U.S. National Assessment Technical Report
Effects of Climate Change on U.S. Crop Production
Part I: Wheat, Potato, Corn, and Citrus

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Abstract. The effects of predicted climate change on US crop production were investigated by using climate scenarios from two general circulation models (GCMs), Hadley and CCCM, and a family of dynamic crop-growth models. The transient climate change scenarios were characterized by a 1% yearly increase in atmospheric forcing, due to projected future increases in atmospheric CO_2 and other greenhouse gases, but moderated by the effects of anthropogenic emissions of sulfuric aerosols. For each GCM scenario, two time windows were considered, centered in 2030 and 2090. Forty-five representative sites were chosen across the US, to simulate present and future agricultural production of major US crops: winter and spring wheat; corn; potato; and citrus. Under the scenarios considered, overall US crop production increased due to the beneficial effects of elevated CO_2 on crop yields and to marked precipitation increases. These two factors counterbalanced negative effects of warmer temperatures on crop yields. Rainfed crop production increased about 20-50%, especially benefiting winter wheat, corn, soybean, and citrus crops. In specific cases where precipitation decreased, however, the models predicted significant declines in crop yields and a significant increase in variability, for example in Kansas and Oklahoma under the CCCM scenarios. Underlying the positive outcomes obtained at the national level, the study projected a regional distribution of winners and losers. Generally, northern producing regions such as the Pacific North-West and the Northern Great Plains benefited from increased temperatures, which tend to extend growing seasons. By contrast, southeast coastal regions were negatively affected by the projected climate changes.

1. INTRODUCTION

Atmospheric CO_2 concentration has risen since pre-industrial times, from 280 ppm to 365 ppm today, a direct result of human activities (IPCC, 1996). At current emission rates it should double by 2100. GCM simulations suggest that increase greenhouse forcing will raise surface air temperatures in the range 2-4°C, and alter precipitation regimes, increasing the frequency of severe weather events such as drought spells and flooding.

Agricultural crop production might be significantly affected by the predicted changes in climate and atmospheric CO_2 (Rosenzweig and Hillel, 1998). Elevated CO_2 alone increases plant photosynthesis and thus crop yields (Kimball, 1983). But the predicted changes in temperature and precipitation might further affect crop yields, by hastening plant development, and by altering the water and nutrient budgets in the field, modifying plant stress (Long, 1991). The net effects on yields of increased CO_2 and climate change 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. By contrast, warmer temperatures during crop development could depress yields in those regions where summer temperature and water stress are already limiting (Rosenzweig and Tubiello, 1997).

The response of agricultural systems to future climate change will also depend on management practices, such as the type and levels of water and nutrients applied. Crop response to elevated CO_2 is relatively greater when water is a limiting factor, 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).

A wide range of adaptations may exist within cropping systems, to help maintain or increase crop yields under climate change. Farmers usually respond to environmental change by choosing the most favorable crops, cultivars, and rotations. Assessment studies help to select adaptation strategies that might succeed in the future, and identify thresholds beyond which crop yields cannot 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 help in assessing future yield potential (e.g., Rosenberg, 1993; Rosenzweig and Parry, 1994). This work is a simulation analysis of the effects of climate change and elevated CO_2 on US crop production, using two recently developed scenarios of climate change.

2. MATERIALS AND METHODS

2.1. Site selection and generation of climate change scenarios

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 (see Table 1 in the Appendix). We used a network of major crop growing sites, based on current USDA national and state-level statistics. A subset of these sites had been used in previous work (Rosenzweig et al., 1995; Adams, et al., 1990; Curry et al., 1995). The study sites we selected do not necessarily span the US homogeneously, but rather focus on areas of major production, of importance to the National output. We simulated crops at current sites of production for winter and spring wheat, maize, soybean, potato, and citrus. In addition, we simulated at more northerly sites the production of some crops currently limited to southern locations, to estimate the potential for northward shifts under climate warming. At each site we collected observed time series of daily temperatures (minima and maxima), precipitation, and solar radiation for the period 1951-1994, thus representing 44 years of “baseline” climate. Scenarios of climate change were produced using transient simulations performed with two general circulation models (GCMs), as distributed by the US National Assessment: the Canadian Community Climate Model (CCCM); and the Hadley Centre Model (Hadley). Two time periods were considered in this analysis: “2030” and “2090”. Each new time period was generated by applying to each month of the baseline years the changes in temperature, precipitation, and solar radiation predicted by the GCMs, using twenty-year averages centered around the years 2030 and 2090 respectively (see example in Fig. 2. For comprehensive data see Tables A-F in the Appendix). Atmospheric CO_2 concentrations were obtained from the “business as usual” IPPC scenario (IPCC, 1995). These were: 350 ppm for the baseline; 445 ppm for “2030”; and 660 ppm for “2090”.

A total of 5 scenarios, each composed of 44 years, were used in this study: 1) baseline, representing current conditions; HCGS-2030 and CCGS-2030, representing climate and CO_2 levels averaged over the period 2020-2039; HCGS-2090 and CCGS-2090, representing climate change conditions averaged over the period 2080-2099.

2.2. Crop Models

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, and potato (Tsuji et al., 1994). The model of Ben Mechlia and Carrol (1989) was used to simulate citrus production.

All models employed have been used extensively to assess crop yields across the U.S. under current conditions as well as under climate change (Rosenzweig et al., 1995; Parton et al., 1994, Tubiello et al., 1999). The models employed 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 (e.g., irrigation and fertilization) on crop growth. The simulations performed for this study considered at each site: 1) rainfed production; and 2) optimal irrigation, defined as automatic re-filling of the soil water profile whenever water levels fell below 50% of field capacity at 30 cm depth. Fertilizer applications were assumed to be optimal at all sites. Finally, simulations were run sequentially at each site, i.e., without restarting the soil water profile at the beginning of each simulation year.

The climate change scenarios used in this study are considered to be more realistic than previously available. Because they include sulfuric aerosols, they predict temperature increases (until about 2050) than are smaller than previous transient GCM simulations. By contrast, temperature increases become substantial by 2090, as the “masking” effect of aerosols on climate warming becomes small compared to anthropogenic forcing.

Model limitations. Current crop models are developed under a range of soil and climate conditions, and are used at local, regional, and global scales to systematically assess adaptation strategies in agricultural systems, as climate and/or other factors change.

However, the models assume that soil nutrients and micronutrients are not limiting, and that pests (insects, diseases, weeds) pose no threat to crop growth and yield. Therefore, simulations under climate change conditions and elevated CO_2 may be overestimates of actual yield increases.

2.3. Simulations under current climate.

Model simulations, scaled to state level by using statistical information of percent irrigation, agreed well with reported yield across the US states (Fig. 3).

Winter wheat. Winter wheat was simulated at Abilene, TX; Boise, ID; Columbus, OH; Dodge City, KS; Topeka, KS; Goodland, KS; North Platte, Nebraska; Oklahoma City, OK; and Spokane, WA. 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%, and 30-50% for rainfed conditions. 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. Spring wheat was simulated at 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 impacts of 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

Corn. Simulated maize yields well agreed 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. Crop simulations were performed at Alamosa, CO; Boise, ID; Buffalo, NY; Caribou, ME; Fargo, ND; Indianapolis, IN; Madison, WI; Medford, OR; Muskegon, Michigan; Pendleton, OR; Scott Bluff, NE; and Yakima, WA. Continuous rainfed potato production was simulated as viable at Buffalo, NY; Caribou ME; Fargo, ND; and Indianapolis, IN; and Madison, WI. Under current climate, crop simulations well correlated with reported production. The highest simulated irrigated yields, slightly above 80 t/ha, were simulated at the Northwestern sites, at Medford, OR; Pendleton, OR; and Yakima, WA, where the 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%. They were 30-40% under rainfed conditions.

Citrus. We simulated the effects of current and predicted future climate on Valencia Orange across the Southern United States. We considered a total of eight sites for our analysis of climate change effects, 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, ND, producing 4-6 t/ha, representing marginal production levels. Another additional five sites were chosen for simulations, to investigate potential for citrus expansion northward of the current production area. They 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.

3. SIMULATION RESULTS UNDER CLIMATE CHANGE

Crop simulations were repeated under scenarios of climate change. Two sets of simulations were considered: non-adapted (see Fig. 4), using current management practices, and adapted.

The adaptation techniques considered in this study were simple ones, and consisted of testing the effects of early planting (a realistic scenario at many northern sites under climate change), and in assessing the performance of cultivars better adapted to warmer climates, using crop parameters derived from currently available genetic stock. Early planting was simulated for spring crops, to avoid heat and drought stress in the late summer months (Fig. 5). Crop yields of new, heat-adapted cultivars were simulated for winter crops, to allow an increase of the time to maturity (shortened under climate change scenarios) and thus yield potential. In addition to these quantitative assessments, our simulations allow one to assess, qualitatively, the potential for changes in irrigation management in the future, by comparing the relative performance of dryland and irrigated yields under baseline and climate change conditions. Quantitative assessments of the effects of potential changes in dryland and irrigated areas in response to climate change were carried out within the economic modeling efforts of the Agriculture Assessment Team, and have been reported elsewhere (http://www.nacc.usgcrp.gov).

3.1 Winter Wheat

The two GCMs considered in this study gave opposite responses for US wheat production, mainly due to differences in forecast precipitation, with the CCCM scenario (drier) resulting in large negative to small positive impacts on crop yields, while the Hadley scenario (wetter) 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.

Rainfed Production. The CCCM scenarios resulted in large negative impacts for both continuous and fallow production at all sites, including the major production centers in the Great Plains. 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 (CV) of yield consistently increased in both decades, indicating that in the future the risk of obtaining low grain yields in any given year might be higher than present. The exception under CCCM was Columbus, OH, where yield increased in the range 3-8% in 2030 and 16%-24% in 2090. The Hadley scenarios resulted in increases across all sites considered. Rainfed production increased in the range 6%-20% in 2030 and by 13% to 48% by 2090. Year-to-year variation decreased at most sites.

Irrigated Production. Irrigated wheat yields increased under both GCM scenarios, although increases were larger under the Hadley than under the CCCM 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%.

Adaptation. Crop simulations indicated no need to adapt current crop practices and water management of wheat production under the Hadley scenario. Under the CCCM scenario, however, major adaptation techniques would be required to avoid the sizable losses simulated in the Central Great Plains. Simulations suggest that rainfed cultivation in Kansas might be too risky for production under such a scenario, and that therefore irrigation would be necessary to maintain current production, all else being equal.

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. Shifting to a southern-grown variety counterbalanced the predicted yield decreases at North Platte NE. 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 CCCM model at these sites.

3.2 Spring Wheat

Warmer temperatures were the major factor affecting spring wheat yields across sites, time horizon, and management practice, as they hastened crop development thus affecting crop yields negatively. The ultimate outcome on yields depended on predicted precipitation changes.

Rainfed Production. In 2030, rainfed spring wheat production increased under both GCM scenarios by 10-20%, due to increased precipitation and despite warmer temperatures, with reduced CVs and thus production risks. This positive trend continued in 2090 under the Hadley scenario, generating yield increases in the range 6-45%. The largest increases were simulated at Pierre, SD (47%).

The 2090 CCCM scenario resulted in significant decreases in spring wheat yields at current production sites. Yields decreased at Fargo, ND (-16%); and Glasgow, MT (-24%). The CCCM scenario also generated yield decreases in Fresno, CA (-20%). By 2090, the CCCM-predicted spring-summer temperatures were about 4°C higher than current at all sites considered, affecting wheat development and grain filling negatively, and depressing yields despite the gains due to precipitation increases.

Irrigated Production. Irrigated spring wheat production decreased in the range 5%-20% at five of the eight sites considered, under both scenarios. In 2030, yields decreased at Boise, ID (-17% to –7%); Spokane, WA (-1% to –4%); Tucson, AZ (-6% to –3%); and Fresno, CA (-24% to –16%). 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.

Adaptation. 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 CCCM scenario.

Additional adaptation strategies would be necessary in order to maintain current yield levels at Fargo, ND; and Glasgow, MT. Simulations indicated that yields there could be maintained at current levels by planting two to three weeks earlier, compared to current practices.

3.3 Corn

Rainfed production. 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 increases 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.

Irrigated Production. 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 CCCM scenario were almost three times as much as current levels.

Adaptation. 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.

3.4 Potato

Simulated results indicated that at several sites potato production would not be viable under climate change, with little room for adaptation. This is mainly due to the high sensitivity of yields to the predicted warmer winter temperatures. The Northwestern sites of major production, however, registered the smallest simulated losses.

Rainfed Production. The two GCM 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 CCCM 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 CCCM 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 CCCM 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 Production. Irrigated yields decreased in 2030, by 1% to 10%, but a few sites registering no change or even small percentage increases. The predicted temperature increases affected crop production negatively. The CCCM scenario resulted in simulated yield reductions from –13% to –6%. Exceptions were found at 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 GCM. 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 (30-40%) at Boise, ID; and Scott Bluff, NE (27%-50%), and smaller ones at Pendleton, OR; Medford, OR (10%-15%); and Buffalo, NY (8%-18%).

Adaptation. Similarly to the results obtained for other crops, simulations suggested that rainfed production could become more competitive over irrigation 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 to reduce yield losses 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. For example, anticipating planting by as much as one month at Boise, ID, helped to reduce yield losses under climate change by 50%, relative to simulations without adaptation.

3.5 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 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.

4. DISCUSSION AND CONCLUSIONS

A number of key factors shaped the prediction of future US crop yields in this study. These factors include primarily:

- Effects of increased precipitation, as forecast by the GCMs used in the assessment;
- Important differences in regional forecasts between the Hadley and CCCM scenarios;
- Effects of increased temperature;

- Assumptions about CO_2 fertilization effects;

Precipitation. Both climate scenarios used in this assessment produced warmer and much wetter conditions, compared to present, over areas of major US rainfed cereal production, with few exceptions. For example, when averaged across all grain corn production sites and GCM scenarios, growing season precipitation was 20% higher than present for 2030s, and 23% higher in 2090s (Tab. 1). When these averages are restricted to the major Corn Belt sites used in the study, these numbers increase to 22% in 2030s and 40% in 2090s.

In fact, the precipitation effect was a significant factor leading to the projected increase in total US national output, because rainfed cereal production is one of its major components. Because GCM predictions of regional precipitation are poor, the use in this study of scenarios with marked precipitation increases may not have allowed the crop models to assess the full range of potential effects of climate change on US agriculture.

To this extent, it is important to analyze those cases where sharp differences in precipitation occurred between Hadley and CCCM. Perhaps the most important of such cases is rainfed hard red winter wheat production in western Kansas, a key US breadbasket region (Tab. 2). The Hadley scenario predicted 3-17% higher annual precipitation compared to present for this region. Under such circumstances, modeled rainfed wheat production increased by 30%, averaged across time horizons. But under the CCCM scenario, which predicted marked decreases in precipitation (in the range 10-20% but as high as –40% in the fall season), rainfed production was severely affected, with average yields were -30% or lower. Most importantly, interannual yield variability, a major factor of production risk, nearly doubled in this region under the CCCM scenario.

Temperature. Effects of precipitation and temperature can be, to some extent, separated by comparing the effects of the climate scenarios over both rainfed and irrigated production, the latter being insensitive to precipitation changes (Tab. 1). Using US corn as an example, when averaged across sites and scenarios, rainfed production increased 11% in 2030s but irrigated production decreased by 6%. In 2090s, rainfed production was 15% higher than present, while irrigated production decreased 8%.

Precipitation increases aside, our study confirmed (in agreement with previous work) that warmer temperatures have negative effects on yields except at northernmost latitudes, where a lengthening of the growing season is beneficial to crop growth. At all other sites, and in particular at southern sites where current temperatures are already high, warmer climates generally decreased irrigated yields.

Strength of CO_2 fertilization effects. The magnitude, and sometimes even the direction, of climate change effects on crop yields depend on the simulated CO_2 response (Fig. 6). We have used state-of-the art parameterizations in our crop models. However, the CO_2 formulations currently implemented are still largely based on controlled-environment studies, and should be regarded as an upper limit to the potential response in the field, where a variety of mechanisms, including resource competition, plant-pest interactions, soil limitations, etc., will likely limit crop response to elevated CO_2. What if such responses were much smaller than assumed in the models? Table 3 shows, as an example, the effects of climate change on corn yields, with and without CO_2 fertilization. Under rainfed conditions, corn yields averaged across sites, scenarios, and time horizons, would remain unchanged (+0.3%) with no CO_2 response, and increase (+12%) with CO_2 fertilization. Similarly, under irrigated conditions, corn yields averaged across sites and scenarios would decrease more with no CO_2 response (-12%) than with CO_2 fertilization (-7.5%). Tables 1 and 3 suggest that precipitation and elevated CO_2 each contributed about half of the simulated yield increases.

In conclusion, this study finds that US agriculture as a whole, and the US ability to feed itself, may not be under serious threat from future climate change. In addition, it is fair to expect that farmers' resources and future technology will further contribute to successful adaptation to changing conditions, over and beyond the simple techniques considered in this study. It is however important to remember that future positive change will be a sum of winners and losers, distributed regionally. In fact, if one of the principles underlying the National Assessment is to provide guidance in devising "insurance policies" against projected risk, then it is very important, despite the overall positive picture, to analyze those specific regional cases where negative outcomes are likely. It is those cases that need to be considered when devising “no regrets” policies to face our future challenges.

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Table 1. National Assessment simulations summary for corn. Percentage yield changes from the baseline due to climate change and elevated CO_2, under rainfed and irrigated conditions. The last column indicates changes in daily precipitation during the crop growing period.

	Rainfed	Irrigated	Precipitation d^{-1}
2030s	11%	-6%	20%
2090s	15%	-8%	23%
ALL	13%	-7.5%	21.5%

Table 2. National Assessment simulations summary for rainfed winter wheat in western Kansas. Percentage yield changes from the baseline due to climate change and elevated CO_2, under rainfed conditions. The last column indicates changes in growing season precipitation.

	Rainfed	Precipitation
Hadley	+30%	+20%
CCCM	-35%	-30%

Table 3. National Assessment simulations summary for corn. Percentage yield changes from the baseline due to climate change without and with fertilization due to elevated CO_2, averaged across time horizons and GCM scenarios.

	Rainfed	Irrigated
W/o CO_2	0.3%	-12%
With CO_2	13%	-7.5%

Appendix 1.

This section contains Tables with all the raw simulated data relative to Winter and Spring Wheat; Potato; Citrus; and Corn.

Table A. Crops Study Sites, symbols, and crops simulated at each location.

Site	SYMBOL	Crops simulated
1. Abilene, TX	ABTX	Winter Wheat, Sorghum
2. Alamosa, CO	ALCO	Potato
3. Bakersfield, CA	BACA	Citrus, Rice
4. Boise, ID	BOID	Winter Wheat, Spring Wheat, Potato
5. Buffalo, NY	BUNY	Potato, Tomato
6. Caribou, ME	CAME	Potato
7. Columbus, OH	COOH	Tomato, Winter Wheat, Corn
8. Columbia, SC	COSC	Soybean, Sorghum, Tomato
9. Corpus Christi, TX	CCTX	Citrus
10. Daytona Beach, FL	DBFL	Citrus
11. Des Moine, IA	DEIA	Corn, Soybean
12. Dodge City, KS	DOKS	Winter Wheat
13. Duluth, MN	DUMN	Corn, Soybean
14. El Paso, TX	EPTX	Citrus, Rice, Sorghum, Tomato
15. Fargo, ND	FAND	Spring Wheat, Potato, Corn
16. Fresno, CA	FRCA	Rice, Spring Wheat, Tomato
17. Glasgow, MT	GLMT	Spring Wheat
18. Goodland, KS	GOKS	Winter Wheat, Sorghum
19. Indianapolis, IN	ININ	Potato, Corn, Soybean, Tomato
20. Las Vegas, NV	LVNE	Citrus
21. Louisville, KY	LOKY	Soybean, Sorghum
22. Madison, WI	MAWI	Potato, Corn, Soybean
23. Medford, OR	MEOR	Potato
24. Memphis, TN	METN	Corn, Soybean
25. Miami, FL	MIFL	Rice, Citrus
26. Montgomery, AL	MOAL	Citrus, Rice, Soybean, Sorghum, Tomato
27. Muskegon, MI	MUMI	Potato, Soybean, Tomato
28. North Platte, NE	NONE	Winter Wheat, Corn, Soybean, Sorghum
29. Oklahoma City, OK	OKOK	Winter Wheat, Sorghum
30. Pendleton, OR	PEOR	Potato
31. Peoria, IL	PEIL	Corn, Soybean, Sorghum
32. Pierre, SD	PISD	Spring Wheat, Sorghum
33. Port Arthur, TX	PATX	Rice, Citrus
34. Raleigh, NC	RANC	Soybean, Sorghum, Tomato
35. Red Bluff, CA	RBCA	Rice, Citrus
36. Savannah, GA	SAGA	Citrus, Soybean, Sorghum
37. Scott Bluff, NE	SBNE	Potato
38. Sioux Falls, SD	SFSD	Corn, Sorghum
39. Shreveport, LA	SHLA	Rice, Citrus
40. Spokane, WA	SPWA	Winter Wheat, Spring Wheat
41. St. Cloud, MN	SCMN	Spring Wheat, Corn, Soybean
42. Tallahassee, FL	TAFL	Citrus, Tomato
43. Topeka, KS	TOKS	Winter Wheat, Corn, Soybean, Sorghum
44. Tucson, AZ	TUAZ	Spring Wheat, Citrus
45. Yakima, WA	YAWA	Potato

TABLE B1. Predicted climate change parameters for temperature and precipitation at winter wheat sites.

SITE	**GCM**	**TIME**	**Spring** %	**Summer** %	**Fall** %	**Winter** %	**Annual P** %	**Annual T** ∆C
ABTX	CCCM	2030	3.65	14.59	-10.28	-49.16	-6.76	1.33
ABTX	CCCM	2090	8.91	-51.63	-8.67	-28.47	-14.78	5.27
ABTX	HAD	2030	0.45	2.85	-2.04	-5.23	-0.73	1.16
ABTX	HAD	2090	16.72	39.16	16.36	-8.76	16.86	2.86
BOID	CCCM	2030	33.58	5.9	30.53	19.8	23.85	1.9
BOID	CCCM	2090	16.21	-2.12	42.02	68.47	40.69	4.94
BOID	HAD	2030	8.24	-2.28	36	8.81	12.58	1.73
BOID	HAD	2090	13.43	-7.16	25.62	27.29	17.55	3.82
COOH	CCCM	2030	-5.64	42.94	-23.59	-6.64	0.88	1.95
COOH	CCCM	2090	17.66	26.79	-7.04	-6.21	9	4.88
COOH	HAD	2030	9.53	16.79	0.06	4.09	8.82	0.85
COOH	HAD	2090	23.08	30.98	28.58	13.61	24.54	2.26
DCKS	CCCM	2030	-9.96	-25.94	-41.13	-30.66	-23.75	2.64
DCKS	CCCM	2090	-21.94	8.12	-20.77	-10.68	-10.7	6.07
DCKS	HAD	2030	-3.7	4.26	17.78	2.29	3.35	1.25
DCKS	HAD	2090	17.82	14.53	17.7	24.02	17.46	2.94
GOKS	CCCM	2030	3.98	-26.03	-47.32	-11.83	-19.06	2.85
GOKS	CCCM	2090	-28.97	4.03	-44.39	2.84	-16.51	6.43
GOKS	HAD	2030	4.87	-3.01	13.08	10.17	3.91	1.4
GOKS	HAD	2090	22.08	2.39	20.48	42.83	17.16	3.16
NPNE	CCCM	2030	1.47	-9.58	-40.95	-5.13	-11.98	2.83
NPNE	CCCM	2090	-15.1	4.67	-20.8	5.46	-6.6	6.25
NPNE	HAD	2030	6.3	3.81	7.19	10.33	5.97	1.34
NPNE	HAD	2090	22.77	9.91	25.05	36	19.84	2.98
OKOK	CCCM	2030	-30.34	-17.26	-31.4	-53.57	-31.1	2.37
OKOK	CCCM	2090	4.94	-36.82	80.65	-33.44	6.2	5.29
OKOK	HAD	2030	-0.11	1.75	5.56	-6.94	0.4	1.11
OKOK	HAD	2090	27.56	23.38	17.57	5.68	20.92	2.62
SPWA	CCCM	2030	0.71	-10.81	38.02	-2.42	6.14	1.3
SPWA	CCCM	2090	-1.91	-15.64	52.66	29.05	18.86	4.11
SPWA	HAD	2030	7.89	5.46	26.9	8.26	12.69	1.64
SPWA	HAD	2090	8.78	-0.86	21.63	12.46	12.33	3.8
TOKS	CCCM	2030	0.03	6.23	-23.87	-18.32	-5.01	2.48
TOKS	CCCM	2090	27.17	37.96	26.89	2.97	27.79	5.25
TOKS	HAD	2030	1.28	8.62	11.74	8.04	6.37	1.03
TOKS	HAD	2090	20.43	24.35	24.65	13.47	21.36	2.47

TABLE B2. WINTER WHEAT BASE YIELDS AND CHANGES. Data is expressed in percentage change from the baseline, except when in bold type. Numbers in bold are absolute numbers, representing 44 year-averages for current conditions: Yield (kg/ha); Irrigation (mm).

Site	GCM	Scenario	Dry Yield (%)	Yield CV	Irr Yield (%)	Yield CV	IRR (%)	Irr CV	Fallow Yield (%)	Yield CV
ABTX		**Base**	**2012**	**.90**	**4766**	**.18**	**151.9**	**.43**	**2100**	**.85**
ABTX	CCC	2030	-19.0	.84	-5.5	.20	-45.6	.53	-20.5	.82
ABTX	CCC	2090	-31.8	.90	6.0	.23	-29.8	.47	-33.4	.88
ABTX	HC	2030	18.4	.82	4.7	.19	-11.9	.42	17.2	.79
ABTX	HC	2090	34.9	.80	18.6	.20	-17.5	.40	31.8	.78
BOID		**Base**	**1004.3**	**.96**	**8465.3**	**.12**	**376.9**	**.19**	**1586.0**	**.80**
BOID	CCC	2030	179.4	.77	5.1	.12	-33.0	.25	136.8	.60
BOID	CCC	2090	335.5	.63	17.7	.12	-44.3	.27	227.5	.44
BOID	HC	2030	100.9	.86	11.9	.12	-18.6	.22	73.3	.68
BOID	HC	2090	312.2	.72	28.2	.12	-41.1	.27	244.4	.52
COOH		**Base**	**4626**	**.29**	**5407**	**.15**	**120.5**	**.47**	**4626**	**.29**
COOH	CCC	2030	3.1	.24	1.2	.12	-12.2	.49	3.1	.24
COOH	CCC	2090	16.2	.18	4.3	.14	-42.6	.54	16.2	.18
COOH	HC	2030	8.2	.24	1.9	.16	-16.3	.52	8.2	.24
COOH	HC	2090	23.6	.15	8.5	.13	-48.0	.60	23.6	.15
DCKS		**Base**	**2291**	**.64**	**5725**	**.12**	**286.8**	**.34**	**3120**	**.55**
DCKS	CCC	2030	-38.8	.96	-.2	.13	17.0	.25	-35.8	.78
DCKS	CCC	2090	-31.8	.99	-1.3	.14	2.9	.33	-32.5	.86
DCKS	HC	2030	16.5	.66	7.5	.12	-5.7	.36	6.3	.58
DCKS	HC	2090	72.5	.54	16.7	.11	-28.0	.41	41.4	.45
GOKS		**Base**	**2002**	**.68**	**5984**	**.12**	**349.5**	**.32**	**3172**	**.48**
GOKS	CCC	2030	-17.1	.96	13.1	.11	3.7	.30	-25.8	.77
GOKS	CCC	2090	-37.8	1.12	2.7	.14	1.5	.30	-48.2	1.02
GOKS	HC	2030	22.2	.71	12.0	.11	-10.1	.36	12.7	.51
GOKS	HC	2090	81.4	.63	23.6	.12	-29.9	.43	47.5	.45
NPNE		**Base**	**2848**	**.43**	**5132**	**.13**	**215.2**	**.29**	**2885**	**.42**
NPNE	CCC	2030	-17.1	.57	5.9	.14	11.9	.33	-17.0	.56
NPNE	CCC	2090	-33.6	.68	-6.4	.18	14.4	.32	-33.8	.67
NPNE	HC	2030	20.5	.40	11.7	.12	-2.1	.33	20.1	.40
NPNE	HC	2090	44.3	.41	22.5	.12	-18.5	.37	42.7	.41
OKOK		**Base**	**2695**	**.36**	**4596**	**.13**	**148.2**	**.50**	**3850**	**.32**
OKOK	CCC	2030	-52.3	.57	-12.3	.16	60.9	.30	-38.8	.57
OKOK	CCC	2090	-20.7	.47	-6.9	.18	19.8	.41	-28.6	.51
OKOK	HC	2030	6.2	.37	4.2	.14	.7	.51	-6.9	.39
OKOK	HC	2090	28.0	.27	13.6	.15	-35.3	.69	20.0	.24

TABLE B2 (CONTINUED) WINTER WHEAT.

Site	GCM	Scenario	Dry Yield (%)	Yield CV	Irr Yield (%)	Yield CV	IRR (%)	Irr CV	Fallow Yield (%)	Yield CV
SPWA		**Base**	**1986**	**.63**	**7600**	**.12**	**313.7**	**.20**	**2525**	**.56**
SPWA	CCC	2030	8.0	.56	1.9	.13	-6.9	.19	1.1	.52
SPWA	CCC	2090	185.2	.43	17.0	.13	-34.5	.26	139.4	.33
SPWA	HC	2030	87.8	.49	9.1	.12	-18.0	.23	64.7	.41
SPWA	HC	2090	198.6	.43	24.8	.12	-32.6	.27	161.0	.31
TOKS		**Base**	**5093**	**.25**	**5585**	**.16**	**97.9**	**.63**	**5266**	**.22**
TOKS	CCC	2030	-11.3	.25	-10.6	.16	20.1	.60	-11.5	.23
TOKS	CCC	2090	-4.4	.20	-9.7	.17	-21.0	.68	-7.5	.20
TOKS	HC	2030	7.3	.21	4.1	.15	-8.0	.61	6.3	.19
TOKS	HC	2090	17.3	.17	8.9	.14	-44.9	.92	13.4	.17

TABLE C1. Predicted climate change parameters for temperature and precipitation at spring wheat sites.

SITE	GCM	TIME	Spring	Summer	Fall	Winter	Annual P	Annual T
			%	%	%	%	%	∆C
BOID	CCCM	2030	33.58	5.9	30.53	19.8	23.85	1.9
	CCCM	2090	16.21	-2.12	42.02	68.47	40.69	4.94
	HAD	2030	8.24	-2.28	36	8.81	12.58	1.73
	HAD	2090	13.43	-7.16	25.62	27.29	17.55	3.82
FAND	CCCM	2030	52.92	29.59	-23.96	12.64	21.78	1.95
	CCCM	2090	40.98	-38.92	-9.34	24.86	-5.4	5.56
	HAD	2030	-6.22	12.79	8.02	4.99	5.18	1.37
	HAD	2090	1.81	10.92	34.01	29.08	14.42	3.15
FRCA	CCCM	2030	65.15	-0.59	75.77	108.24	86.73	1.86
	CCCM	2090	219.14	185	77.26	226.72	194.6	4.14
	HAD	2030	36.9	21.39	36.07	19.37	25.71	1.54
	HAD	2090	65.58	112.83	36.16	88.35	75.9	3.39
GLMT	CCCM	2030	13.78	15.49	3.85	-15.89	5.04	1.81
	CCCM	2090	25.22	-38.7	37.04	-14.52	-1.47	5.49
	HAD	2030	8.21	13.19	6.12	8.5	10.06	1.45
	HAD	2090	12.12	4.47	37.42	29.89	14.69	3.35
PISD	CCCM	2030	17.37	15.54	-26.88	-1.34	5.61	2.62
	CCCM	2090	13.16	-17.44	1.79	2	-3.11	6.24
	HAD	2030	3.32	10.69	-4.23	15.06	6.75	1.37
	HAD	2090	16.18	10.15	27.18	30.39	16.86	3.05
SCMN	CCCM	2030	39.45	34.22	-12.91	17.02	24.52	1.63
	CCCM	2090	35.51	-16.44	23.9	28.22	10.89	4.63
	HAD	2030	-2.6	14.04	8.97	-0.15	5.88	1.21
	HAD	2090	6.77	15.44	29.34	21.27	16.28	2.85
SPWA	CCCM	2030	0.71	-10.81	38.02	-2.42	6.14	1.3
	CCCM	2090	-1.91	-15.64	52.66	29.05	18.86	4.11
	HAD	2030	7.89	5.46	26.9	8.26	12.69	1.64
	HAD	2090	8.78	-0.86	21.63	12.46	12.33	3.8
TUAZ	CCCM	2030	142.67	-9.35	-56.83	18.57	0.75	2.47
	CCCM	2090	128.29	42.89	9.89	166.18	67.15	4.99
	HAD	2030	30.32	-22.12	-13.05	67.35	18.55	1.47
	HAD	2090	78.24	-8.38	31.95	77.45	44.85	3.36

TABLE C2. SPRING WHEAT BASE YIELDS AND CHANGES. Data is expressed in percentage change from the baseline, except when in bold type. Numbers in bold are absolute numbers, representing 44 year-averages for current conditions: Yield (kg/ha); Irrigation (mm).

Site	GCM	Scenario	Dry Yield (%)	Yield CV	Irr Yield (%)	Yield CV	IRR (%)	Irr CV
BOID		**Base**	**793**	**.63**	**1681**	**.25**	**182.9**	**.31**
BOID	CCC	2030	36.6	.48	-16.9	.35	-31.5	.41
BOID	CCC	2090	40.5	.37	-26.1	.33	-43.8	.44
BOID	HC	2030	19.5	.53	-7.4	.31	-11.2	.35
BOID	HC	2090	38.0	.48	-7.3	.27	-17.2	.29
FAND		**Base**	**2089**	**.45**	**3271**	**.18**	**183.0**	**.38**
FAND	CCC	2030	14.8	.34	-9.6	.22	-26.7	.42
FAND	CCC	2090	-16.2	.44	-19.6	.26	-10.9	.37
FAND	HC	2030	19.3	.41	5.7	.18	-17.4	.42
FAND	HC	2090	21.8	.39	6.9	.19	-19.0	.42
FRCA		**Base**	**4885**	**.48**	**7226**	**.14**	**104.8**	**.56**
FRCA	CCC	2030	11.9	.17	-24.1	.16	-61.3	.72
FRCA	CCC	2090	-20.8	.26	-46.5	.26	-73.6	.80
FRCA	HC	2030	20.5	.19	-16.2	.16	-50.2	.61
FRCA	HC	2090	6.1	.17	-28.3	.17	-73.6	.75
GLMT		**Base**	**1293**	**.50**	**2039**	**.20**	**137.5**	**.31**
GLMT	CCC	2030	7.0	.44	-17.5	.28	-29.7	.43
GLMT	CCC	2090	-24.1	.53	-31.1	.35	-27.4	.40
GLMT	HC	2030	16.1	.44	.2	.23	-14.0	.38
GLMT	HC	2090	24.2	.40	-.3	.22	-26.1	.42
PISD		**Base**	**1958**	**.60**	**3239**	**.16**	**204.8**	**.41**
PISD	CCC	2030	26.5	.40	-3.7	.15	-37.3	.61
PISD	CCC	2090	16.2	.42	-9.4	.18	-44.2	.66
PISD	HC	2030	23.4	.48	1.3	.18	-22.0	.50
PISD	HC	2090	47.3	.37	7.1	.17	-28.9	.50
SCMN		**Base**	**2744**	**.29**	**3642**	**.14**	**165.3**	**.33**
SCMN	CCC	2030	7.0	.23	-11.4	.17	-24.2	.35
SCMN	CCC	2090	-.2	.24	-12.9	.17	-26.2	.45
SCMN	HC	2030	15.4	.24	4.9	.14	-17.4	.38
SCMN	HC	2090	22.3	.24	11.5	.15	-20.0	.39
SPWA		**Base**	**1399**	**.66**	**5330**	**.13**	**290.2**	**.14**
SPWA	CCC	2030	24.5	.50	-1.4	.14	-3.9	.14
SPWA	CCC	2090	90.6	.43	-7.4	.16	-18.2	.17
SPWA	HC	2030	43.7	.54	.1	.14	-5.2	.16
SPWA	HC	2090	63.6	.51	-1.3	.16	-10.4	.17
TUAZ		**Base**	**733**	**1.06**	**8121**	**.10**	**380.2**	**.17**
TUAZ	CCC	2030	43.8	1.25	-5.8	.14	-21.9	.22
TUAZ	CCC	2090	604.5	.39	-14.9	.17	-59.4	.46
TUAZ	HC	2030	122.4	1.10	-2.9	.13	-22.6	.26
TUAZ	HC	2090	476.8	.70	3.2	.14	-50.2	.35

TABLE D1. Predicted climate change parameters for temperature and precipitation at potato sites.

SITE	**GCM**	**TIME**	**Spring** %	**Summer** %	**Fall** %	**Winter** %	**Annual P** %	**Annual T** ∆C
ALCO	CCCM	2030	18.52	-26.99	-19.26	14.73	-9.26	2.17
ALCO	CCCM	2090	2.57	-13.72	-6.53	40.2	-1.65	5.68
ALCO	HAD	2030	14.65	-7.44	6.05	25.12	7.72	1.6
ALCO	HAD	2090	23.58	-2.4	13.05	56.71	18.87	3.62
BOID	CCCM	2030	33.58	5.9	30.53	19.8	23.85	1.9
BOID	CCCM	2090	16.21	-2.12	42.02	68.47	40.69	4.94
BOID	HAD	2030	8.24	-2.28	36	8.81	12.58	1.73
BOID	HAD	2090	13.43	-7.16	25.62	27.29	17.55	3.82
BUNY	CCCM	2030	-24.18	34.27	-35.42	11.6	-3.59	1.77
BUNY	CCCM	2090	21.32	8.7	-17.99	1.94	4.82	5.03
BUNY	HAD	2030	0.42	22.74	10.93	1.58	8.98	0.84
BUNY	HAD	2090	6.69	32.45	21.55	19.83	19.92	2.51
CAME	CCCM	2030	21.53	44.96	0.88	6.03	18.16	1.18
CAME	CCCM	2090	22.68	-11.58	-9.84	7.73	1.33	3.61
CAME	HAD	2030	5.15	6.1	3.56	10.16	6.08	1.04
CAME	HAD	2090	-0.91	16.28	13.46	39.43	16.07	2.8
FAND	CCCM	2030	52.92	29.59	-23.96	12.64	21.78	1.95
FAND	CCCM	2090	40.98	-38.92	-9.34	24.86	-5.4	5.56
FAND	HAD	2030	-6.22	12.79	8.02	4.99	5.18	1.37
FAND	HAD	2090	1.81	10.92	34.01	29.08	14.42	3.15
ININ	CCCM	2030	-19.52	0.33	-7.88	-6.66	-9.33	2.29
ININ	CCCM	2090	14.36	24.36	11.07	-15.8	9.56	4.89
ININ	HAD	2030	8.83	13.37	6.38	7.94	9.59	0.87
ININ	HAD	2090	25.69	30.08	33.35	8.97	25.11	2.21
MAWI	CCCM	2030	-6.41	48.34	-11.94	11.86	11.83	1.99
MAWI	CCCM	2090	40.61	28.83	45.48	-2.86	30.13	4.77
MAWI	HAD	2030	3.18	13.96	9.54	1.85	7.69	1
MAWI	HAD	2090	17.59	26.15	31.03	16.18	22.78	2.55
MEOR	CCCM	2030	8.26	0.75	36.06	5.55	12.97	1.58
MEOR	CCCM	2090	-5.57	15.4	45.72	73.19	41.88	3.75
MEOR	HAD	2030	-1.18	9.69	57.8	7.39	16.02	1.48
MEOR	HAD	2090	8.98	-4.77	26.63	24.94	19.99	3.59
MUMI	CCCM	2030	-3.98	34.52	-19.04	8.63	6.86	2
MUMI	CCCM	2090	37.11	16.43	40.76	-11.14	21.84	4.93
MUMI	HAD	2030	5.67	18.56	12.75	-2.38	8.97	0.87
MUMI	HAD	2090	15.4	26.33	28.63	14.56	21	2.53
PEOR	CCCM	2030	4.02	-5.9	42.99	3.32	10.93	1.54
PEOR	CCCM	2090	-2.92	-10.27	44.51	43.06	24.05	4.19
PEOR	HAD	2030	4.87	0.55	34.15	4.28	11.21	1.71
PEOR	HAD	2090	9.44	-5.64	20.46	12.15	11.41	3.83
SBNE	CCCM	2030	5.81	-3.57	-32.38	-10.25	-8.22	2.77
SBNE	CCCM	2090	14.81	-13.69	-25.1	9.93	-6.14	6.13
SBNE	HAD	2030	12.06	1.89	-0.86	14.66	6.7	1.51
SBNE	HAD	2090	19.24	0.05	12.87	42.55	14.14	3.36
YAWA	CCCM	2030	-9.41	5.92	49.45	-3.84	8.23	1.36
YAWA	CCCM	2090	-15.45	-2.95	46.39	30.8	17.97	3.85
YAWA	HAD	2030	5.03	1.79	31.31	4.91	11.3	1.7
YAWA	HAD	2090	9.51	-7.18	21.97	12.53	12.19	3.84

TABLE D2. POTATO BASE YIELDS AND CHANGES. Data is expressed in percentage change from the baseline, except when in bold type. Numbers in bold are absolute numbers, representing 44 year-averages for current conditions: Yield (kg/ha); Irrigation (mm).

Site	GCM	Scenario	Dry Yield (%)	Yield CV	Irr Yield (%)	Yield CV	IRR (%)	IRR CV
ALCO		**Base**	**8.31**	**.42**	**52.66**	**.06**	**375.3**	**.17**
ALCO	CCC	2030	-17.0	.35	-3.9	.06	17.0	.15
ALCO	CCC	2090	6.6	.56	-75.5	.39	-54.1	.26
ALCO	HC	2030	-8.5	.34	-1.0	.06	7.7	.16
ALCO	HC	2090	-5.6	.37	-7.8	.07	8.4	.16
BOID		**Base**	**5.94**	**.25**	**47.04**	**.10**	**467.7**	**.08**
BOID	CCC	2030	1.8	.31	-6.9	.13	-2.6	.09
BOID	CCC	2090	-35.0	.55	-41.6	.26	12.0	.08
BOID	HC	2030	-7.0	.31	-8.4	.13	3.7	.09
BOID	HC	2090	-32.9	.47	-34.3	.24	13.7	.09
BUNY		**Base**	**20.91**	**.42**	**43.24**	**.07**	**222.3**	**.20**
BUNY	CCC	2030	20.3	.33	-13.3	.10	-15.3	.21
BUNY	CCC	2090	-27.9	.38	-18.2	.12	7.6	.19
BUNY	HC	2030	22.1	.36	-3.9	.09	-13.5	.21
BUNY	HC	2090	21.9	.35	-7.8	.10	-16.7	.21
CAME		**Base**	**29.42**	**.33**	**46.44**	**.07**	**180.3**	**.27**
CAME	CCC	2030	34.0	.22	4.8	.08	-13.3	.30
CAME	CCC	2090	-17.4	.46	3.7	.09	22.1	.24
CAME	HC	2030	6.6	.32	3.3	.08	6.2	.27
CAME	HC	2090	16.0	.30	3.7	.09	-2.7	.28
FAND		**Base**	**19.01**	**.41**	**42.93**	**.07**	**309.5**	**.21**
FAND	CCC	2030	11.4	.38	-2.5	.08	-6.0	.22
FAND	CCC	2090	-63.9	.51	-28.0	.16	33.6	.14
FAND	HC	2030	20.7	.40	2.1	.08	-6.9	.23
FAND	HC	2090	10.9	.41	-.8	.10	-3.8	.23
ININ		**Base**	**20.19**	**.43**	**34.78**	**.12**	**255.6**	**.23**
ININ	CCC	2030	-33.2	.45	-36.1	.21	4.2	.21
ININ	CCC	2090	-47.4	.49	-51.2	.29	-5.4	.21
ININ	HC	2030	7.4	.36	-5.5	.13	-5.8	.24
ININ	HC	2090	14.3	.33	-8.6	.16	-12.3	.24
MAWI		**Base**	**22.65**	**.34**	**42.94**	**.08**	**257.2**	**.23**
MAWI	CCC	2030	23.5	.25	-12.7	.13	-16.0	.26
MAWI	CCC	2090	-9.2	.37	-19.2	.16	-7.2	.24
MAWI	HC	2030	19.5	.29	.2	.10	-8.8	.25
MAWI	HC	2090	26.2	.30	1.5	.11	-13.8	.25
MEOR		**Base**	**9.56**	**.32**	**81.12**	**.06**	**917.6**	**.09**
MEOR	CCC	2030	-5.6	.31	-2.0	.07	3.6	.09
MEOR	CCC	2090	10.9	.37	-9.8	.10	8.4	.10
MEOR	HC	2030	5.6	.29	-1.8	.06	4.2	.10
MEOR	HC	2090	6.4	.27	-11.6	.10	13.9	.10
MUMI		**Base**	**15.65**	**.40**	**44.65**	**.07**	**266.9**	**.20**
MUMI	CCC	2030	25.5	.41	-12.9	.10	-8.3	.22

TABLE D2 (continued). POTATO BASE YIELDS AND CHANGES.

Site	GCM	Scenario	Dry Yield (%)	Yield CV	Irr Yield (%)	Yield CV	IRR (%)	IRR CV
MUMI	CCC	2090	-17.3	.32	-18.6	.13	1.1	.18
MUMI	HC	2030	33.1	.39	-.8	.08	-10.6	.23
MUMI	HC	2090	40.0	.38	-1.5	.09	-12.4	.22
PEOR		**Base**	**7.93**	**.34**	**81.34**	**.06**	**958.0**	**.05**
PEOR	CCC	2030	-9.9	.40	-1.0	.07	1.2	.06
PEOR	CCC	2090	-11.0	.38	-15.3	.12	9.4	.06
PEOR	HC	2030	12.3	.30	-2.7	.07	2.0	.06
PEOR	HC	2090	8.8	.33	-12.9	.11	11.4	.06
SBNE		**Base**	**9.45**	**.43**	**36.86**	**.09**	**350.6**	**.18**
SBNE	CCC	2030	-9.9	.49	-9.3	.12	3.8	.17
SBNE	CCC	2090	-70.3	1.17	-50.1	.24	13.5	.16
SBNE	HC	2030	-6.7	.44	-6.3	.10	2.2	.17
SBNE	HC	2090	-37.8	.60	-27.6	.17	8.4	.18
YAWA		**Base**	**12.47**	**.20**	**80.39**	**.07**	**547.5**	**.09**
YAWA	CCC	2030	-.3	.22	4.8	.08	-3.5	.10
YAWA	CCC	2090	-6.5	.22	-1.4	.10	12.0	.10
YAWA	HC	2030	2.7	.21	2.1	.08	3.3	.09
YAWA	HC	2090	-13.5	.21	-3.4	.10	18.7	.10

TABLE E2. CITRUS BASE YIELDS AND CHANGES. Data is expressed in percentage change from the baseline, except when in bold type. Numbers in bold are absolute numbers, representing 44 year-averages for current conditions: Yield (kg/ha); Irrigation (mm).

ORANGES*

Site	GCM	Scenario	CO_2 ppm	Change in Irr Yield (%)	Irrigated Yield CV	Change in IRR (%)	IRR CV
BACA		**Base**	**355**	**11.14**	**.22**	**1092.3**	**.08**
BACA	CCC	2030	445	26.0	.23	-5.2	.09
BACA	CCC	2090	660	50.7	.26	-11.0	.14
BACA	HC	2030	445	36.2	.19	-1.8	.06
BACA	HC	2090	660	57.6	.22	-.6	.08
CCTX		**Base**	**355**	**9.49**	**.49**	**453.1**	**.53**
CCTX	CCC	2030	445	45.5	.38	-14.4	.74
CCTX	CCC	2090	660	40.7	.33	13.9	.54
CCTX	HC	2030	445	46.9	.38	-7.3	.63
CCTX	HC	2090	660	103.6	.32	13.8	.53
DBFL		**Base**	**355**	**12.10**	**.38**	**106.1**	**1.44**
DBFL	CCC	2030	445	20.0	.34	-33.2	1.83
DBFL	CCC	2090	660	75.2	.24	219.4	.59
DBFL	HC	2030	445	24.6	.27	11.6	1.36
DBFL	HC	2090	660	52.0	.22	-1.2	1.44
EPTX		**Base**	**355**	**2.12**	**1.09**	**1167.2**	**.10**
EPTX	CCC	2030	445	30.1	1.09	-.2	.10
EPTX	CCC	2090	660	306.1	.63	4.4	.08
EPTX	HC	2030	445	32.3	1.09	1.0	.10
EPTX	HC	2090	660	215.7	.75	-.1	.10
LVNV		**Base**	**355**	**4.49**	**.50**	**1199.6**	**.06**
LVNV	CCC	2030	445	58.2	.45	-.3	.08
LVNV	CCC	2090	660	197.1	.29	1.3	.09
LVNV	HC	2030	445	67.1	.43	1.4	.06
LVNV	HC	2090	660	139.5	.30	1.8	.06
MIFL		**Base**	**355**	**14.43**	**.14**	**84.9**	**1.51**
MIFL	CCC	2030	445	12.2	.15	-69.3	3.10
MIFL	CCC	2090	660	10.6	.15	-5.3	1.51
MIFL	HC	2030	445	6.3	.14	-20.0	1.82
MIFL	HC	2090	660	17.9	.15	53.6	1.22
MOAL		**Base**	**355**	**2.05**	**1.13**	**38.0**	**2.44**
MOAL	CCC	2030	445	30.7	.90	312.1	1.10
MOAL	CCC	2090	660	258.5	.77	916.3	.53
MOAL	HC	2030	445	28.5	1.04	-10.5	2.69
MOAL	HC	2090	660	90.5	.90	40.8	1.98
PATX		**Base**	**355**	**5.61**	**.72**	**82.0**	**1.81**
PATX	CCC	2030	445	60.3	.65	194.2	1.31
PATX	CCC	2090	660	197.2	.35	403.7	1.06
PATX	HC	2030	445	41.2	.67	324.2	1.15
PATX	HC	2090	660	162.3	.33	323.9	1.16
RBCA		**Base**	**355**	**7.19**	**.32**	**636.7**	**.32**
RBCA	CCC	2030	445	41.7	.22	-43.5	.72

TABLE E2 (continued). CITRUS BASE YIELDS AND CHANGES.

Site	GCM	Scenario	CO_2 ppm	Irr Yield (%)	Yield CV	IRR (%)	IRR CV
RBCA	CCC	2090	660	90.0	.31	-55.3	.92
RBCA	HC	2030	445	45.7	.22	-20.2	.45
RBCA	HC	2090	660	79.9	.23	-27.2	.52
SAGA		**Base**	**355**	**2.43**	**1.23**	**66.5**	**1.61**
SAGA	CCC	2030	445	17.8	1.10	53.5	1.38
SAGA	CCC	2090	660	315.4	.66	354.0	.67
SAGA	HC	2030	445	8.4	1.25	-10.7	1.55
SAGA	HC	2090	660	83.8	1.00	-43.0	2.35
SHLA		**Base**	**355**	**2.20**	**1.11**	**114.8**	**1.26**
SHLA	CCC	2030	445	66.3	.88	194.2	.64
SHLA	CCC	2090	660	299.0	.61	202.9	.69
SHLA	HC	2030	445	13.0	1.14	10.2	1.25
SHLA	HC	2090	660	138.6	.88	29.9	1.41
TAFL		**Base**	**355**	**2.30**	**1.63**	**17.0**	**3.28**
TAFL	CCC	2030	445	-5.3	1.47	114.7	2.41
TAFL	CCC	2090	660	292.0	.85	1304.1	.87
TAFL	HC	2030	445	45.2	1.27	52.4	3.21
TAFL	HC	2090	660	65.0	1.44	35.9	3.49
TUAZ		**Base**	**355**	**6.12**	**.63**	**1081.4**	**.09**
TUAZ	CCC	2030	445	66.9	.41	7.6	.07
TUAZ	CCC	2090	660	114.6	.22	-.7	.17
TUAZ	HC	2030	445	69.9	.42	3.3	.09
TUAZ	HC	2090	660	111.6	.28	3.9	.08

TABLE F1. Predicted climate change parameters for temperature and precipitation at corn sites.

SITE	GCM	TIME	Spring %	Summer %	Fall %	Winter %	Annual P %	Annual T ∆C
COOH	CCCM	2030	-5.64	42.94	-23.59	-6.64	0.88	1.95
COOH	CCCM	2090	17.66	26.79	-7.04	-6.21	9	4.88
COOH	HAD	2030	9.53	16.79	0.06	4.09	8.82	0.85
COOH	HAD	2090	23.08	30.98	28.58	13.61	24.54	2.26
DEIA	CCCM	2030	4.93	56.45	-26.25	1.55	13.15	2.04
DEIA	CCCM	2090	36.42	63.04	50.8	-5.85	41.35	4.83
DEIA	HAD	2030	5.14	4.18	9.27	10.85	6.43	1.07
DEIA	HAD	2090	26.75	25.93	32.07	16.65	25.86	2.41
DUMN	CCCM	2030	31.16	30.91	3.16	18.59	24.34	1.36
DUMN	CCCM	2090	27.82	-29.53	23.76	38.23	4.61	4.32
DUMN	HAD	2030	-9.9	11.71	6.78	-2.29	1.83	1.19
DUMN	HAD	2090	-3.63	13.18	29.23	22.07	12.86	2.92
FAND	CCCM	2030	52.92	29.59	-23.96	12.64	21.78	1.95
FAND	CCCM	2090	40.98	-38.92	-9.34	24.86	-5.4	5.56
FAND	HAD	2030	-6.22	12.79	8.02	4.99	5.18	1.37
FAND	HAD	2090	1.81	10.92	34.01	29.08	14.42	3.15
FAND	CCCM	2030	52.92	29.59	-23.96	12.64	21.78	1.95
FAND	CCCM	2090	40.98	-38.92	-9.34	24.86	-5.4	5.56
FAND	HAD	2030	-6.22	12.79	8.02	4.99	5.18	1.37
FAND	HAD	2090	1.81	10.92	34.01	29.08	14.42	3.15
ININ	CCCM	2030	-19.52	0.33	-7.88	-6.66	-9.33	2.29
ININ	CCCM	2090	14.36	24.36	11.07	-15.8	9.56	4.89
ININ	HAD	2030	8.83	13.37	6.38	7.94	9.59	0.87
ININ	HAD	2090	25.69	30.08	33.35	8.97	25.11	2.21
MAWI	CCCM	2030	-6.41	48.34	-11.94	11.86	11.83	1.99
MAWI	CCCM	2090	40.61	28.83	45.48	-2.86	30.13	4.77
MAWI	HAD	2030	3.18	13.96	9.54	1.85	7.69	1
MAWI	HAD	2090	17.59	26.15	31.03	16.18	22.78	2.55
METN	CCCM	2030	-28.93	9.35	-58.04	-36.5	-31.05	2.11
METN	CCCM	2090	8.57	-37.3	-38.13	19.16	-13.46	4.71
METN	HAD	2030	3.08	10.42	7.44	7.41	6.45	0.88
METN	HAD	2090	20.4	36.72	32.75	0.93	21.73	2.16
NPNE	CCCM	2030	1.47	-9.58	-40.95	-5.13	-11.98	2.83
NPNE	CCCM	2090	-15.1	4.67	-20.8	5.46	-6.6	6.25
NPNE	HAD	2030	6.3	3.81	7.19	10.33	5.97	1.34
NPNE	HAD	2090	22.77	9.91	25.05	36	19.84	2.98
PEIL	CCCM	2030	4.91	53.76	-23.15	1.52	11.62	2.02
PEIL	CCCM	2090	35.98	62.84	50.73	-6.11	42.05	4.79
PEIL	HAD	2030	6.14	4.09	9.02	11.15	6.37	1.05
PEIL	HAD	2090	27.01	25.56	30.07	15.57	25.81	2.44
SCMN	CCCM	2030	39.45	34.22	-12.91	17.02	24.52	1.64
SCMN	CCCM	2090	35.51	-16.44	23.9	28.22	10.89	4.63
SCMN	HAD	2030	-2.6	14.04	8.97	-0.15	5.88	1.21
SCMN	HAD	2090	6.77	15.44	29.34	21.27	16.28	2.85
TOKS	CCCM	2030	0.03	6.23	-23.87	-18.32	-5.01	2.48
TOKS	CCCM	2090	27.17	37.96	26.89	2.97	27.79	5.25
TOKS	HAD	2030	1.28	8.62	11.74	8.04	6.37	1.03
TOKS	HAD	2090	20.43	24.35	24.65	13.47	21.36	2.47

TABLE F2. CORN BASE YIELDS AND CHANGES. Data is expressed in percentage change from the baseline, except when in bold type. Numbers in bold are absolute numbers, representing 44 year-averages for current conditions: Yield (kg/ha); Irrigation (mm).

Site	GCM	Scenario	Dry Yield (%)	Yield CV	Irr Yield (%)	Yield CV	IRR (%)	IRR CV
COOH		**Base**	**8346**	**.23**	**10645**	**.15**	**99.8**	**.43**
COOH	CCC	2030	.3	.18	-10.9	.17	-46.1	.59
COOH	CCC	2090	-1.3	.11	-10.5	.13	-58.7	.71
COOH	HC	2030	5.3	.18	-5.3	.17	-39.5	.57
COOH	HC	2090	6.2	.14	-5.8	.17	-71.3	.85
DEIA		**Base**	**9037**	**.37**	**11109**	**.14**	**134.7**	**.43**
DEIA	CCC	2030	18.4	.17	-11.7	.13	-44.8	.58
DEIA	CCC	2090	16.7	.10	-15.2	.14	-67.5	.69
DEIA	HC	2030	11.6	.25	-5.3	.14	-24.7	.50
DEIA	HC	2090	27.6	.12	-3.3	.15	-61.0	.67
DUMN		**Base**	**6119**	**.57**	**9965**	**.24**	**137.4**	**.50**
DUMN	CCC	2030	29.2	.42	9.5	.08	-18.3	.48
DUMN	CCC	2090	11.4	.33	-8.4	.10	-19.7	.38
DUMN	HC	2030	25.2	.42	-.3	.21	-31.2	.65
DUMN	HC	2090	59.0	.23	6.2	.08	-57.9	.74
FAND		**Base**	**6156**	**.56**	**9877**	**.21**	**135.5**	**.48**
FAND	CCC	2030	24.9	.43	8.3	.10	-16.0	.46
FAND	CCC	2090	10.6	.32	-9.5	.11	-20.7	.41
FAND	HC	2030	24.0	.41	-.1	.18	-28.6	.61
FAND	HC	2090	52.7	.25	4.2	.11	-56.8	.72
ININ		**Base**	**8075**	**.30**	**10950**	**.14**	**108.4**	**.47**
ININ	CCC	2030	-5.3	.23	-15.2	.13	-26.7	.53
ININ	CCC	2090	-3.9	.20	-17.9	.16	-60.0	.84
ININ	HC	2030	6.5	.22	-4.1	.14	-34.7	.56
ININ	HC	2090	11.4	.10	-5.7	.12	-67.2	.85
MAWI		**Base**	**8974**	**.28**	**10700**	**.27**	**63.0**	**.75**
MAWI	CCC	2030	-2.0	.16	-5.8	.16	-52.7	.96
MAWI	CCC	2090	-3.1	.14	-4.9	.16	-70.6	1.26
MAWI	HC	2030	-1.3	.22	-3.7	.22	-42.2	.86
MAWI	HC	2090	7.4	.16	5.5	.17	-74.1	1.32
METN		**Base**	**7889**	**.16**	**9779**	**.12**	**73.7**	**.75**
METN	CCC	2030	-8.2	.12	-16.4	.13	-26.7	.89
METN	CCC	2090	-14.1	.12	-23.3	.14	-32.8	.82
METN	HC	2030	1.6	.12	-.9	.13	-28.1	.92
METN	HC	2090	-.6	.11	-1.9	.15	-57.5	1.17
NPNE		**Base**	**5994**	**.45**	**11008**	**.13**	**137.3**	**.42**
NPNE	CCC	2030	24.7	.26	-11.3	.13	-42.5	.58
NPNE	CCC	2090	33.5	.14	-14.0	.13	-65.8	.76
NPNE	HC	2030	23.6	.26	-6.5	.15	-39.4	.69
NPNE	HC	2090	31.2	.26	-4.4	.15	-47.3	.69
PEIL		**Base**	**6651**	**.46**	**11117**	**.14**	**133.0**	**.50**
PEIL	CCC	2030	18.5	.28	-9.3	.12	-31.8	.63
PEIL	CCC	2090	24.8	.19	-10.5	.15	-60.3	.86
PEIL	HC	2030	16.3	.31	-4.2	.13	-21.4	.59
PEIL	HC	2090	37.9	.18	1.1	.12	-59.6	.83

TABLE F2 (continued). CORN BASE YIELDS AND CHANGES

Site	GCM	Scenario	Dry Yield	Yield CV	Irr Yield	Yield CV	IRR	IRR CV
SCMN		**Base**	**3597**	**.59**	**4484**	**.61**	**69.0**	**.50**
SCMN	CCC	2030	131.9	.30	131.2	.30	-2.6	.47
SCMN	CCC	2090	196.7	.13	191.3	.10	-3.0	.56
SCMN	HC	2030	74.8	.42	67.5	.43	-31.6	.61
SCMN	HC	2090	166.4	.31	151.7	.31	-59.7	.73
SFSD		**Base**	**6777**	**.41**	**11263**	**.13**	**143.0**	**.35**
SFSD	CCC	2030	19.2	.20	-7.3	.13	-35.1	.48
SFSD	CCC	2090	8.2	.16	-22.9	.15	-54.5	.58
SFSD	HC	2030	17.6	.28	-4.6	.13	-27.0	.43
SFSD	HC	2090	34.4	.15	-3.2	.13	-59.8	.60
TOKS		**Base**	**6655**	**.37**	**10103**	**.14**	**129.5**	**.46**
TOKS	CCC	2030	3.6	.27	-14.5	.14	-23.2	.55
TOKS	CCC	2090	4.8	.17	-22.0	.16	-53.3	.75
TOKS	HC	2030	11.6	.27	-3.6	.13	-20.3	.49
TOKS	HC	2090	21.9	.15	-3.9	.13	-53.4	.69

Figure Captions.

FIGURE 1. Map showing acres planted to wheat for grain in the US, and the corresponding simulation sites (blue circles) chosen to represent national production.

FIGURE 2. An example of climate change conditions at Fargo, North Dakota, as predicted by the two GCM scenarios used in the National Assessment.

FIGURE 3. Examples of Simulated versus observed crop state-level yields under current climate.

FIGURE 4. Examples from the National Assessment. Projected changes in spring wheat yields under rainfed and irrigated conditions in 2030 and 2090, for the two GCM scenarios.

FIGURE 5. Examples of Adaptation techniques and their effects on projected yields.

FIGURE 6. Examples of CO2 fertilization. Without CO2 effects, not only the magnitude, but even the direction of predicted yield changes may greatly differ from predictions including CO2 effects.

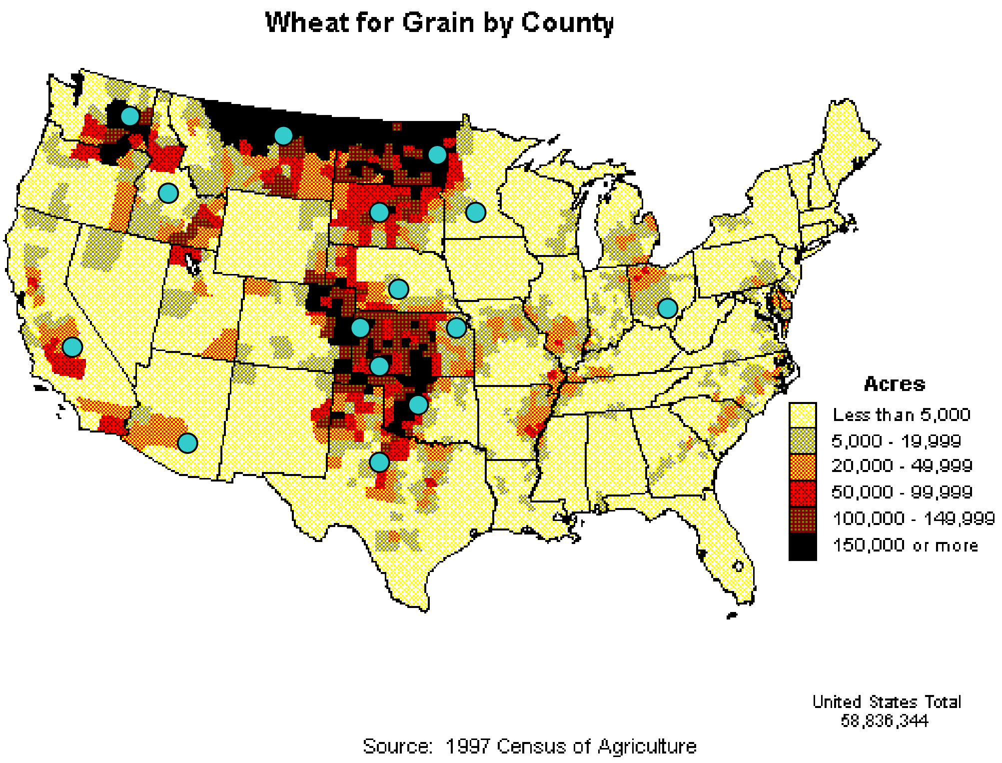
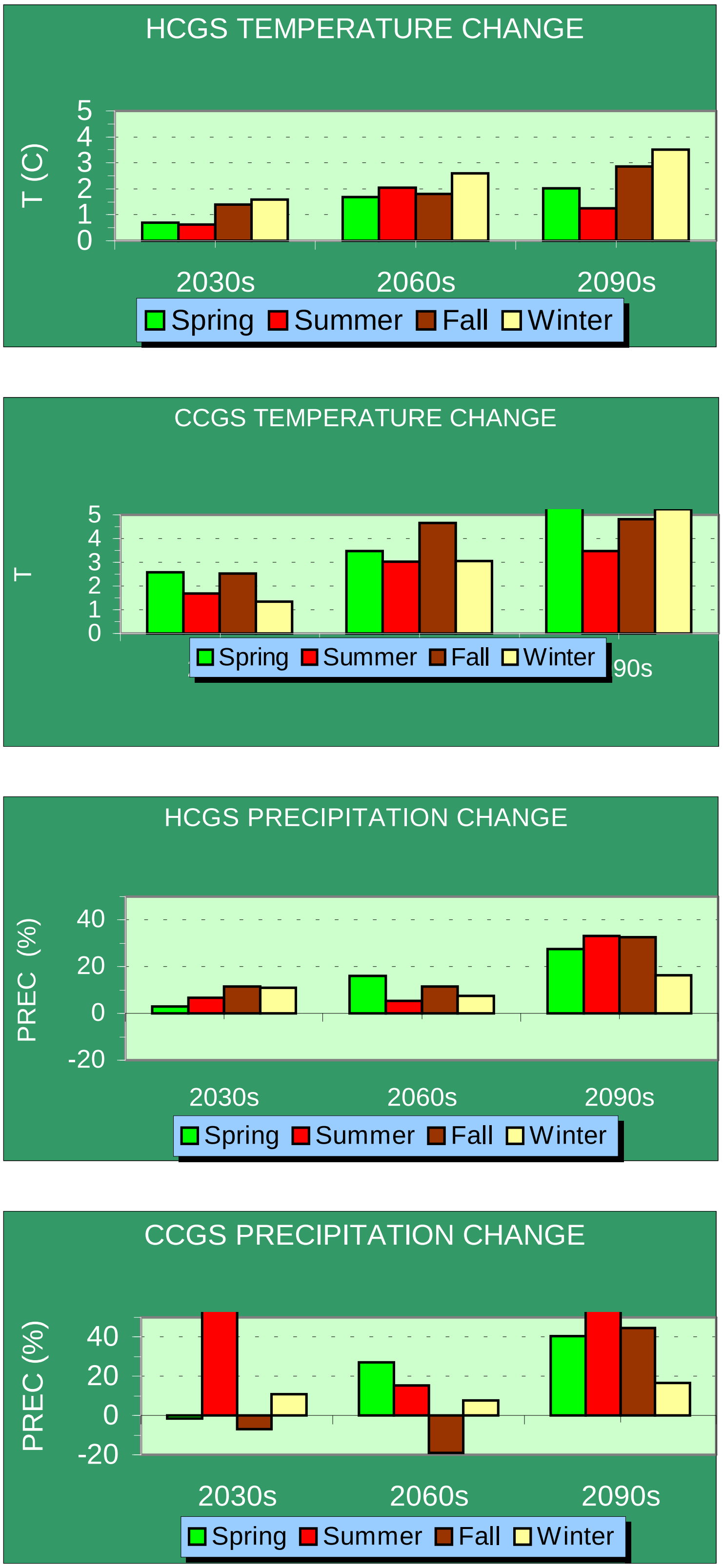


FIGURE 1. Map showing acres planted to wheat for grain in the US, and the corresponding simulation sites (blue circles) chosen to represent national production.

FIGURE 2. An example of climate change conditions at Des Moines, IA, as predicted by the two GCM scenarios used in the National Assessment.



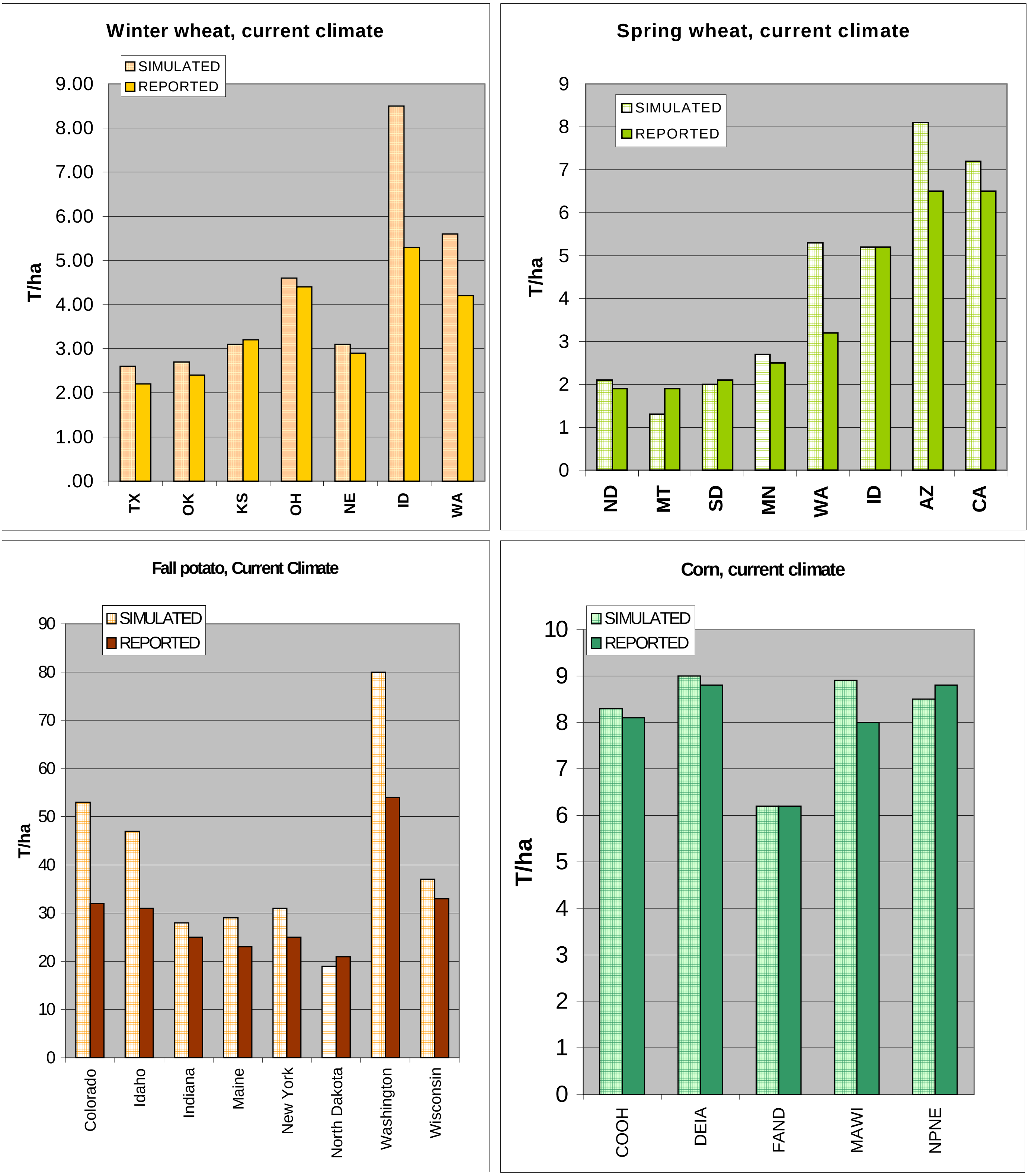
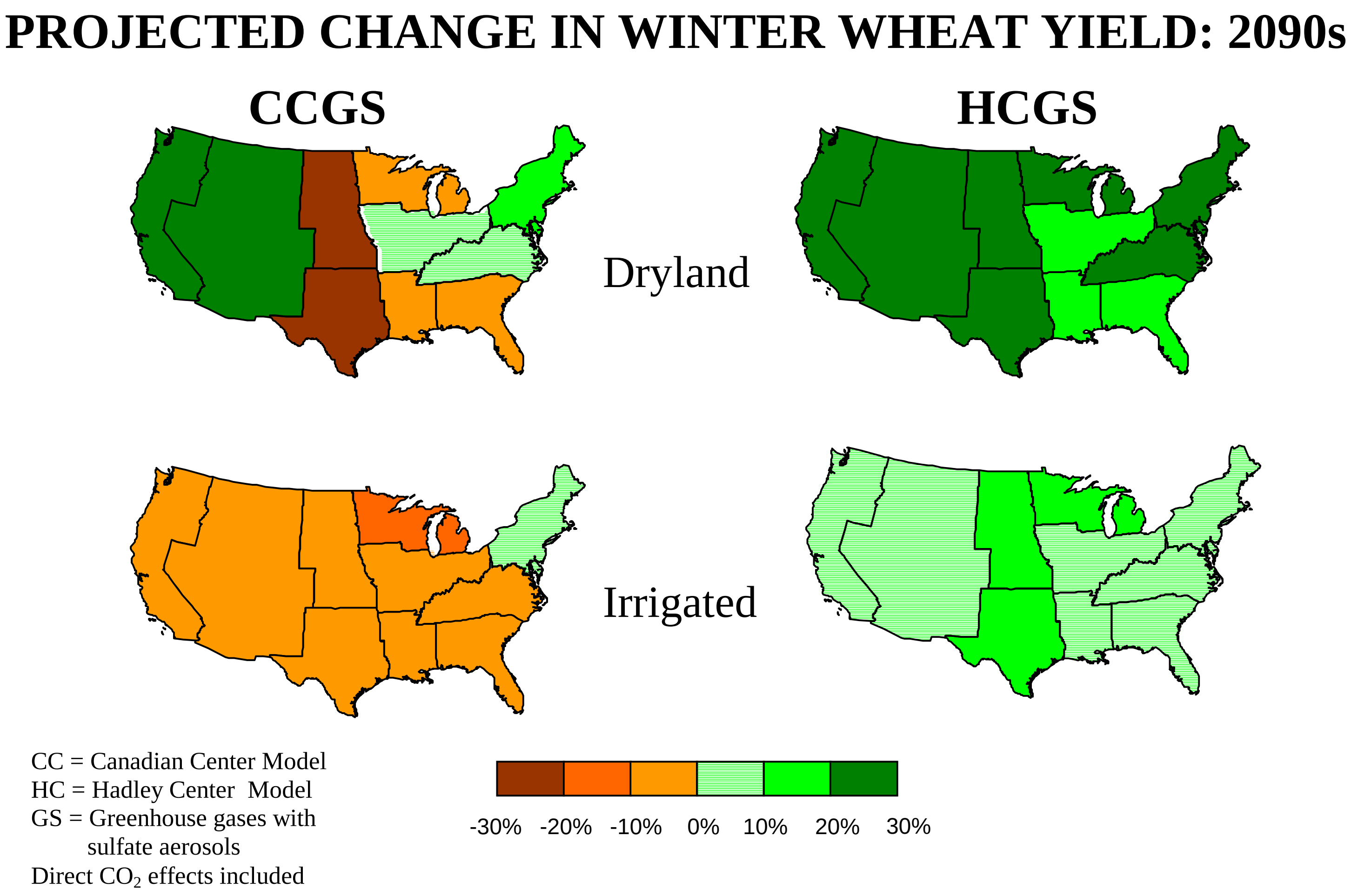


FIGURE 3. Examples of Simulated versus observed crop state-level yields under current climate.



PROJECTED CHANGE IN WINTER WHEAT YIELD: 2090s

CC = Canadian Center Model
HC = Hadley Center Model
GS = Greenhouse gases with
sulfate aerosols
Direct CO_2 effects included

FIGURE 4. Examples of the National Assessment Study. Projected changes inwinter wheat yields under rainfed and irrigated conditions in 2090, for the two GCM scenarios.

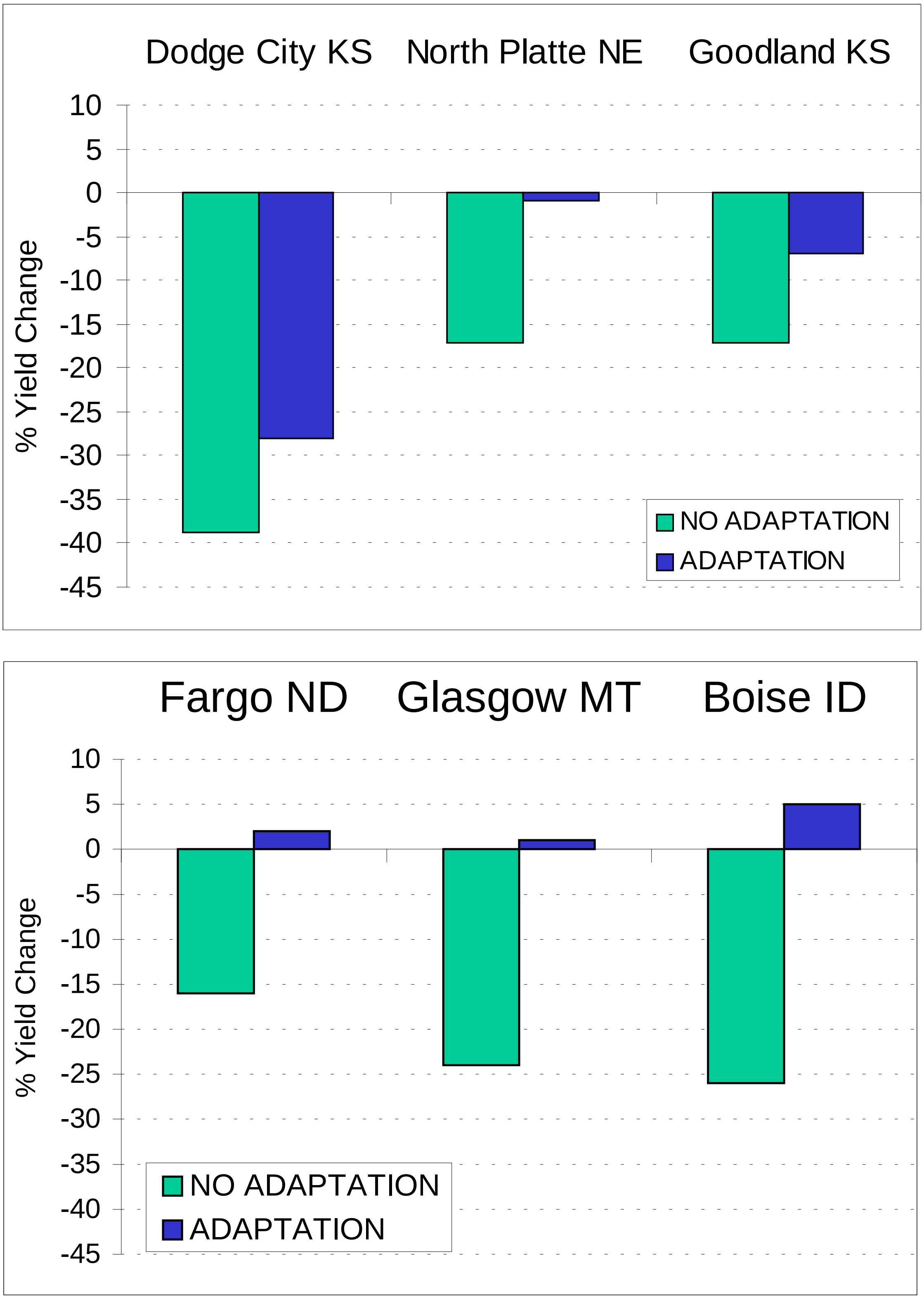


FIGURE 5. Examples of adaptation techniques and their effects on projected yields   Adaptation for winter wheat (top figure) was a change of cultivar; for spring (bottom figure) was early planting.

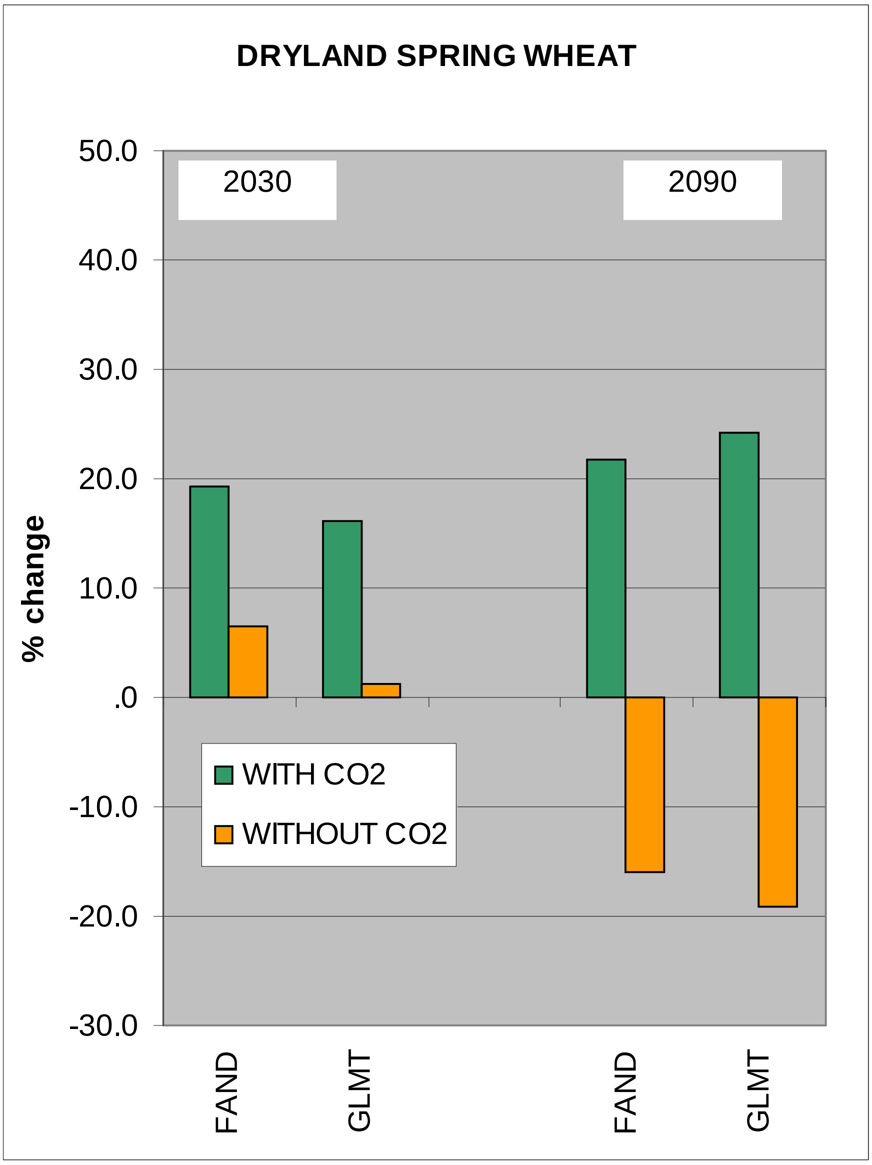


FIGURE 6. Examples of CO2 fertilization. Without CO2 effects, not only the magnitude, but even the direction of predicted yield changes may greatly differ from predictions including CO2 effects.