussed, crop-by-crop, in the "results" section of this work.

3.2.2 Simulations Under Current Climate

A test of the basic validity of the models was to simulate yields under current climate and compare them, coarsely scaled, to the state level by using statistical information of percent irrigation. These comparisons showed generally good agreement with reported yields variations across the US.

In addition to current practices at each site, we also simulated different adaptation techniques for use under climate change. These consisted largely in testing the effects of early planting, a realistic scenario at many northern sites under climate change; and in testing the performance of cultivars better adapted to warmer climates, using currently available genetic stock. In general, early planting was considered for spring crops, to avoid heat and drought stress in the late summer months, while taking advantage of warmer early temperatures. New, better-adapted cultivars were tested for winter crops, like wheat for example, to increase the time to maturity (shortened under climate change scenarios) and to increase yield potential. Results of these comparisons with current yields are presented below.

Winter wheat. Winter wheat was simulated at Abilene, TX; Boise, ID; Columbus, OH; Dodge City, KS; Topeka, KS; Goodland, KS; North Platte, NE; Oklahoma City, OK; and Spokane, WA. The calculated distribution of irrigated and rainfed production sites correlated well with actual county-level maps of irrigated versus rainfed production. Record irrigated yields were simulated at Boise, ID, with all remaining sites producing from 4.5 to 5.5 t/ha. Coefficients of variation for irrigated production were 10-15%. The largest impacts of irrigation over rainfed practice were at Boise, ID (more 400%) and Spokane, WA (150%). The smallest gains with irrigation were at the wet sites, i.e., Columbus, OH, and Topeka, KS.

Spring wheat. Spring and durum wheat are grown extensively in North and South Dakota and Montana, with some important production centers in the Northwest, California, and Arizona. A total of eight sites of importance to US spring wheat production were chosen: Boise, ID; Fargo, ND; Fresno, CA; Glasgow, MT; Pierre, SD; St. Cloud, MN; Spokane, WA; and Tucson, AZ. Simulated irrigated yields were 50-60% higher than rainfed, with lower year-to-year variability (CV). The simulated marginal returns on irrigation were large at Boise, ID; Spokane, WA; and Tucson, AZ, where irrigated yields were 100%, 300%, and 1000% higher than under rainfed conditions. The highest irrigated yields, 7-8 t/ha, were simulated at Tucson, AZ and Fresno, CA, with all remaining sites producing 3-5 t/ha. Coefficients of variation for irrigated production were 10-15%, and 40-50% for rainfed production.

Maize. Simulated maize yields agreed well with reported state-level averages, with the highest dryland yields, above 8 t/ha, simulated at Columbus, OH; Madison, WI; and Indianapolis, IN. Production at the remaining sites was in the 5-7 t/ha range, with low yields and high CVs simulated at St. Cloud, MN, currently at the northern margin of the main US corn production area.

Potato. We chose a total of twelve sites of importance to national potato production: Alamosa, CO; Boise, ID; Buffalo, NY; Caribou, ME; Fargo, ND; Indianapolis, IN; Madison, WI; Medford, OR;

Muskegon, MI; Pendleton, OR; Scott Bluff, NE; and Yakima, WA. Continuous rainfed potato production was simulated as viable at Buffalo, NY, Caribou, ME, Fargo, ND, Indianapolis, IN, and Madison, WI. Under current climate, crop simulations correlated well with reported production. The highest simulated irrigated yields, slightly above 80 t/ha, were at the Northwestern sites, Medford, OR, Pendleton, OR, and Yakima, WA, where the marginal impact of irrigation was also the greatest (irrigated yields were about ten times rainfed yields). At all remaining sites production was between 40 and 50 t/ha. Coefficients of variation for irrigated production were 6-9%. The CVs were between 30 and 40% under rainfed conditions.

Citrus. Simulations for Valencia Oranges were conducted at eight sites with substantial current production, of which five sites, Bakersfield, CA; Corpus Christi, TX; Daytona Beach, FL; and Miami, FL, correspond to high-producing areas in the US, yielding above 11 t/ha of fruit. One site, Red Bluff, CA, represented mid-level production, around 7 t/ha; and three sites, Tucson, AZ; Port Arthur, TX; and Las Vegas, NV, producing 4-6 t/ha, representing marginal production levels. An additional five sites were chosen to investigate potential for citrus expansion northward of the current production area. These were El Paso, TX; Montgomery, AL; Savannah, GA; Shreveport, LA; and Tallahassee, FL. Under current climate, simulations at these latter sites yielded 2-2.5 t/ha.

Soybean. Soybean production was simulated across the US at fifteen sites: Charleston, SC; Louisville, KY; Raleigh, NC; Des Moines, IA; Duluth, MN; Indianapolis, IN; Madison, WI; Memphis, TN; Montgomery, AL; Muskegon, MI; North Platte, NE; Peoria, IL; Savannah, GA; S. Cloud, MN; and Topeka, KS. Simulated yields at these sites had been previously validated under current conditions, and were well correlated with production data at the state level.

Sorghum. Sorghum production was simulated across the US at fourteen sites: Charleston, SC; Louisville, KY; Raleigh, NC; Abilene, TX; El Paso, TX; Goodland, KS; Montgomery, AL; North Platte, NE; Oklahoma City, OK; Peoria, IL; Pierre, SD; Savannah, GA; Sioux Falls, SD; and Topeka, KS. Simulated yields at these sites well compared to state-level variations across the US sorghum production area.

Rice. Eight sites accounting for 48% of US rice production were selected to represent the US rice growing regions: Louisville, KY; Bakersfield, CA; Des Moines, IA; El Paso, TX; Fresno, CA; Miami, FL; Montgomery, AL; Port Arthur, TX; Peoria, IL; Red Bluff, CA; Shreveport, LA; and Topeka, KS. The sites were chosen to include both regions with current production and those where rice production could potentially be viable under climate change. The highest simulated yield under current conditions was 9 t/ha, in California, and the lowest 5 t/ha, for Louisiana, in agreement with observed state-to-state yield differences.

Tomato. Tomato production was simulated across the US, at eighteen sites: Charleston, SC; Louisville, KY; Raleigh, NC; Boise, ID; Buffalo, NY; Duluth, MN; El Paso, TX; Fresno, CA; Indianapolis, IN; Montgomery, AL; Muskegon, MI; North Platte, NE; Oklahoma City, OK; Peoria, IL; Tallahassee, FL;

Topeka, KS; Tucson, AZ; and Yakima, WA. Simulated yields at these sites, validated under current conditions, correlated well with state-level data.

3.2.3 Simulation Results Under Climate Change

We provide here a brief summary of the main climate change results, including those for adaptation.

Winter Wheat. The two climate scenarios considered in this study gave opposite responses for US wheat production, with the Canadian Center climate scenario resulting in large negative to small positive impacts, while the Hadley scenario generated positive outcomes. The warmer temperatures predicted under climate change were favorable to northern site production, but deleterious to southern sites. Increased precipitation in the Northwest and decreased precipitation in the central plains were the major factors controlling the response of wheat yields to the future scenarios considered in this study. We first analyze results for the current production management at each site, and then proceed to discuss the potential for management shifts and adaptation.

In agreement with the results presented here, the PNNL study found that "winter wheat exhibited consistent trends of yield increase under the [Hadley] scenarios of climate change across the U.S" (Izaurralde et al., 1999). The study did not consider the Canadian Center climate scenario.

Under rainfed conditions, Columbus, OH, was the only site where all climate scenarios resulted in yield increases of 3-8% in 2030 and 16%-24% in 2090. At all other sites, including the major production centers in the Great Plains, the Canadian Center scenarios resulted in large negative impacts for both continuous and fallow production. Grain yields decreased 10%-50% in 2030 and a bit less, by 4-30% in 2090. Most importantly, at Dodge City, KS; Goodland, KS; and North Platte, NE, coefficients of variation of yield consistently increased in both decades. Under the Hadley climate scenario yields increased at all sites considered. Rainfed production increased by 6%-20% in 2030 and by 13% to 48% by 2090. Year-to-year variation decreased at most sites.

Irrigated wheat yields increased under both GCM scenarios, although increases were larger under the Hadley than under the Canadian Center predicted climate change. In 2030, yield increases ranged between 2-10%. In 2090, yields were 6%-25% greater than under current conditions. At the same time, irrigation water use decreased by 10%-40%.

Crop simulations showed no benefit to changing from the current crop and water management of practices for wheat production under the Hadley scenario. Under the Canadian Center scenario, simulations of rainfed cultivation was subject to a high frequency of years with very low yields, suggesting that rainfed production may no longer be viable in Kansas if these climate conditions are observed in the future. Maintenance of current production, all else being equal, would require irrigation.

Adaptation strategies simulated for wheat in the central plains involved shifting to cultivars better adapted to a warmer climate. Specifically, cultivars that require less vernalization, and with longer grain filling periods could be planted, to counterbalance the hastening of maturity dates due to warmer spring and summer temperatures. For example, cultivars currently grown in the south could be planted at northern locations. The predicted yield decreases at North Platte NE were eliminate by shifting to a southern-grown variety. The same strategy did not yield positive results for the Kansas and Oklahoma sites considered in this study, due to the large decreases in precipitation predicted by the Canadian Center model at these sites.

Spring Wheat. Warmer temperatures were the major factor affecting spring wheat yields across sites, time horizon, and management practice. Considered alone, they hastened crop development and affected crop yields negatively.

Despite warmer temperature in 2030, rainfed spring wheat production increased by 10-20% under both GCM scenarios due to increased precipitation that also reduced CVs and thus year-to year production risks. This positive trend continued in 2090 under the Hadley scenario, generating yield increases of 6-45%. The largest increases (47%) were simulated at Pierre, SD. The 2090 Canadian Center scenario resulted in significant decreases in spring wheat yields at current production sites. Yields decreased at Fargo, ND (16%); and Glasgow, MT (24%). The Canadian Center scenario also generated yield decreases at Fresno, CA (20%). By 2090, the Canadian Center-predicted temperatures were high at all sites considered, affecting wheat development and grain filling negatively, and depressing yields despite the gains due to precipitation increases.

Irrigated spring wheat production decreased by 5-20% at five of the eight sites considered, under both scenarios. In 2030, yields decreased at Boise, ID (7 to 17%), Spokane, WA (1 to 4%), Tucson, AZ (3 to 6%), and Fresno, CA (16 to 24%). The same negative trends continued at these sites in 2090, with the largest reduction simulated at Fresno, CA (30 to 45%).

Under every scenario and at all sites irrigation water use decreased significantly, due to the accelerated growing periods under the warmer climates rather than to stomatal closure under elevated CO_2. By 2090, simulated yield reductions at all sites were in the range of 20-40%, and consistently above 50-60% at Fresno, CA.

Simulated rainfed production became increasingly more competitive with irrigation under all scenarios, due to increased precipitation. For example, at Spokane, WA; and Boise, ID, which are currently irrigated sites, today's production levels could be maintained under the scenarios considered by shifting some irrigated land to rainfed production. By 2090, there would be no need for irrigated production at Boise, ID under the Canadian Center scenario.

At Fargo, ND and Glasgow, MT additional simulations indicated that yields could be maintained at current levels by planting two to three weeks earlier, compared to current practices.

Corn. Climate change affected dryland corn yields positively. The predicted increases in precipitation more than counterbalanced the otherwise negative effects of warmer temperatures across the US sites analyzed. Increases were simulated at current major production sites: Des Moines (15-25%), IA; Peoria, IL (15-38%); Sioux Falls, SD (8-35%). Larger increase were simulated at northern sites: Fargo, ND (25-50%); Duluth, MN (30-50%), and St. Cloud, MN, where both warmer temperatures and increased precipitation contributed to increased corn yields compared to current levels. Smaller changes, in the range –5% to +5%, were simulated at the remaining sites.

The PNNL results were in agreement with the findings of our study for rainfed corn production, for which "increases were predicted for future production of dryland corn in the Lakes, Corn Belt and Northeast regions of the U.S" (Izaurralde et al., 1999). On the other hand, the PNNL study predicted increases in irrigated corn yields in almost all regions of the country, in contrast to the site results as discussed below.

A study for the Corn Belt region, conducted at Indiana University (Southward et al., 1999), was in general agreement with our findings, predicting increases in corn yields across the northern Corn Belt region. For five southwestern locations in Indiana and Illinois, the Indiana University work predicted corn yield decreases, in the range 10-20%. The coordinated site studies we conducted did not show yield losses in the southern cornbelt sites but we did no have as many sites in this Southern portion of the Corn Belt. The PNNL analysis that provides a much denser sampling showed yield declines for corn consistent with the Indiana results for this area. There were also differences in the analysis protocol used by the Indiana group that likely led to differences in results. Clearly, for reliability at substate levels a far denser sampling is needed than the 45 sites we chose to cover the entire nation.

Climate change affected irrigated yields negatively, in the range of – 4% to – 20%, at the two major production sites considered, in Kansas and Nebraska. At northern sites, simulated irrigated yields, which are currently limited by cold temperature, increased substantially. For instance, at St. Cloud, MN, the simulated yields under the 2090 Canadian Center scenario were almost three times as much as current levels.

Additional simulations suggested that early planting would help maintain or slightly increase current production levels at those sites experiencing small negative yield decreases. In general, dryland corn production could become even more competitive over irrigation, with higher yields and decreased year-to-year variability. Great potential for both increased production and improved water management was simulated at the northernmost sites, in ND and MN.

Potato. Irrigated potato yields generally fell while, under rainfed conditions, yield changes were generally positive.

Under rainfed conditions, both climate scenarios considered in this study resulted in sizable gains in 2030. At four of the five sites considered, crop production increased on average by 20%, except at Indianapolis, IN, where the Canadian Center scenario predicted a -33% reduction, while the Hadley scenario resulted in a 7% increase. CVs for all sites generally decreased due to increased precipitation.

In 2090, the Canadian Center scenario resulted in large decreases at most sites, while under Hadley potato yields increased by 10-20%, largely maintaining the gains reached by 2030. Under the Canadian Center scenario, rainfed production decreased on average by more than 20%, with the smaller effects simulated at Madison, WI, and the largest at Indianapolis, IN (47%), and at Fargo, ND (63%). Under this scenario, large increases in temperature in 2090 counterbalanced the beneficial effects of increased precipitation.

Irrigated yields decreased in 2030, by 1% to 10%, with a few sites registering no change or small percentage increases. The predicted temperature increases affected crop production negatively. Under the Canadian Center scenario most sites showed simulated yield reductions from 6% to 13%. Exceptions were Indianapolis, IN (-36%) and Yakima, WA (+5%). Under the Hadley scenario, yields decreased from 6% to 8%, however small increases (2%) were simulated in Fargo, ND and Yakima, WA. Both GCM scenarios predicted 5% increases in yield at Caribou, ME.

In 2090 the simulated decreases continued under both climate scenarios. Potato yields decreased by 10% at two of the three major production sites in the Northwest, while water use increased by 10% on average. Both GCMs resulted in larger decreases (30 to 40%) at Boise, ID and Scott Bluff, NE (27 to 50%); and smaller ones at Pendleton, OR, Medford, OR (10 to 15%) and Buffalo, NY (8 to 18%).

Similar to the results obtained for other crops, simulations suggested that rainfed production could become more competitive with irrigated production compared to today. Cultivar adaptation would do little to counterbalance the negative temperature effects seen in our simulations. Current US potato production is limited to cultivars that need a period of cold weather for tuber initiation. The only viable strategy would be a change in planting dates, to allow for increased storage of carbohydrates and sufficient time for leaf area development prior to tuber initiation. However, additional simulations suggested that current production levels could not be re-established even with a shift in the planting date. For example, moving planting ahead by as much as one month at Boise, ID and Indianapolis, IN, helped reduce yield losses under climate change by 50%, relative to simulations without adaptation. This is a substantial offset but still leaves sizable losses compared to current yields.

Citrus. Fruit production benefited greatly from climate change. Simulated yields increased 20-50% while irrigation water use decreased. Crop loss due to freezing was 65% lower on average in 2030; and 80% lower in 2090, at all sites. Of the main production sites considered in this study, Miami, FL, experienced small increases, in the range 6-15%. Of the other three remaining major production sites, increases in the range 20-30% were predicted in 2030, and in the range of 50-70% in 2090. Irrigation water use decreased significantly at Red Bluff, CA; Corpus Christi, TX; and Daytona Beach, FL. All sites experienced a decrease in CV, due to the reduction of crop loss due to freezing.

Fruit yields increased in Tucson, AZ and Las Vegas, NV. However, slight to no changes in simulated water use imply that these sites, currently at the margin of orange production, will be even less competitive in 2030 and 2090 than they are today. In fact, all of the additional sites, chosen to investigate the potential for northward expansion of US citrus production, continued to have lower fruit yield, and higher risk of crop loss due to freezing, compared to the southern sites of production.

Hay and Pasture. Simulated dryland pasture and hay production increased under all scenarios and at most sites, except under the 2030 Canadian Center scenario, which resulted in decreases of up to 40% in the Southeast, Delta, and Appalachian regions. The largest increases, in the range 40-80%, were simulated for the Pacific Northwest and Mountain regions. By 2090, both climate scenarios resulted in increases above 20% at all sites. Results from the PNNL study were in general agreement with these findings.

Soybean. Under rainfed conditions and the two climate scenarios considered soybean yields increased at most of the sites analyzed, because increased temperatures favored growth and yield compared to current conditions. Notable exceptions were the Southeastern sites. Under the Canadian Center scenario, yields in this area were reduced in 2030 by 1 to 36%. By 2090, losses larger than 70% were simulated at Montgomery, AL and Memphis, TN. Adaptation in this area reduced losses by more than 50%, by shifting the crop maturity group.

At sites in the major producing areas of the Corn Belt, rainfed yields increased significantly, by 10-30%. At the three northernmost sites chosen in this study, Duluth, MN, St. Cloud, MN and Muskegon, MI, currently at the northern margin of US soybean production, yields increased by more than 30% in 2030 and by more than 50% in 2090, due to the positive effects of warmer temperatures.

The PNNL study, simulated for the Hadley climate scenario similarly found increases in soybean yields in the Lake States of Michigan, Minnesota, and Wisconsin and Northeast but found that "soybean yields decreased in the Northern and Southern Plains, the Corn Belt, Delta, Appalachian, and Southeast regions" (Izaurralde et al., 1999). Thus, there is considerable disagreement between the two approaches for soybeans, particularly for the important Corn Belt region.

Irrigated soybean yields increased at all sites and under all scenarios, in a 10-20% range in 2030 and by 10-40% in 2090. Again, increasing temperature was the main factor enhancing soybean yields in this simulation analysis. As for the rainfed case, at the northern sites yields increased by more then 50% in 2030 and by more than 100% in 2090.

Sorghum**.** Under rainfed conditions, the two climate scenarios analyzed in this study produced opposite results at many sites, due to differences in predicted changes in precipitation. Under the Hadley scenario, rainfed production increased at all sites, due to increased precipitation with respect to the current climate, in a range of 1-10% in 2030, and by significantly more, 10-60%, in 2090. Under the Canadian Center climate, reductions of about 10-20% were simulated at southern and southeastern sites. The largest decreases were simulated in 2090 at Savannah, GA (15%), Charleston, SC (20%), and Oklahoma City, OK (30%). Under both GCM scenarios, warmer temperatures and, where predicted, increased precipitation enhanced production at the northernmost sites. Large increases in sorghum yields were simulated at North Platte, NE (30%, 80%), Pierre, SD (45%, 100%), and Sioux Falls, SD

(50%, 60%), in 2030 and 2090, respectively.

Under irrigated production, the generally negative effects of increased temperature on sorghum development and growth, resulted in yield reductions by 10 to 20% at most sites, under both scenarios, and time horizons. The largest decreases were simulated in 2090, at Oklahoma City, OK (38%). By contrast, yields increased by 10-15% at two of the northernmost sites, while they decreased at Pierre, SD (3%).

Early planting by two to four weeks helped to counterbalance the negative effect of warmer temperatures at most sites analyzed.

Rice**.** Under irrigated production, the two climate scenarios analyzed resulted in much different projections of future rice yields, largely due to differences in the predicted magnitudes of temperature change. In 2030, the Hadley scenario resulted in small positive yield increases, in the range 1-10%, with larger increases at two northern sites, currently well outside of the US rice production region, i.e. Peoria, IL, and Des Moines, IA, but considered because of the potential for climate change to make rice production viable. The Canadian Center scenario predicted small reductions, in the order of –1% to –5%, at major production sites in California and at sites in the Delta region. In 2090, the patterns of simulated changes among scenarios, as well as their geographic distribution, was similar to that predicted for 2030. Yields increased under Hadley, except in Bakersfield, CA (-12%). The Canadian Center scenario predicted larger yield decreases then predicted in 2030, up to –20% in California and the Delta region, and by –50% in El Paso, TX.

Adaptation was simulated by planting cultivars better adapted to warmer temperatures, and by early planting. These techniques helped to reduce, but not to counterbalance completely, the reductions simulated under climate change and no adaptation.

Tomato. Under irrigated production, the climate change scenarios generated yield decreases or small increases, depending on the scenario chosen, at most sites. At the northernmost locations analyzed in this study, increased temperatures were highly beneficial in terms of yield.

In 2030 under the Canadian Center scenario, tomato yields decreased at most sites, by 10 to 20%. The largest decreases were simulated at Oklahoma City, OK (45%), and at Tucson, AZ (37%). At northern sites simulated yields increased: at Boise, ID (20%), Duluth, MN (80%), Muskegon, MI (40%), and at Yakima, WA (30%). This trend continued in 2090 under the Canadian Center scenario, with larger magnitudes of both predicted gains and losses. General decreases at most sites were in the range of 20 to 40%. Decreases greater than 70% were simulated in Oklahoma and Texas. Northern sites continued to benefit under warmer temperatures with yield increasing by as much as 170% at Duluth, MN.

The same patterns were simulated under the Hadley scenario, except that, due to the smaller predicted increases in temperatures compared to Canadian Center, both the simulated losses at most sites and the gains at northern locations were smaller than predicted under the Canadian Center scenario. Specifically under the Hadley scenario, sites in the Delta region and in the Southeast experienced moderate gains, in the range 5-15%, with respect to current production levels.

3.2.4 The PNNL Results

As already discussed briefly, the PNNL results were based on slightly different assumptions and were produced only for the Hadley Center scenario, for climates representative of 2030 and 2095 (H1 and H2). The climate change scenarios are applied with two levels of atmospheric CO_2 concentration ([CO_2]) -- 365 ppm (current ambient) and 560 ppm to represent a CO_2-fertilization effect. The results are shown in Figures 3.1 and 3.2 and summarized in Tables 3.1 and 3.2. The land areas indicated in the figures are the 4-digit (USGS nomenclature) hydrologic basins. Data in the table are aggregated from these regions into production regions as defined by the USDA.

Temperatures rise modestly (1-2 ºC) by 2030 and precipitation increases by 25 to 125 mm y^{-1} over most of the corn-growing region. By 2095, temperatures increase by 2.0 to 3.5 ºC and precipitation increased by more than 175 mm y^{-1} over the entire region. Yield in the EPIC model used for this analysis is directly proportional to biomass production which is favored by a reduction in cold stress and a lengthening of the growing season in the Lake region, Cornbelt and Northeast (Fig. 3.1). Table 3.1 shows that yields increase at current CO_2 and improve still more at the higher concentration. Yields are slightly depressed in the Delta, Appalachian and Southeastern region where higher temperatures shorten the growing season (Fig. 3.1). With no CO_2-fertilization, regional yields are reduced in both 2030 and 2095 in the Delta and Southeast but only in 2030 in the Appalachian region. Climate-related losses are more than offset by CO_2-fertilization in all cases.

Baseline winter wheat yields and deviations due to the climate and CO_2 scenarios are shown for the Northern and Southern Plains, Mountain (Great Plains portions of Montana, Wyoming and Colorado) and the Western regions in Figure 3.2 and summarized by USDA production region in Table 3.2. Temperatures in these regions increase by 1-2 ºC by 2030 scenario but are considerably higher by 2095. By 2030, precipitation increased by 25-50 mm y^{-1} over much of the Plains and Mountain growing regions and in Washington and Idaho, but was lower in California. By 2095 precipitation increases still more in the Plains and Mountain regions, increases in California and is variable in the northwestern states. CO_2-fertilization alone increases yields in all regions. The C-3 crops, of which wheat is one, experience increased photosynthetic and decreased transpiration rates under elevated CO_2. The reduction in transpiration is particularly important for wheat, which is generally grown in semi-arid regions. Aggregate regional production increases under all scenarios in the Pacific region, and most scenarios in the Mountain and Plains regions. Decreases in aggregate production were predicted for the Mountain and Plains regions when wheat growth was simulated without CO_2-fertilization effect in 2030 and for the Southern Plains in 2095 also without the CO_2-fertilization effect. Higher temperatures reduce the frequency of cold stress and increase the length of the growing season by shortening the winter dormancy period. In the more northerly regions the crop matures before the extreme heat of summer.

3.3 National level yield changes

Translating crop simulation results into data that can be used in a national economic model raises two methodological issues: (1) How to treat crops for which crop simulations were not conducted? and (2) How to extrapolate from sites to regional scale impacts? In this section we discuss these issues and present the aggregate national yield changes derived from our extrapolation assumptions.

With regard to omitted crops, the basic issue is that production and resource effects in the economic model depend on *relative* changes in yield and water use among crops. As a result, the production of crops omitted from the simulation studies are affected in the economic model even if no direct climate effects are assumed for them. This could create regional and resource use shifts that reflected the relative importance of omitted crops rather than the estimated climate effects. Left unaffected by climate change, the omission of impacts on some crops could lead to a bias in the estimate of the overall economic impact of climate change. Generally improving conditions would be underestimated if no yield increase were included with the converse true if conditions were generally worsening, leading to an underestimate of the impact, either positive or negative. Yield changes of omitted crops could potentially be opposed to the general direction of other crops, their omission leading to an overestimate of impact. These considerations lead to the conclusion that, for assessment purposes, it is useful to make a best guess for these omitted crops.

We assumed that, for each omitted crop, one of the crops for which yields were simulated in the crop studies could serve as a proxy, an assumption that has been commonly used. The exception was cotton, an economically important crop for which there was no obvious proxy crop. For cotton, we adapted the results of NCAR/Southeastern US study. The specific approach for each omitted crop is discussed below.

Proxy Crops. A direct proxy crop approach was used for the crops as shown below. For example, silage sensitivity was assumed to be the same as corn sensitivity.

Crop with missing data	Crop used as proxy
Hard Red Spring Wheat	Wheat
Hard Red Winter Wheat	Wheat
Soft Wheat	Wheat
Durham Wheat	Wheat
Barley	Wheat
Oats	Wheat
Silage	Corn
Oranges, fresh	Oranges
Oranges, processed	Oranges

Grapefruit, fresh	Oranges
Grapefruit, processed	Oranges
Tomatoes, processed	Tomatoes
Tomatoes, fresh	Tomatoes
Sugarcane	Rice
Sugarbeet	Hay

Cotton. Cotton yields were developed based on estimates from an NCAR study (Mearns, forthcoming) of the Southeastern US that included several additional crops. The study simulated yield effects using many of the same crop models used in our assessment and for several climate scenarios including the Hadley Center scenario. However, a climate representative of 2060 was used and no simulations were conducted based on the CCC modeled climate. Comparing yield effects among the NCAR crops showed no one of the other crops to respond similarly to cotton, offering evidence that no single crop would serve as a proxy for cotton. An attempt to statistically relate cotton yields using multiple regression analysis to the yields of all other crops verified the conclusion that no single crop nor any combination of crops explained the site level variation in yield impacts of cotton. The approach adopted instead, was to adapt the NCAR cotton yield sensitivity data directly as explained in the document underlying this section (McCarl, 2000). Operationally this involved extrapolating the 2060 spatial distribution of cotton yield and water use sensitivity from the NCAR study to 2030 and 2090 based directly on the climate in these years relative to the Hadley climate for 2060.

The intent of these assumptions is to avoid a particular bias of underestimating overall economic impacts of climate on the US agriculture economy by assuming no effect at all on these crops. Crop coverage has been an issue in all assessments of this type. Early agricultural assessments were often limited to the corn, wheat, rice, and soybeans. Recent assessments, including this one, have worked to provide broader crop coverage. Caution is obviously warranted in using the detailed crop results from the economic model where the crop yield effects were not simulated directly. These uncertainties also introduce uncertainties in the overall economic results. In a very limited way, we explored this uncertainty by simulating the economic model using the different approaches we developed for cotton.

With regard to extrapolation from site-level data, the ASM model includes 63 regions (Figure 3.3 with overlay of the USDA production regions). The crop simulations were done for no more than 46 sites with some crops simulated for only a subset of these sites. In some cases multiple sites were located in a single ASM region. When multiple simulation sites appeared in a region an unweighted average across those sites was used. Proxy regions were used for those regions in which no sites were located. Adjacent regions were used for proxies. The use of adjacent regions as proxies is discussed in greater detail the underlying supporting document (McCarl, 2000).

As with the use of crop proxies, the lack of direct estimates for a site within a region introduces considerable uncertainty in estimates for that region. Even for regions with site estimates, a sample of one or two sites may not be representative of the region. The PNNL crop yield model results were based on a far denser selection of representative sites. As a sensitivity analysis, we used the available PNNL results in the economic model as a substitute for the coordinated site-level results. While not a pure test of potential site selection bias because the crop models differed as well as other aspects of the scenarios, this comparison offers a check on the potential bias introduced by the limited number of sites.

These assumptions provide the basis for estimating yield impacts for all crops in each region of the ASM. The national average change in yields for dryland and irrigated crops with and without adaptation are given in Tables 3.3a,b and 3.4a,b. Table 3.5a,b gives the national results for changes in water use on irrigated crops. The national averages were constructed by weighting ASM regional estimates generated from the crop model results as described above by harvested acreage in each ASM region where the weights are based on data from the 1992 National Resource Inventory (NRI). McCarl (2000) provides additional details.

The estimates in Tables 3.3 through 3.5 are a summary of input into the ASM model. Actual national production depends on changes in the agricultural economy induced by these changes. The estimates are, however, a useful intermediate result that summarizes the crop modeling simulations. The site simulation results by themselves can give a misleading impression of overall impacts because crops were simulated at many sites where little of the crop is currently grown or at sites under dryland conditions where the crop is mainly grown only with irrigation. Weighting results for the site by area provides a better guide to how climate would affect production. These tables also provide input data for the ASM based on the PNNL crop results. PNNL modeled only corn, wheat, hay, and soybeans. Crops other than these (and those for which one of these crops were proxies) have identical changes as for the core results for the Hadley center climate scenario. These entries are shaded in the table.

The results vary across crops, time periods and climate scenarios but some broad patterns emerge.

- Even without adaptation the weighted average yield impact for many crops grown under dryland conditions across the entire US is positive under both the Canadian and Hadley Center climate models. In many cases, yields under the 2030 climate conditions are improved compared with the control yields under current climate and improve further under the 2090 climate conditions. These generally positive yield results are observed for cotton, corn for grain and silage, soybeans, sorghum, barley, sugar beet, tomatoes, and citrus fruit. The yield results are mixed for other crops (wheat, rice, oats, hay, sugar cane, and potatoes) showing yield increases under some conditions and declines other conditions.
- Changes in irrigated yields, particularly for the grain crops, were more often negative or less positive than dryland yields. This reflected the fact that under these climate scenarios precipitation increases were substantial. Precipitation increases do not provide a yield benefit

to irrigated crops because no water stress occurs because all the water needed is provided through irrigation. Higher temperatures sped development of crops and reduced the grain filling period thereby reducing yields. For dryland crops the negative effect of higher temperatures was counterbalanced by the positive effect of more moisture.

- Water demand by irrigated crops dropped substantially for most crops. The faster development of crops due to higher temperatures reduced the growing period and thereby reduced water demand more than offsetting increased evapotranspiration due to higher temperatures while the crops were growing. To a large extent the reduced water use thus reflects the reduced yields on irrigated crops. Increased precipitation also reduced the need for irrigation water.
- Adaptation contributed small additional gains in yields of dryland crops, particularly for those with large yield increases due to climate change. Adaptation options were considered for both sites with losses and those with gains but, for the most part, had little additional benefit where yields increased from climate change. This suggests that adaptation may be able to partly offset changes in comparative advantage across the US that results under these scenarios. Other strategies for adaptation such as whether to switch crops or to irrigate or not are part of the economic model. The decisions to undertake these strategies are driven by economic considerations: i.e. whether they are profitable under market conditions simulated in the scenario. We did not consider adaptation for several crops because the measures we considered such as planting date were not applicable to many perennial and tree fruit crops. Adaptation studies were conducted for only a limited number of sites.
- Adaptation contributed greater yield gains for irrigated crops. Shifts in planting dates are able to reduce some of the heat-related yield losses. With higher yields than in the not adaptation case, water demand declines were not as substantial. Again, this reflected the fact that the adaptations considered extended the growing (and grain-filling period) and this extension meant a longer period over which irrigation water was required.

The PNNL results for dryland crop yields are very similar in most cases to those estimated using the more detailed site-level crop models. PNNL did not consider adaptation. PNNL also only considered irrigation for corn and alfalfa. The PNNL results for these irrigated yields differ substantially from the site-level models. Whereas the site-level models show yield losses and reductions in irrigation water use, the PNNL results show yield gains. In the site-level models, higher temperatures speed development of the crop and reduce yield and water demand. The EPIC model on which the PNNL results are based do not show this negative effect of temperature, instead temperature is increasing yield.

3.3.1 Irrigation water supply

Water supply for irrigation is also an important consideration. The ASM includes a description of agricultural water supply that is allocated to crops. An estimate of the change in water supply under the climate scenarios considered was derived from simulated total water supply changes developed in the Water Sector Assessment effort of the National Assessment. The critical assumption made was that the change in water supply to agriculture was proportional to the change in total water supply; i.e. that agriculture and non-agricultural users faced the same proportional change in water supply. More detail on the specific changes and how they were derived from the estimates developed by the Water Sector Assessment are provided in McCarl (2000).

3.3.2 Crop input usage

Yield changes can also imply changes in some inputs such as chemical inputs and those related to crop harvesting, drying, and storage. A larger (or smaller) yield will require more (or less) of these other inputs. This association between yield and input use can be seen over time. As technical progress that increased yield has been accompanied by increases in input usage. On the other hand, yield, by definition, is per unit of land and other inputs such as labor and water are more closely related to area than to yield. As part of the earlier EPRI study (Adams et al., 1999) using the ASM model, a yield-input relationship was estimated. Land, labor, and water inputs were excluded from the estimation. For most crops the increase in use of these other inputs was 40 percent of the yield change. Thus if yield went down by one percent crop input use went down by 0.4 %. Similarly a two percent yield increase would be matched by a 0.8% input usage increase. This relationship was included in the simulations. It has the effect of making yield improvements less economically beneficial than they otherwise would be because to obtain the increases requires purchase of these other inputs. Conversely, yield losses are as economically costly because purchase of material inputs is reduced. This type of adjustment is appropriate for the consideration of ongoing climate change, for which technical change, the basis for the estimate, provides a good analogy.

3.4 Livestock performance and grazing and pasture usage

Much of the work on climate change impacts on agriculture considers mainly impacts on crops and only indirectly impacts on the livestock sector through changes in crop yields. Temperature change can also cause livestock to achieve altered rates of gain. As part of the earlier EPRI study (Adams et al., 1999) changes in livestock performance due to temperature change were estimated. These estimates were used as a basis for developing temperature-related declines in livestock performance. McCarl (2000) provides the assumed changes in livestock production on a per head basis.

Altered livestock performance in terms of altered ending weights of sale animals or sales of livestock products means that animals need different amounts of feedstuffs to produce that ending weight or volume of products. In this study we assumed that feedstuff usage was strictly proportional to the volume of products, although changes in climate could change this proportion. Thus, if 10 percent more milk were produced, then 10 percent more feedstuffs had to be consumed. When the livestock unit produced multiple products then a weighted average of the percentage change in output is used to adjust the feedstuff usage. The feed usage quantities for which we applied these adjustments included not only traditional grains but also the number of animal unit months required of grazing and the acreage of pasture required. Similar to the case of crops and with the same rationale, nonfeed input use was assumed to increase by 40 percent of the production increase.

Grazing and pasture use are also important assumptions in the ASM model and are influenced by climate change. The crop modeling component of the agriculture sector assessment included estimates of changes in grass and pasture growth due to climate change. Alterations in the growth rate of grass changes the available feed supply from a given area of pasture. Pasture use and grazing land availability are represented in the ASM and were changed to reflect the change in grass and pasture growth. Pasture use was adjusted by the change in grass growth. Thus if grass growth increased by 10 percent then livestock pasture use was multiplied by 0.9 (1/1.1). This adjustment was done after changing the pasture required as a result of any change in body weight directly due to temperature.

Grazing on western rangelands was addressed in a manner similar to the adjustment for pasture, however, the availability of such lands traditionally has been measured in terms of animal unit months (AUMs) of grazing. An estimate of the AUM supply sensitivity to climate change was developed by assuming the change in AUM supply was the same as the change in grass supply. Thus if grass growth increased by 10 percent then the AUMs available increased by 10 percent.

This combination of climate effects on livestock includes most of the primary effects of climate on the livestock sector. The principal omissions are direct losses of livestock due to extreme storms. More or fewer floods or extreme winter weather events are potentially additional changes to the livestock sector not considered here.

3.5 Pesticide Costs

A change in the incidences and range of agricultural pests is another likely effect of climate change. Most insects, weeds, and diseases are sensitive to climate; climatic factors are an important determinant of the range of many important agricultural pests. No previous assessment of agricultural impacts of climate change has integrated this affect fully into an economic assessment. To consider how climate could affect agriculture through its affect on pests we conducted a statistical analysis relating pesticide expenditures to climate. This analysis was conducted on cross-section data and is explained in greater detail in Chapter 6.   The change in pesticide expenditures for corn, cotton, soybeans, wheat and potatoes due to a percentage change in precipitation and temperature was estimated. Based on these statistical relationships, a change in pesticide costs under each climate scenario was estimated. The limitations and advantages of such cross-section evidence applied to time-series phenomena such as climate change have been discussed in the context of other such efforts, the broadest such effort being the Ricardian rent method developed by Mendelsohn, Nordhaus, and Shaw (1994). A main additional limitation in the context used here is that, as applied, this approach implicitly assumes that any additional potential damage due to pest range and incidence expansion is fully controlled by the use of additional pesticides. Thus, the only economic loss to farmers is the additional pesticide expenditures. If, even with additional pesticide expenditures, there were greater crop losses the lost revenue from the reduced sale of crops would be an additional loss.

3.6 International trade

As reviewed in Chapter 2, studies that have considered global impacts of climate change have demonstrated that the economic impact on a country can be heavily affected by how climate change affects agriculture production in major agricultural exporting and consuming countries. The ASM includes an international sector and thus, in all scenarios, climate impacts on the US affect US competitiveness in export markets. However, in the base scenarios, while US agricultural production is affected by climate there is no climate impact elsewhere in the world. It was, however, beyond the scope of Agricultural Sector Assessment to conduct a full assessment of the rest of the world. This is roughly equivalent to assuming that, while there may be positive and negative impacts of climate change on agriculture elsewhere in the world, the net impact is to balance out to no change. In fact, in the global studies that have been conducted, the net global effect is often relatively small due to a combination of gainers and losers around the world. To consider the sensitivity of our results to the implicit assumption of no impact elsewhere in the world, we constructed 3 sensitivity scenarios for potential climate impacts on the rest of the world based on previous global assessments. Two scenarios were developed from the earlier work based on an economic modeling analysis of international yield changes based on climate scenarios of the GISS and UKMO climate scenarios (Reilly, et al., 1993). The production changes in other regions is given in Tables 3.6a,b. Another scenario was developed based on a global modeling exercise using the Hadley center climate scenario (Darwin, personal communication) although the analysis was not conducted directly as part of the National Assessment. This scenario is based on a model developed at the Economic Research Service (Darwin, et al., 1995). The GISS/UKMO climate scenarios are fairly old, the impact analysis dating to the early 1990s, and are doubled CO_2 equilibrium scenarios. The advantage of these scenarios is that the underlying approach used for the crop studies are similar to the approach used in this assessment and the study provides details on the major crops and world regions represented in the ASM. For the Darwin scenario we based adjustments on changes in net exports from the US.

None of these scenarios are completely consistent with the analysis of the US we conducted but they provide a useful way to demonstrate the sensitivity of the economic estimates we obtained to different assumptions about how climate change could affect the rest of the world. The GISS/UKMO scenarios were chosen, in part, because in the study from which they were taken they represented the mildest (GISS) and the most severe (UKMO) scenarios considered among those that considered both adaptation and the CO_2 fertilization effect.

3.7 Economic Results

We discuss below the main economic results. We first discuss the results from the core scenarios. We then consider sensitivity cases. These include the trade sensitivity results, the alternative Hadley Center Scenarios based on the PNNL crop modeling, and a set of miscellaneous sensitivities. We report here the major results. Altogether we ran 43 scenarios representing different impact combinations (e.g. with and without adaptation or pest effects) and alternatives (e.g. alternative trade and crop yield effects), producing results for aggregate economic effect, regional production, and resource use for each scenario. In most cases, the general pattern of change across regions and resource use closely reflects differences in the aggregate economic effect across scenarios. We have tried to highlight here the broad pattern of results. Complete tables of results are provided in McCarl (2000).

3.7.1 Results from the Core Scenarios

A value of an economic model like the ASM is that it can summarize the net impact of a combination of many different changes. The model also provides the ability to consider distributional and resource use effects, reported below.

3.7.1.1 Aggregate Economic Impacts

We report the aggregate results in terms of a change in welfare, here measured as the sum of producer and consumer surplus. Welfare is preferred as a measure of economic impact over measures such as change in agricultural production or consumption because it includes consideration of the fact that with less production fewer inputs are used and that consumers, in shifting consumption away from agricultural goods, are able to substitute consumption of other goods. Figure 3.4a displays the results based on the Canadian Center (CC) climate model and Figure 3.4b displays results based on the Hadley Center (HC) model. Included in these figures are changes of consumer and producer surplus in the US as well as a change in total surplus. The difference between the two is the economic impact on producers and consumers outside the US. The scenarios reported in Figures 3.4a,b do not include any direct climate impact on agriculture outside the US but impacts on foreign producers and consumers occur because of changes in prices of internationally trade commodities. The figures provide results for 2030 and 2090 under 3 different scenarios. The first is the impact of climate change, including crops, livestock, and water demand and supply effects without adaptation. The second series adds adaptation and the third adds, in addition, the effects of climate on pesticide expenditures.

Given the differences in the climate models and the intermediate crop modeling results, the economic results are generally as expected. Overall, the effects on total surplus are generally positive, much more so for the HC scenario. Net economic benefits range from about -0.5 to 3.5 billion dollars (year 2000$) in the CC scenario and between 6 and 12.5 billion dollars for the HC scenario. In both climate scenarios the total and domestic surplus increases between 2030 and 2090, indicating that the general overall beneficial effects of climate change continue at least through 2100. A number of analysts have suggested that at more extreme levels of climate change one should expect losses. Since we have not conducted a full transient crop model/economic analysis we cannot be sure whether by 2090 benefits are declining from some peak experienced between 2030 and 2090 or whether benefits are continuing on a general upward trend. As illustrated by the CC climate scenario, however, the time path of impact may not be easily described by a simple function. In 2030, at least for the no adaptation case and for

US Surplus, the net effect is an economic loss that turns to gains by 2090 for all but the no adaptation case. Given the multitude of effects across many different regions it is not possible to trace these results conclusively to a specific aspect of the climate scenarios. The pattern of results very likely reflects the fact that in the CC climate scenario, precipitation decreases in the US in 2030 and then increases by 2090. Care must be taken in over-interpreting this time path or any of the specific results. Climate models produce variability from year-to-year and decade-to-decade. Even for specific models such as the CC or HC models, a particular decade of climate drawn from a particular scenario must be considered only one possible draw from a distribution of possibilities. By 2030, the additional greenhouse gas forcing beyond that of current climate is relatively smaller compared with 2090 and so the natural variability on a decade-scale can have a large effect relative to the signal due to greenhouse gas forcing.

The distribution of benefits between foreign and domestic is notably different in the two scenarios, with much of the benefit going abroad in the CC scenario and relatively little flowing abroad in the HC scenario. This difference occurs because of the differential effects on crops where exports are important versus those that are mainly consumed domestically.

As observed for the intermediate crop yield results, adaptation is considerably more important when the impacts are adverse than when they are beneficial. While this shows up in the comparison of the two climate scenarios, more research is required to assess the robustness of this result. It is possible that a more expansive exploration of adaptation options such as double cropping could reveal further gains in northern regions.

The net effect on pesticide expenditures is an increase, thereby reducing total economic surplus. This effect is quite small. The size of the effect is not surprising, however, given that pesticide expenditures account for only a few percent of total costs. As previously noted, however, this estimate may understate losses because it does not include any increase in damage that cannot be eliminated through the increased use of pesticides.

3.7.1.2 Distributional Effects

Both the distribution of economic effects between producers and consumers and among regions can vary. Figures 3.5a and 3.5b display the distribution of effects between domestic US producers and consumers. Across all the scenarios, consumers generally gain from lower prices whereas these lower prices cause producer losses despite the fact that climate change has improved productivity. The CC climate scenario produces an approximate balance in terms of domestic consumer gains and producer losses in most scenarios. In contrast, the HC climate produces large consumer gains. The productivity gains are so substantial, however, that the volume and output and export gains to producers nearly offset the price declines. While the absolute level of change is comparable between producer and consumers, in percentage terms the changes to producers are much more substantial. For comparison purposes, the total economic benefit derived from food consumption in the base is estimated at approximately 1.1 trillion dollars whereas total producer surplus is on the order of 30 billion dollars. Thus, the 4 to 5 billion dollar surplus losses in the CC scenario represent 13 to 17 percent loss of surplus to producers whereas the gains of 12 to 14 billion dollars of consumer surplus in the HC scenarios represent only a 1.1 to 1.3 percent gain to consumers. We would expect producer losses to ultimately be realized as changes in the value of land. A 13 to 17 percent loss in this asset value is substantial but, to place this in context, agricultural land values fell on the order of 50 percent between 1980 and 1983.

Figures 3.6a and 3.6b display the regional differences. We report an aggregate index of the production across crops. The plotted values are percentage change from base production. The figures show substantial regional differences in both scenarios. The basic regional pattern is similar in both scenarios. The Lake States, Pacific, Mountain, and the Corn Belt regions, in that order, show large increases in production, generally between 50 and 150 percent increases in output. The pattern of absolute (or relative) losers varies more across the scenarios. The Southeast, Southern Plains, and Delta States lose absolutely in the CC scenario or show the smallest increases in production in the HC scenario. Appalachia is also more negatively affected. Impacts on the other regions vary substantially across the two climate scenarios or over the two time periods.

In the HC climate scenario no region shows a production decline but with substantial overall producer losses in the US due to declining commodity prices farmers in those regions that show only modest increases in production are clearly suffering substantial economic loss. In these cases we expect economic losses to show up as declines in the value of assets located in these regions—primarily agricultural land. In the CC climate scenario, several regions show absolute declines in production. This adjustment process over the longer term explains why production can continue to increase even though the region experiences economic loss. Owners of land may be forced out of business and the resulting price of land would reflect the reduced production potential due to degrading climatic conditions. A new buyer, paying the lower price could then profit because the asset cost was lower. Thus, production continues despite the fact that owners of farmland take a significant economic loss. In the CC scenarios, regions with production losses are also suffering from price declines, though not as severe as in the HC case.

3.7.1.3 Resource Use

Overall, measures of resource use generally decline across all categories, both climate scenarios, and both time periods (Figure 3.7). Irrigated land and water use decline most, reflecting both the overall increase in production and decline in prices and the relative yield effects between irrigated and dryland. Overall, the results for these scenarios suggest considerable less pressure on resources, a result of the overall increase in productivity.

3.7.2 Trade Scenarios

Table 3.7 provides the aggregate economic results for the three different trade scenarios for 2030 and 2090. All three foreign trade scenarios were run against both the CC and HC domestic US scenarios. The trade scenarios generally do not lead to a substantial change in total surplus or total US surplus. This result reflects the fact that the US is a substantial commodity exporter but also a substantial food consumer. Hence, global price changes have roughly offsetting effects—consumers gain from price decreases while producers lose. With price increases these effects go in the opposite direction but again roughly offset one another. The biggest effect of the trade scenarios is thus a reallocation of the total domestic effect between producers and consumers. The Darwin scenario creates somewhat greater losses for US producers, the implication being that the impact on production in the rest of the world for those goods in which the US trades is positive with generally lower world prices than in the comparable cases where world production was left unchanged. For the GISS and UKMO scenarios, the effect is the opposite. World prices increase, very modestly in the GISS case and more substantially in the UKMO case thereby shifting some of the gains from US consumers to US producers.

These trade scenarios, as previously noted, were not developed consistently with the domestic impacts. If the results obtained for the US with these climate scenarios, generally more positive yield effects than in past assessments, would be observed across the world then we would expect world prices to generally decline. The result would be further gains by US consumers and losses by producers as observed in the Darwin scenario rather than in the GISS or UKMO scenario. On the other hand, a factor that is no doubt important in moderating the climate impacts on the US is the cooling effect of sulfate aerosols in the Northern Temperate regions. Earlier assessments used climate scenarios that did not include the sulfate aerosol effects. Often these showed warming benefits in more northerly regions and losses in tropical regions. Sulfate aerosol effects could produce a regional pattern of climate change that reduces benefits to some northern regions compared with earlier assessment while leaving unchanged the losses in the tropical regions. If such a result would hold, the implication would be perhaps world price increases and a shift of benefits from US consumers to US producers. More complete global studies with newer climate scenarios are required to resolve this effect.

3.7.3 The Alternative PNNL Crop Scenarios

Table 3.8 provides the aggregate economic results for the alternative PNNL crop simulations. These were produced only for the Hadley scenario and did not include adaptation. We did not include the pest changes in this comparison, the purpose here being primarily to evaluate scenarios for PNNL crop simulations versus the core crop simulations for a comparable set of scenarios. The overall conclusion of this comparison is that the PNNL scenarios show very similar results to those obtained with the detailed site simulations. The total economic welfare gain is somewhat higher in 2030 and somewhat lower in 2090. While not reported here, the regional effects differ somewhat. In the PNNL scenarios the Southeast does not show up as a particularly severely affected region and the Southern Plains and Northeast are considerably more positive than in the core scenarios. The Northern Plains appears as the more negatively affected region in the PNNL scenario. The Lake States, Corn Belt, and Pacific regions are among the more positively affected regions in both scenarios.

Overall, this comparison is reassuring in the sense that the limited site selection in the core scenarios does not appear to have created a substantial bias in aggregate estimates. The aggregate effects offer a relatively weak test, however, as several crops were left unchanged between the core and PNNL results because the crops were not simulated by PNNL. Clearly, some differences do occur at the regional level, emphasizing the uncertainties in producing consistent predictions at the regional level.

3.7.4 Other Scenarios and Sensitivities

As indicated previously, we were unable to generate yield changes for cotton using a cotton crop model. Instead we adapted results from another study. We also simulated results using soybeans as a proxy for cotton. Soybean results were generally quite negative in the South in the CC scenarios whereas the alternative cotton scenarios showed more positive effects. As a result, this alternative assumption produced quite different results. Notably, under the CC scenarios the .6 billion dollar total surplus loss in 2030 doubled and the approximately 1 billion dollar gain in 2090 was changed to a 1 billion loss. Most of this change accrued to domestic and foreign consumers. Producers losses were actually slightly reduced in 2090 due to higher cotton prices. The negative production effects were most substantial in the Delta regions.

The results derived by projecting the agricultural economy forward to 2030 and 2090 were not qualitatively different. The specific quantitative results depend crucially on highly uncertain forward projections. The two basic aspects of these projections are yield growth and demand. Projecting ahead historical yield growth and increases in demand due to population growth increases the absolute size of the agricultural economy. If we consider yield changes in percentage terms as operating on the new higher yields, the percentage effect is similar. Differences can arise due to different assumptions about yield and demand growth for different crops and differences in yield impacts among crops.

We also jointly considered the impacts of changes in agriculture and forestry. Because of the long growth cycle of forests, there is a far greater need to look forward and consider the present value of changes over a number of years. The forest sector assessment was conducted under as part of the National Assessment (Joyce et al., 2000; Ireland et al., 2000; McCarl, 2000; Alig and Adams, 1997). Forest yield scenarios were derived based on the Canadian and Hadley climate models and two ecological process models. Results suggest that consideration of both sectors suggests generally beneficial effects for the US economy. Increased supplies from forests lead to reductions in log prices that in turn, decreases producers' welfare (profits) in the forest sector. At the same time, lower forest product prices mean that consumers generally benefit. This pattern of distributional impacts on forestry producers and consumers is similar to results obtained in the agricultural sector. Increases in the net present value of total economic welfare (combined forestry and agriculture) ranged between 0.9 and 1.2 percent, with the higher positive impacts under the Hadley climate change scenarios. More details on these results are provided in McCarl (2000).

Land use changes between forestry and agricultural uses are an important avenue of adjustment to climate-induced shifts in production, and there are notable differences in these adjustments across climate change scenarios. Over the full projection period the Base and Canadian GCM cases project a net shift of land from agriculture to forests, the latter at about half the rate of the former, while the Hadley GCM scenarios project a net loss of forest land to agriculture. Yields from the land generally increase in both the forest and agricultural sectors in all four scenarios. In the Canadian scenarios these shifts are relatively more favorable for forestry profits compared to agriculture, while the opposite is true in the Hadley scenarios.

3.7.5. Summary of the Main Economic Results

The main results of the economic analysis are:

1. Climate change as modeled under the climate scenarios considered is mostly beneficial for total society in terms of agricultural impacts particularly if adaptation is considered. This differs from the results of previous scenario analysis where results have been mixed and generally negative in the absence of adaptation.
2. Climate change uniformly shows increases in crop production and exports with decreases in crop prices. Livestock production and prices are mixed.
3. Climate change is found to be largely detrimental for producers. Climate changes are also found to be beneficial for foreign surplus and for consumers. These results reflect the overall positive effect on production which leads to decreasing prices.
4. There are substantial shifts in regional production with gainers and losers. The Lake states, Mountain states and Pacific region show gains in production while the Southeast, the Delta, Southern Plains and Appalachia generally lose. Results in the Corn Belt are generally positive. Results in other regions are mixed depending on the climate scenario and time period. The regional results show broadly that climate change favors northern areas and can worsen conditions in southern areas, a result shown by many previous studies.
5. Our analysis suggests increases in pesticide expenditures due to climate change, a partial offset to the overall benefits. The magnitude of this effect is relatively small.
6. The overall benefits of climate change are greater in 2090 than in 2030 for the US as a whole and, even for regions with losses, these are generally less in 2090 than in 2030. Changes in precipitation are likely the source of this result.
7. Climate change largely causes a decrease in resource usage due to expanded productivity. In particular dryland, total crop land, pasture land, and water usage declines.
8. Farm-level adaptation increases the climate change benefits to total society by about a billion dollars. Producer losses are generally reduced by adaptation.
9. Consideration of climate effects in other countries did not greatly alter the climate change benefits to total society. It can have substantial distributional assumptions depending on how climate affects the rest of the world.

10. Changing the base year does not alter the sign of the climate change benefits to total society.
11. The results obtained from using two different crop yield simulation approaches were quite similar in overall magnitude.
12. Jointly considering forest and agricultural changes due to climate does not change the impacts substantially. The net effect on society of both changes is positive and the distribution effects are similar, with producers suffering surplus losses due to declining prices while consumers benefit.

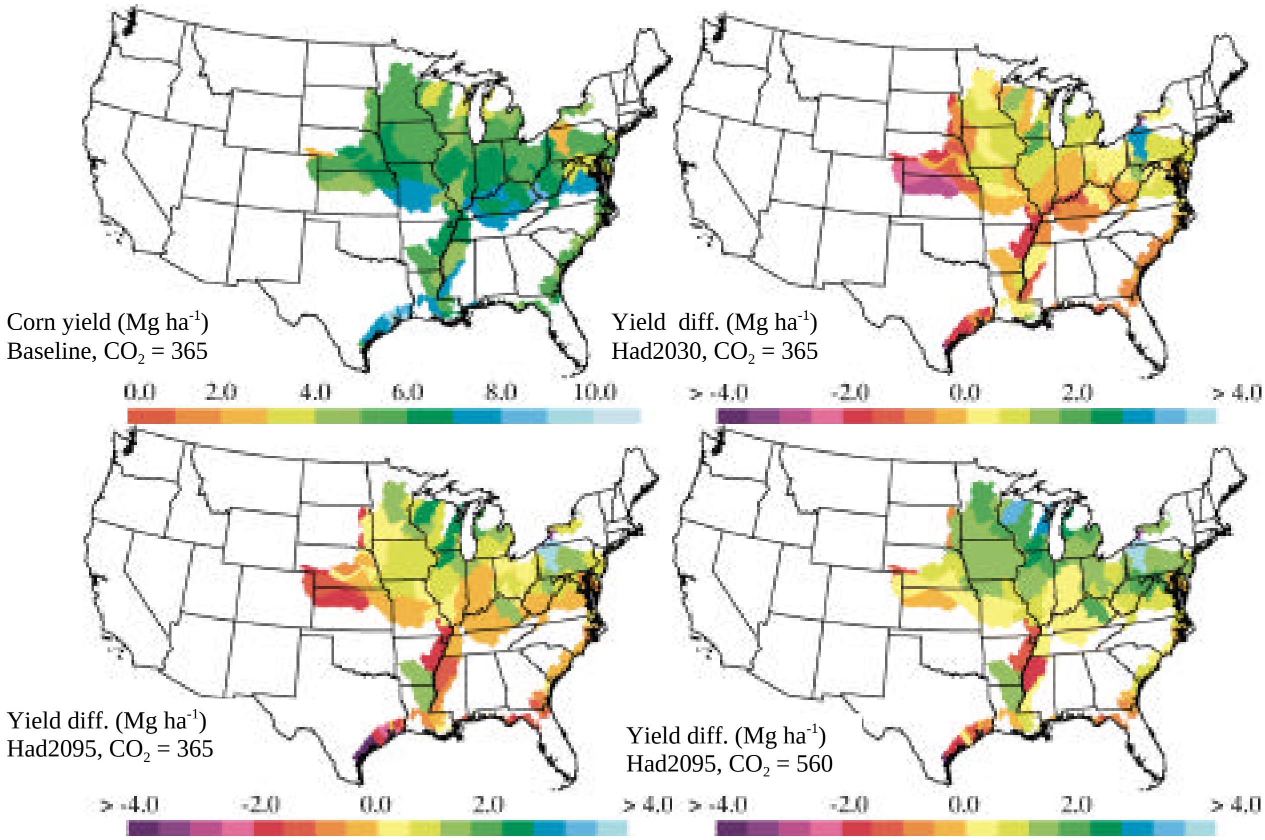

Fig. 3.1. Simulated yield changes from baseline for dryland corn grown in (a) 2030 and (b) 2095 under climate scenarios projected with the HadCM2 general circulation model.

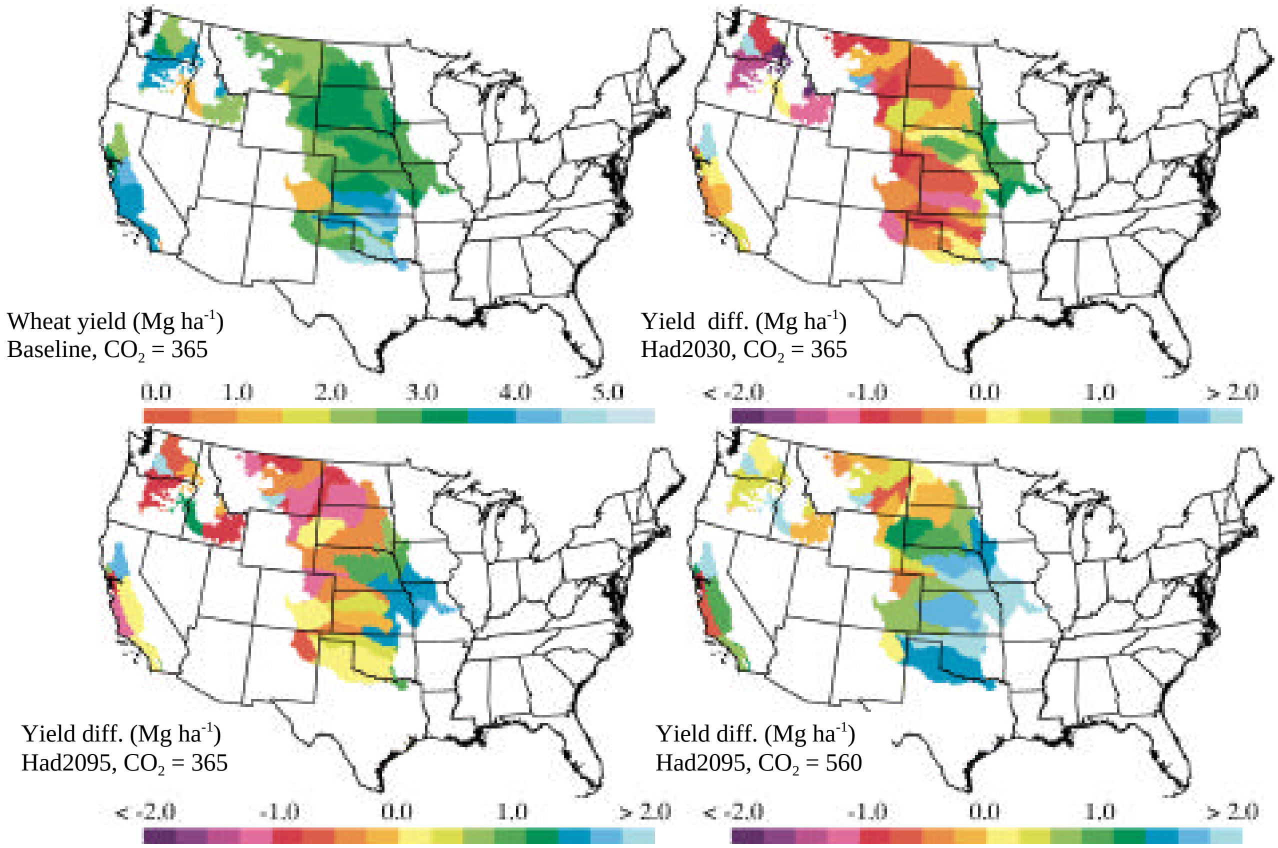

Fig. 3.2. Simulated yield changes from baseline for winter wheat grown in (a) 2030 and (b) 2095 under climate scenarios projected with the HadCM2 general circulation model.

Figure 3.3 ASM Regions with USDA Regions Overlaid
(ASM regions follow state boundaries except where further disaggregated)

Figure 3.4a. Economic Impacts of Climate Change, Canadian Center Climate

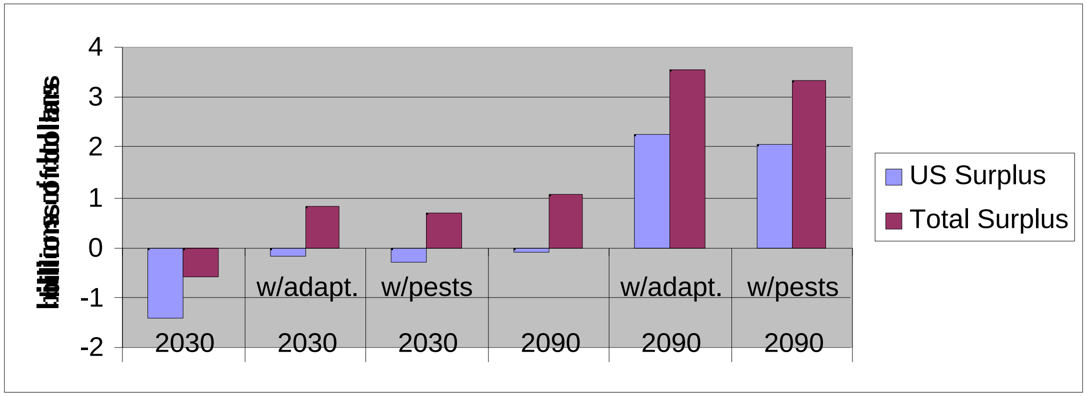

Figure 3.4a. Economic Impacts of Climate Change, Hadley Center Climate

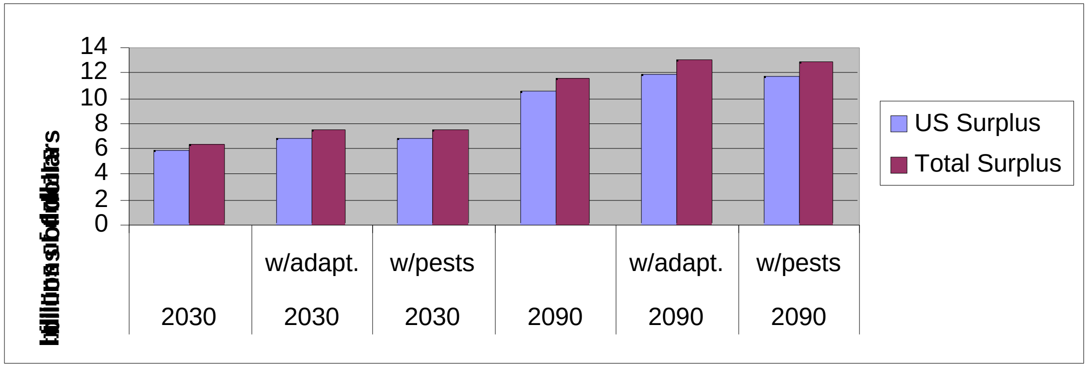

Figure 3.5a. Producer versus Consumer Impacts of Climate Change, Canadian Center Climate

Figure 3.5a. Producer versus Consumer Impacts of Climate Change, Hadley Center Climate

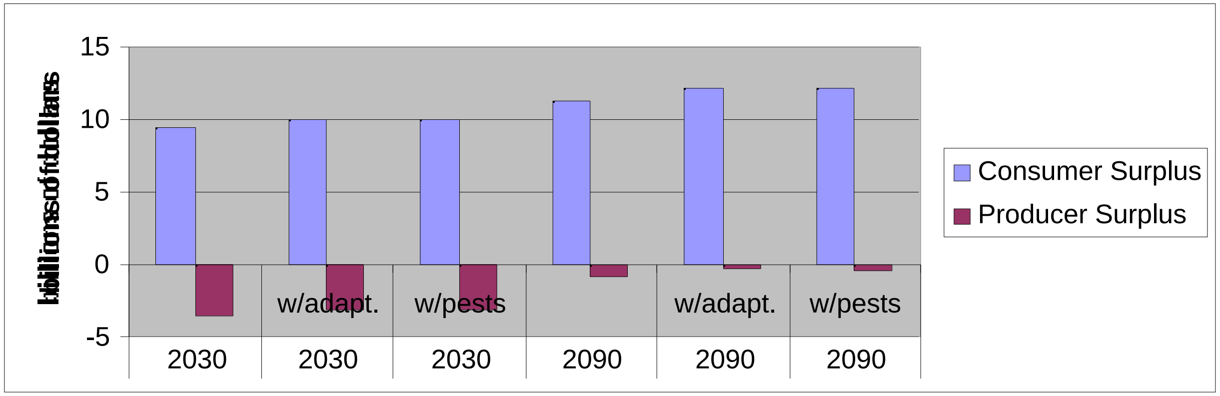

Figure 3.6a. Regional Production Changes, Canadian Center Climate

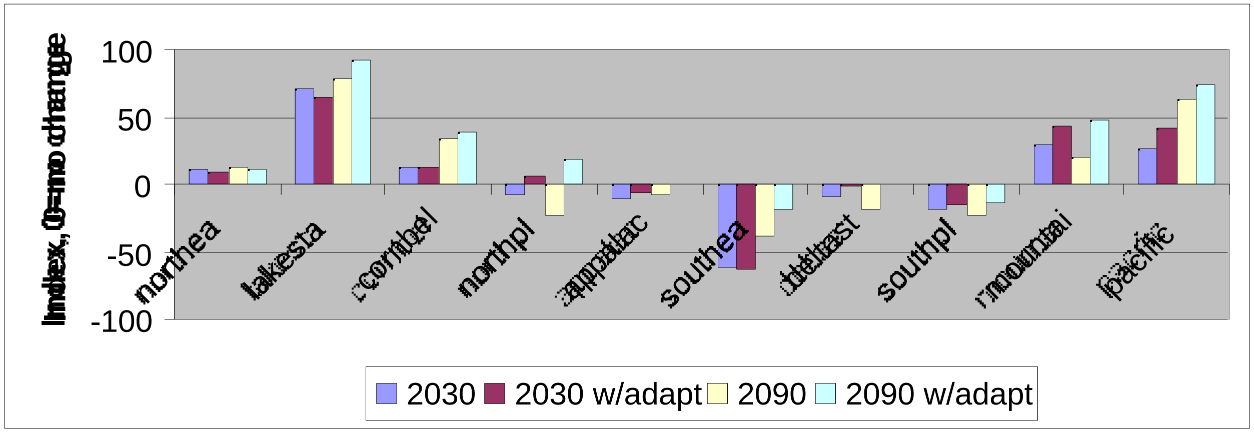

Figure 3.6b. Regional Production Changes, Hadley Center Climate

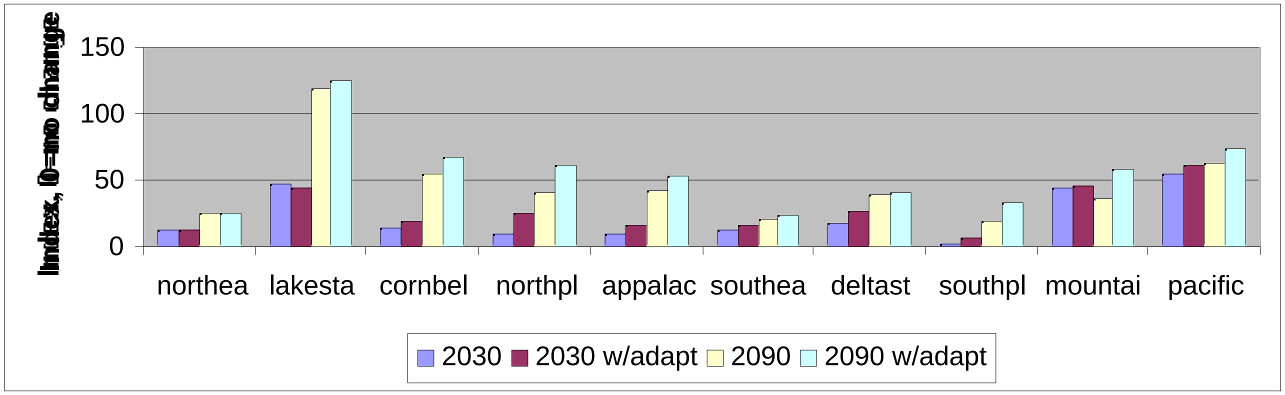

Figure 3.7. Changes in Resource Use, Canadian and Hadley Center Climates, without Adaptation

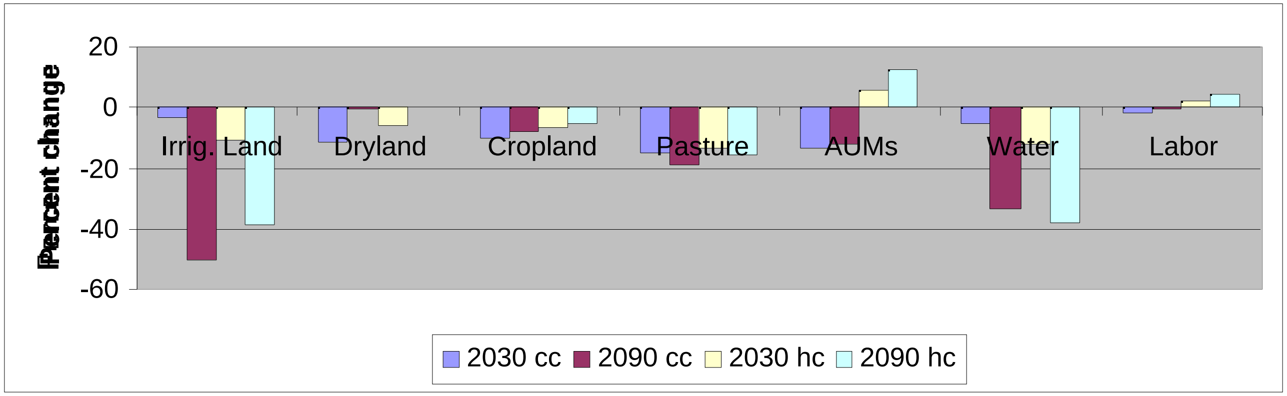

Table 3.1. Simulated yields of dryland corn under baseline climate (B) and Hadley Center projections in 2030 (H1) and 2095 (H2), each at two CO_2 concentration levels (365 and 560 ppm) for the six major growing regions of the U.S.

CO_2 / Scenario	Region					
	Lakes	Corn Belt	Delta	Northeast	Appalachian	Southeast
	Mg ha^{-1}					
B-365	4.57	6.05	6.26	4.16	6.13	5.76
B-560	4.95	6.53	6.55	4.54	6.73	6.35
H1-365	5.30	6.31	5.84	4.70	5.94	5.34
H1-560	5.94	6.98	6.74	5.24	6.70	6.13
H2-365	6.04	6.53	5.84	4.81	6.27	5.04
H2-560	6.69	7.09	6.32	5.35	6.95	5.76

Table 3.2. Simulated winter wheat yields under baseline climate (B) and Hadley Center projections in 2030 (H1) and 2095 (H2), each at two CO_2 concentration levels (365 and 560 ppm) for the four major growing regions of the U.S.

CO_2 / Scenario	Region			
	Pacific	Mountain	Northern Plains	Southern Plains
	Mg ha^{-1}			
B-365	3.37	1.84	3.09	3.75
B-560	4.08	2.44	3.71	4.61
H1-365	3.68	1.74	2.90	3.65
H1-560	4.45	2.38	3.85	4.66
H2-365	3.81	2.42	3.20	3.21
H2-560	4.59	3.21	4.21	4.02

Table 3.3a National average change in dryland yields without adaptation, percentage change from base conditions

	CC	CC	HC	HC	HC-PNNL	HC-PNNL
Crop	2030	2090	2030	2090	2030	2090
Cotton	18	96	32	82	32	82
Corn	19	23	17	34	11	16
Soybeans	20	30	34	76	7	9
Hard Red Sum Wheat	15	-4	20	30	17	24
Hard Red Win. Wheat	-16	-1	21	55	24	41
Soft Wheat	-5	3	8	20	58	68
Durum Wheat	15	-5	21	30	10	18
Sorghum	17	21	15	70	15	70
Rice	-2	-8	3	10	3	10
Barley	56	25	83	132	70	124
Oats	23	-2	54	101	158	182
Silage	17	18	15	32	11	24
Hay	-10	-1	2	15	43	57
Sugar Cane	-5	-5	0	8	0	8
Sugar Beet	7	11	9	24	30	45
Potatoes	7	-25	6	-3	6	-3
Orange, Fresh	32	91	40	69	40	69
Orange, Processed.	13	120	28	49	28	49
Grapefruit, Fresh	21	101	33	60	33	60
Grapefruit, Processed	15	112	29	53	29	53
Pasture	3	20	22	38	22	38

Note: Shaded cells are those yields that were not based on PNNL crop yield simulations.

Table 3.3b National average change in dryland yields with adaptation, percentage change from base conditions

	CC	CC	HC	HC	HC-PNNL	HC-PNNL
Crop	2030	2090	2030	2090	2030	2090
Cotton	18	96	32	82	32	82
Corn	20	24	17	34	11	16
Soybeans	39	64	49	97	7	9
Hard Red Sum Wheat	20	14	23	36	17	24
Hard Red Win. Wheat	-9	13	23	59	24	41
Soft Wheat	-3	4	9	21	58	68
Durum Wheat	18	12	22	33	10	18
Sorghum	43	87	32	96	32	96
Rice	7	4	9	18	9	18
Barley	96	133	105	197	70	124
Oats	33	24	57	106	158	182
Silage	18	20	16	32	11	24
Hay	-10	-1	2	15	43	57
Sugar Cane	6	7	7	16	7	16
Sugar Beet	7	11	9	24	30	45
Potatoes	8	-20	7	1	7	1
Orange, Fresh	32	91	40	69	40	69
Orange, Processed.	13	120	28	49	28	49
Grapefruit, Fresh	21	101	33	60	33	60
Grapefruit, Processed	15	112	29	53	29	53
Pasture	3	20	22	38	22	38

Note: Shaded cells are those yields that were not based on PNNL crop yield simulations.

Table 3.4a National average change in irrigated yields without adaptation, percentage change from base conditions

	CC	CC	HC	HC	HC-PNNL	HC-PNNL
Crop	2030	2090	2030	2090	2030	2090
Cotton	36	122	56	102	56	102
Corn	-1	-2	0	7	21	22
Soybeans	16	28	17	34	17	34
Hard Red Sum Wheat	-10	-18	4	6	4	6
Hard Red Win. Wheat	-4	-6	5	13	5	13
Soft Wheat	-6	-5	3	9	3	9
Durum Wheat	-10	-21	5	6	5	6
Sorghum	-1	-16	1	-2	1	-2
Rice	-2	-8	3	10	3	10
Barley	-40	-71	8	15	8	15
Oats	-17	-31	12	28	12	28
Silage	1	0	1	9	26	30
Hay	3	2	23	24	37	40
Sugar Cane	-5	-5	0	8	0	8
Sugar Beet	22	23	39	42	41	44
Potatoes	-6	-28	-3	-13	-3	-13
Tomato, Fresh	-9	-21	1	-4	1	-4
Tomato, Processed	-16	-6	-6	-14	-6	-14
Orange, Fresh	32	91	40	69	40	69
Orange, Processed.	13	120	28	49	28	49
Grapefruit, Fresh	21	101	33	60	33	60
Grapefruit, Processed	15	112	29	53	29	53

Note: Shaded cells are those yields that were not based on PNNL crop yield simulations.

Table 3.4b National average change in irrigated yields with adaptation, percentage change from base conditions

	CC	CC	HC	HC
Crop	2030	2090	2030	2090
Cotton	36	122	56	102
Corn	1	0	1	9
Soybeans	23	33	23	40
Hard Red Sum Wheat	-1	-6	7	10
Hard Red Win. Wheat	-1	0	8	16
Soft Wheat	-5	-3	5	11
Durum Wheat	2	-4	9	10
Sorghum	22	8	22	21
Rice	7	4	9	18
Barley	3	-16	28	40
Oats	-6	-15	17	33
Silage	3	3	2	10
Hay	3	2	23	24
Sugar Cane	6	7	7	16
Sugar Beet	22	23	39	42
Potatoes	-4	-21	-1	-8
Tomato, Fresh	1	6	10	13
Tomato, Processed	10	44	10	17
Orange, Fresh	32	91	40	69
Orange, Processed.	13	120	28	49
Grapefruit, Fresh	21	101	33	60
Grapefruit, Processed	15	112	29	53

Note: Shaded cells are those yields that were not based on PNNL crop yield simulations.

Table 3.5a National average change in water use on irrigated crops, without adaptation, percentage change from base conditions

	CC	CC	HC	HC
Crop	2030	2090	2030	2090
Cotton	-11	107	36	60
Corn	-34	-54	-30	-60
Soybeans	0	3	-12	-26
Hard Red Sum Wheat	-28	-22	-17	-21
Hard Red Win. Wheat	5	-9	-8	-29
Soft Wheat	5	-29	-12	-44
Durum Wheat	-28	-15	-18	-21
Sorghum	-7	-23	-9	-35
Rice	-10	37	-2	-4
Barley	-98	-90	-61	-85
Oats	-57	-73	-47	-80
Silage	-35	-50	-33	-63
Hay	2	26	-29	-36
Sugar Cane	-23	3	-8	-1
Sugar Beet	-12	40	-28	-28
Potatoes	-5	7	-1	4
Tomato, Fresh	-9	14	-5	5
Tomato, Processed	-3	-6	-4	-4
Orange, Fresh	-21	94	-6	-6
Orange, Processed.	0	438	11	24
Grapefruit, Fresh	-1	324	8	21
Grapefruit, Processed	1	401	11	24

Note: Shaded cells are those yields that were not based on PNNL crop yield simulations.

Table 3.5b National average change in water use on irrigated crops, with adaptation, percentage change from base conditions

	CC	CC	HC	HC
Crop	2030	2090	2030	2090
Cotton	-11	107	36	60
Corn	-33	-55	-32	-60
Soybeans	18	12	0	-20
Hard Red Sum Wheat	-12	-15	-12	-15
Hard Red Win. Wheat	9	-3	-6	-25
Soft Wheat	5	-24	-10	-45
Durum Wheat	-3	-5	-9	-12
Sorghum	3	-19	2	-27
Rice	2	48	5	8
Barley	-40	-57	-41	-61
Oats	-37	-60	-38	-68
Silage	-35	-52	-35	-62
Hay	2	26	-29	-36
Sugar Cane	-19	-11	-6	7
Sugar Beet	-12	40	-28	-28
Potatoes	-3	10	0	7
Tomato, Fresh	-8	6	2	13
Tomato, Processed	3	-14	-3	-6
Orange, Fresh	-21	94	-6	-6
Orange, Processed.	0	438	11	24
Grapefruit, Fresh	-1	324	8	21
Grapefruit, Processed	1	401	11	24

Note: Shaded cells are those yields that were not based on PNNL crop yield simulations.

Table 3.6a International Trade Scenarios: Percent Production Changes Based on GISS Climate Scenario

Region	Wheat	Coarse Grains	Rice	Other Crops	Secon-dary
Canada	20	17.2	2.2	20.3	1.4
EC&Western Europe	-0.7	3.1	4.5	12	0.7
FSU	23	12	13.2	17.6	0.1
Eastern Europe	6.8	1.3	1.3	13.7	0.1
Australia&NZ	-11.6	10.7	17.1	8.2	0.4
China, Taiwan, & S. Korea	14.9	0.1	1.1	15.6	-0.1
Other East Asia	-21	-32.9	-5.7	-15.6	0.4
India	-4.4	-13.9	-2.2	-6.1	0.8
Argentina	-25.8	8.5	9.8	6	0.4
Brazil	-35.2	-10.3	-11.8	-0.5	0.2
Mexico	-34.9	-34.8	-18	-19.9	0.2
Japan	-1.9	22.2	11.4	11.2	0.4
Africa (all) & Middle East	-19	-24	3.2	-5.3	1.9
Other Latin America	-29.1	-10.6	-9.7	-18.6	0.1

Table 3.6a International Trade Scenarios: Percent Production Changes Based on UKMO Climate Scenario

Region	Wheat	Coarse Grains	Rice	Other Crops	Secon-dary
Canada	4.5	-6.6	6	-7.5	-2
EC&Western Europe	11	9.8	13.5	11.6	-1.4
FSU	-8.1	-6	-7.4	-1.4	-0.3
Eastern Europe	1.5	3	3.1	11.2	-0.3
Australia&NZ	46.2	19.8	28	27	-0.3
China&Taiwan&S. Korea	0.9	0.7	2.6	12.9	0.5
Other East Asia	-15	-30	-15.7	-10.2	-0.8
India	-19.8	-36	-17.1	-25.6	-1.2
Argentina	-7.6	-0.6	18.7	17.5	0
Brazil	-28.4	-13.7	-18.6	-7	-0.6
Mexico	-27.2	-33.8	-24.1	-16.1	-0.2
Japan	1.6	17.3	8.5	10.4	-1.7
Africa (all) & MiddleEast	-12.8	-25.3	8.7	-8	-1.6
Other Latin America	-28.7	-17.6	-15.5	-25.2	0.1

Table 3.7 Sensitivity to Trade Scenarios, without Adaptation

Year	Scenario	Consumer Surplus	Producer Surplus	Foreign Surplus	Total Surplus
2030	Base,CC	2.819	-4.23	0.807	-0.604
2030	Darwin,CC	4.951	-6.39	0.834	-0.606
2030	GISS,CC	2.162	-3.69	0.808	-0.719
2030	UKMO,CC	2.819	-4.208	0.807	-0.582
2030	Base,HC	9.416	-3.613	0.57	6.373
2030	Darwin,HC	11.034	-5.231	0.529	6.331
2030	GISS,HC	9.285	-3.429	0.572	6.428
2030	UKMO,HC	9.416	-3.629	0.57	6.357
2090	BASE,CC	4.452	-4.531	1.144	1.065
2090	Darwin,CC	5.146	-5.549	1.107	0.703
2090	GISS,CC	4.157	-4.306	1.16	1.012
2090	UKMO,CC	4.452	-4.531	1.144	1.065
2090	BASE,HC	11.351	-0.796	0.987	11.542
2090	Darwin,HC	11.784	-1.459	0.969	11.295
2090	GISS,HC	11.341	-0.75	0.99	11.581
2090	UKMO,HC	11.351	-0.796	0.987	11.541

Table 3.8 PNNL Crop Yield Simulations, without Adaptation

	Consumer Surplus	Producer Surplus	Foreign Surplus	Total Surplus
HC 2030	9.416	-3.613	0.57	6.373
HC-PNNL 2030	11.202	-3.278	0.277	8.2
HC 2090	11.351	-0.796	0.987	11.542
HC-PNNL 2090	13.94	-3.993	0.686	10.633

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