

CLIMATE CHANGE IMPACTS ON US AGRICULTURE

ROBERT BEACH

Environmental, Technology, and Energy Economics Program, RTI International, USA

rbeach@rti.org

ALLISON THOMSON

Joint Global Change Research Institute, Pacific Northwest National Laboratory and the
University of Maryland, USA

BRUCE MCCARL

Department of Agricultural Economics, Texas A&M University, USA

Contributed paper at the
IATRC Public Trade Policy Research and Analysis Symposium
'Climate Change in World Agriculture: Mitigation, Adaptation, Trade and Food Security'
Universität Hohenheim, Stuttgart, Germany, June 27-29, 2010



Copyright 2010 by Robert H. Beach, Allison M. Thomson, and Bruce A. McCarl. All rights reserved. Readers may make verbatim copies of this document for non-commercial purposes by any means, provided that this copyright notice appears on all such copies.

CLIMATE CHANGE IMPACTS ON US AGRICULTURE

Abstract

There is general consensus in the scientific literature that human-induced climate change has taken place and will continue to do so over the next century. The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change concludes with “very high confidence” that anthropogenic activities such as fossil fuel burning and deforestation have affected the global climate. The AR4 also indicates that global average temperatures are expected to increase by another 1.1°C to 5.4°C by 2100, depending on the increase in atmospheric concentrations of greenhouse gases that takes place during this time. Increasing atmospheric carbon dioxide levels, temperature increases, altered precipitation patterns and other factors influenced by climate have already begun to impact U.S. agriculture. Climate change will continue to have significant effects on U.S. agriculture, water resources, land resources, and biodiversity in the future as temperature extremes begin exceeding thresholds that harm crop growth more frequently and precipitation and runoff patterns continue to change. In this study, we provide an assessment of the potential long-term implications of climate change on landowner decisions regarding land use, crop mix, and production practices in the U.S., combining a crop process model (Environmental Policy Integrated Climate model) and an economic model of the U.S. forestry and agricultural sector (Forest and Agricultural Sector Optimization Model). Agricultural producers have always faced numerous production and price risks, but forecasts of more rapid changes in climatic conditions in the future have raised concerns that these risks will increase in the future relative to historical conditions.

Keywords: climate change, crop yields, EPIC, FASOM

JEL Classification: C61, Q18, Q54

Introduction

Agricultural production is inherently risky and producers have always been affected by a number of factors (e.g., weather, disease, pests) that can substantially affect output levels from year to year as well as price risks, both of which affect farm profitability and agricultural commodity markets. However, climate change may lead to more rapid changes in mean yields as well as yield and price variability than has been experienced, making it more difficult for producers to adjust to changing conditions. Changes in average temperature and precipitation, spatial and temporal distribution of temperature and precipitation, and in the frequency and severity of extreme events such as flooding, drought, hail, and hurricanes or other severe weather events are all likely to affect future agricultural production based on available projections of future climatic conditions.

The effects of climate change on agriculture and forests are extremely complex because of nonlinearities, regional and temporal differences, and interaction effects between numerous categories of impacts. For instance, higher temperatures may positively affect yields for at least some crops within some range of temperature increase, but will also tend to increase weed and insect damages, increase ozone damages, and likely have damaging effects above a certain threshold level. The net impacts also depend on precipitation and water availability, management practices, and other factors. In general, impacts on yields could potentially be positive or negative depending on net changes in precipitation, temperature, and other factors relative to the baseline climate for a given region.

In this study, we rely on the assessments developed by the Climate Change Science Program (CCSP) and the Intergovernmental Panel on Climate Change (IPCC) to inform the establishment of reasonable estimates of expected future climate conditions under alternative scenarios (e.g., CCSP, 2008; IPCC, 2007). An important issue in selecting the climate scenarios that are being analyzed in the study is that we selected scenarios where outputs from

global circulation models (GCMs) are publicly available. GCMs characterize the global climate under alternative greenhouse gas (GHG) concentrations, and several sets of model runs have been conducted for IPCC scenarios. GCM output data on spatial distribution of temperature and precipitation changes associated with alternative IPCC scenarios have been archived for selected scenarios. The data used to characterize potential future temperature, precipitation, and carbon dioxide (CO₂) concentrations under alternative climate scenarios are being drawn from these data archives.

In the remainder of this paper, we present background information on projected climate change impacts, describe the data and methods applied, and present our findings.

Background

The literature exploring the impacts of climate change on agriculture has grown substantially over the past two decades. While there has been a growing consensus that there have been and will continue to be changes in climate that will impact agriculture, there remains considerable uncertainty surrounding the magnitude of those impacts. The myriad of different factors that play a role in agricultural production and the interactions among them make a comprehensive analysis of climate impacts an extremely challenging task. Crop simulation models and other agronomic models used in prior research differ in complexity and in the degree to which they incorporate physiological processes (Boote, Jones, and Pickering, 1996). In addition, methods for incorporating GCM data in crop simulation models vary widely (Carbone et al., 2003) and there are a variety of economic modelling approaches that have been applied. Thus, previous studies have yielded a wide range of estimated impacts on expected yields and variance.

In addition, location-specific differences in resource availability will affect mitigation and adaptation possibilities. Thus, climate impacts and the ability to adapt are expected to vary considerably across U.S. regions. Examples of other phenomena that potentially impact

on agriculture and occur simultaneously with changes in temperature and precipitation are changes in CO₂ concentrations and tropospheric ozone levels. However, most of the literature focuses on studying certain aspects of the problem rather than conducting comprehensive analyses.

Temperature and Precipitation Effects

While inputs such as fertilizer, irrigation water, and engineered seed varieties can help expand production possibilities into additional regions, regional temperature and precipitation are still among the most crucial factors influencing agricultural production. Thus, the literature examining the impacts of climate change on agriculture has concentrated on the effects of changes in temperature and precipitation.

In one of the first key papers to examine the potential effects of climate change on U.S. agriculture, Mendelsohn, Nordhaus, and Shaw (1994) employ a hedonic approach to estimate the marginal value of climate by regressing land values on climate, soil, and socioeconomic variables using cross sectional data. Their findings suggest that temperature increases in all seasons except autumn will lower farm values, while increases in precipitation in all seasons except autumn will raise farm values. The paper also recognizes that irrigation is an important adaptation response. The authors estimate the impacts of climate change on U.S. farm values for a climate change scenario assuming a doubling of CO₂ emissions by the middle of the 21st century which is associated with a 5 degree Fahrenheit change in mean temperature and an 8% change in precipitation. This paper shows that the estimated impact of climate change is lower using hedonics rather than a production function approach. This is expected as the production function approach does not account for adaptation possibilities (such as switching of crops, etc) and thus tends to overestimate damages. The reported results range from a 4-6% decline to a slight increase in the value of agricultural output.

Criticisms of the hedonic approach include inadequate treatment of irrigation in the analysis, lack of robustness to weighting schemes and the difficulties in estimating dynamic adjustment costs due to fixed capital constraints in the short run. In an attempt to explore the first issue, Schlenker, Hanneman, and Fisher (2005) examine whether estimated coefficients from a hedonic regression using dryland and irrigated counties are significantly different and also test for differences in the coefficients of the climate variables. The results indicate that the economic effects of climate change on agriculture need to be assessed differently in dryland and irrigated areas and that pooling the dryland and irrigated counties could potentially yield biased estimates. Due to data constraints, the model is estimated for dryland counties and the estimated annual losses are about \$5 to \$5.3 billion for dryland non-urban counties. The study acknowledges that adding the impact on irrigated areas may potentially yield greater estimates of losses but the exact magnitude is uncertain.

Schlenker, Hannemann, and Fisher (2007) examine individual farm values in California by matching farm values with a measure of surface water availability. Using degree days as a measure of climate in addition to various metrics of water availability (i.e. water rights, projected precipitation during growing and snow pack seasons); the authors estimate the economic impact on agriculture. Their findings indicate that climate change could significantly affect irrigated farmland value in California, reducing values by as much as 40%. They suggest that the overall impacts of climate change could be “negative, robust, and large, ranging from 40-percent yield declines (slow-warming scenario) to 80-percent yield declines (fast-warming scenario) by the end of the century”.

A key component of the study of climate change impacts is the effect of climate change on the variability of crop yields (as opposed to focusing solely on mean yields) as this reflects producer risk. Isik and Devadoss (2006) developed a framework for determining climate change impacts on crop yields and variability and yield and the covariance of yields

among crops. Using a stochastic production function and two long-term climate change scenarios (Hadley 2025-2034 and Hadley 2090-2099), the paper estimates the impacts climate change would have on several crops traditionally cultivated in Idaho: potatoes, sugar beets, wheat, and barley. Mean potato yields are projected to increase 0.4 – 1.1% for the 2025–2034 scenario and 7.0–8.7% for the 2090–2099 scenario. Mean wheat yields are projected to increase 0.4–1.0% for the 2025–2034 scenario and by about 1.1–1.2% for the 2090–2099 scenario. On the other hand, barley and sugar beet yields are projected to decline about 4.6% and 1.0% in the 2025–2034 scenario, respectively. Mean yields are projected to decline 10.9% for barley and 2.4% for sugarbeets under the 2090–2099 scenario. Yield variances are estimated to decrease for wheat, barley and sugar beets but increase slightly for potatoes. The covariance between wheat and potato yields and between barley and potato yields is estimated to decline significantly while that between wheat and barley increases marginally.

In an attempt to address the omitted variables problem arising in hedonic models, Greenstone and Deschenes (2007) use a county-level panel data to estimate the effect of weather on agricultural profits, conditional on county and state by year fixed effects. They then multiply the estimates by the simulated change in climate change (from the Hadley 2 model) to obtain the economic impact on agriculture. The authors note adaptation possibilities cannot be fully realized in a single year and thus estimated damages may be overstated. Nonetheless, the estimated increase in annual profits is \$1.3 billion or 4% and this is robust to different specifications. However, this paper demonstrates heterogeneity in impacts across states and the simulated increases in temperature and precipitation do not have any significant effect on the yields of corn or soybeans. This paper also demonstrates that the hedonic approach is sensitive to control variables used, sample, and weighting schemes.

Reilly et al. (2003), using predictions from general circulation models from the Canadian Center Climate Model and the Hadley Centre Model, examined the effects that

changes in temperature and precipitation over the period of 2030-2090 would have on U.S. agriculture. The authors estimated the net effect on economic welfare and found the effects were positive but there were regional differences. The estimated increase in economic welfare was \$0.8 billion (2000 U.S. \$) in 2030 and \$12.2 billion in 2090. Southern regions of the U.S. suffered productivity losses, while the Northern regions experienced cropland expansion and production shifting. Dryland cropping benefited more than irrigated cropping due to the projected increases in precipitation levels. An extension of this study using additional climate scenarios found similar results (McCarl and Reilly, 2006).

As part of its comprehensive analysis, the CCSP SAP 4.3 report (2008) presents estimates that soybean yields in the southern U.S. may fall 3.5% for a 1.2⁰C increase in temperature from the current mean temperature of 26.7⁰C. Meanwhile, soybean yields in the upper Midwest region of the U.S. are projected to increase 2.5% for a 1.2⁰C above the mean of 22.5⁰C (Boote, Jones, and Pickering, 1996; Boote, Pickering, and Allen, 1997). These results are indicative of the production shifts that may occur across regions.

CO₂ Fertilization, Ozone Effects, and Extreme Weather Events

Another important factor associated with climate change scenarios that needs to be assessed in conjunction with temperature and precipitation changes is the effects from CO₂ fertilization – a phenomenon where crop growth increases due to higher concentrations of carbon dioxide. There may also be reductions in yields due to increasing levels of tropospheric ozone (O₃). O₃ is a naturally occurring compound in the troposphere, but can cause detrimental effects on crop growth at high concentrations (Morgan et al., 2006). Another important aspect of climate change is changes in the intensity and frequency of extreme weather events, such as drought, flooding, wildfires, hurricanes, and periods of extreme heat or cold.

One reason that many assessments find relatively small aggregate impacts on U.S. agriculture is that temperature and precipitation changes under climate scenarios occur gradually over time, providing growers with opportunities to mitigate impacts by changing crops, altering planting times, and making other management changes to adapt to changes in climate. However, past assessments have frequently ignored potential increases in yield variability due to increasing occurrence of episodic events such as wildfires, flooding, and hurricanes or changes in El Niño—Southern Oscillation (ENSO) cycles. These events are a potentially major source of crop losses, although there is still considerable uncertainty regarding climate impacts on these events. Chen and McCarl (2009) examined the damages from hurricanes on agriculture and the possible damages from an increase in frequency/intensity, as well as the nature of sectoral reactions to mitigate damages. The reduction of average state-level crop yields due to hurricanes ranges from 0.56% to 13.04%. Crop yield variances are significantly affected by hurricane intensity, and the magnitudes of yield variances due to hurricanes are higher than the impacts on average crop yields. Changes in cropping patterns can harden the sector with vulnerable crops like corn, cotton, and oranges reduced in incidence in the potential strike zone while they increase elsewhere.

In another study of the impacts of extreme weather events on agriculture, Rosenzweig et al. (2000) estimate the total damages from the 1988 summer drought were \$56 billion, while those from the 1993 Mississippi River Valley floods exceeded \$23 billion (both in 1998 dollars). The study highlights certain aspects of climate change such as increases in sequential extremes, e.g., prolonged droughts followed by heavy rains which could reduce important pollinating insects and severely impact soil quality and increase pest infestations.

A number of studies have examined the influence of CO₂ concentrations on agricultural crop and forest growth. These studies have typically found positive effects on growth and improved efficiency of water use, although this effect may be larger in

experimental studies than in the field (e.g., Long et al., 2006). However, these studies tend to hold other factors constant, whereas increases in CO₂ are projected to occur simultaneously with changes in temperature, precipitation, and other factors that may constrain the positive yield response to increasing CO₂. Thus, it is important to assess changes in these factors simultaneously. All else being equal, higher concentrations of CO₂ increases crop growth. However, that does not necessarily imply that the beneficial effects of increased CO₂ will offset negative effects associated with increased temperatures and changes in precipitation. The CCSP SAP 4.3 report notes that a doubling of CO₂ concentrations (from 330ppm to 660ppm) is projected to increase yields of C3 crops (e.g. soybeans, cotton, hay, wheat, rice, barley and potatoes) by 33% and that of C4 crops (e.g. corn and sorghum) by 10%, all else equal (Kimball, 1983).

Summary of General Findings in the Literature

Overall, studies have typically concluded that U.S. agriculture will likely not see major impacts at the national level over at least the next few decades, but findings vary considerably depending on emissions scenario and GCM used for climate simulations. They also depend on the measure of impact; studies that have looked at farm land value or profitability have tended to find smaller negative or more positive impacts than those focused on crop yields. Because the demand for food is relatively inelastic, widespread reductions in yield could result in an increase in revenue and profits to the farm sector. Also, national level results tend to smooth out potential distributional effects across regions as relative yields and cropping patterns shift across regions. There may also be important differences in impacts between irrigated and non-irrigated crops as precipitation patterns and water resource availability changes. In addition, many studies focus on mean yields, not necessarily on the variability of yields though changes in production risk will also have important effects on cropping decisions, commodity markets, and net impacts.

Methods

To conduct these analyses, we used existing data on simulated changes in future temperatures, precipitation, and CO₂ concentrations generated by Global Circulation Models (GCMs) as part of the IPCC AR4 process. The models selected here were chosen on the basis of completeness of data requirements for the Environmental Policy Integrated Climate (EPIC) model. In addition, all models selected are in the top 50 percent of relative skill for the variables considered and have acceptable northern hemisphere error metrics that are higher than mean model error (Glecker, Taylor, and Doutriaux, 2008).

Data for the continental U.S. were downloaded from the Program for Climate Model Diagnosis and Intercomparison website (<http://www-pcmdi.llnl.gov/>) and interpolated to observed historical weather data points for the EPIC database modelling units (8-digit hydrologic units) using a bilinear interpolation. Precipitation bias correction was performed by computing an adjustment factor based on the relationship between observed and modelled climate in the baseline period. Minimum and maximum temperatures were also bias corrected following the same method.

For this study, the IPCC scenario A1B was selected for analysis. This scenario is characterized by a high rate of growth in CO₂ emissions and most closely reproduces the actual emissions trajectories during the period since the scenarios were defined (2000-2008) (van Vuuren and Riahi, 2008). Actual emissions in recent years have been above the A1B scenario projections so it is reasonable to focus on this scenario group versus those in the B1 and B2 scenario groups that have lower emissions projections. At the same time, there has been considerable interest and policy development to encourage non-fossil fuel energy, which is consistent with the A1B scenario vs. A1F1 or A2 that assume a heavier future reliance on fossil fuels. In addition, the climate model intercomparison project that included archiving of daily climate data for the 2045-2055 timeframe was only conducted with A1B and the use of

daily climate projections is important for this study to help capture the effects of climate variability within the growing season.

It is common practice in climate change analyses to use multiple GCM projections to reflect the uncertainty inherent in such projections. Assumptions and procedures vary substantially across different GCMs. Thus, for similar projections of GHG concentrations, there are a range of climate projection results. Multiple scenarios are being used to generate a range of results characterizing some of the uncertainty regarding climate change under the given IPCC scenario selected. The four primary GCMs being analyzed in this study are as follows:

- GFDL-CM2.0 and GFDL-CM2.1 models developed by the Geophysical Fluid Dynamics Laboratory (GFDL), USA,
- Coupled Global Climate Model (CGCM) 3.1 developed by the Canadian Centre for Climate Modelling and Analysis, Canada.
- Meteorological Research Institute (MRI) coupled atmosphere-ocean General Circulation Model (CGCM) 2.2 developed by the Meteorological Research Institute, Japan Meteorological Agency, Japan.

In order to supply the disaggregated climate data needed by the EPIC model, we rely on data from these GCMs to characterize potential future temperature, precipitation, and CO₂ concentrations. Table 1 summarizes national average changes in minimum and maximum temperature as well as precipitation under each of the four GCMs for both spring and summer seasons. Mean temperatures are simulated to rise under all four of the GCMs modeled in this study for both March/April/May (MAM) and June/July/August (JJA). The largest increase in mean temperature (4.34⁰C in JJA max temp) is simulated by GFDL-CM2.0; conversely MRI-CGCM2.2 forecasts the smallest increase in mean temperature (1.23⁰C in JJA max temp). The GFDL-2.0 model also has reductions in total precipitation whereas MRI-CGCM2.2 has the

largest increases in precipitations in both spring and summer. GFDL-CM2.1 has a smaller temperature increase than GFDL-CM2.0, but a more severe reduction in precipitation in the summer months. Average national effects for CGCM3.1 tend to fall in the middle of the other GCMs considered. As mentioned elsewhere, these GCMs cover a range of the different temperature and precipitation outcomes presented in the IPCC and other assessments to help provide a range of outcomes.

Table 1. Changes in Temperature and Precipitation under GCMs Modeled, 2045-2055 Relative to 1990-2000 Climate Baseline

Model	Season	Change Max Temp (°C)	Change Min Temp (°C)	Change in Precipitation (%)
GFDL-CM2.0	MAM	2.78	2.41	-7.4
GFDL-CM2.0	JJA	4.34	3.44	-8.5
GFDL-CM2.1	MAM	1.66	1.72	0.6
GFDL-CM2.1	JJA	4.03	3.45	-16.5
CGCM3.1	MAM	2.45	2.41	2.1
CGCM3.1	JJA	2.27	2.17	0.7
MRI-CGCM2.2	MAM	1.23	1.37	9.5
MRI-CGCM2.2	JJA	1.28	1.57	8.7

Mean minimum and maximum temperatures generally increase for all regions of the U.S. in both spring and summer for the climate models considered, with summer months typically showing larger increases. Changes in precipitation patterns differ by season and climate model, but tend to show drying in the Midwest during the summer growing season. While the central U.S. tends to become hotter and dryer under the climate models used, both temperature increases and drying in the Midwest are less severe in the CGCM3.1 and MRI-CGCM2.2 simulations than in the GFDL-CM2.0 and GFDL-CM2.1 model simulations and many areas in the South, West, and northern Midwest show increases in precipitation. Because water availability is a major issue affecting projected yields under alternative climate

scenarios, the varying precipitation patterns in the climate models selected helps to provide information on the range of outcomes.

In the spring months, the GFDL-CM2.0 model projects decreases in precipitation in the South Central and Midwest regions. Regions with particularly large reductions in precipitation include Louisiana, Alabama, Arkansas, Mississippi, and the Eastern portion of Texas. Modest increases in springtime precipitation are simulated for the Northern U.S. and the Mid-Atlantic. When comparing projected springtime precipitation levels of the two GFDL GCMs, it is apparent that GFDL-CM2.1 model projects a wetter U.S. Rather than receiving less precipitation in the spring, the Midwest and Northeast are projected to become considerably wetter and the South Central U.S. doesn't dry out nearly as much.

The summer growing months are projected to experience substantial declines in precipitation levels under the GFDL-CM2.0 model simulation. States in the Midwest are most affected with parts of Nebraska, Kansas, Iowa, Indiana, Illinois, and Ohio experiencing the largest decreases in the region. Additionally, South Florida is projected to see large reductions in summer precipitation levels. While most of the U.S. sees considerable declines in summertime precipitation, the Carolinas, parts of the Mid-Atlantic, and the Southwest are projected to see substantial increases in precipitation. In contrast to its springtime projections, average precipitation levels during the summer months are projected to fall much more than under any of the other GCMs used in this study with reductions concentrated in the central portion of the U.S. The East Coast from Georgia to New York and Massachusetts, the Northern Great Plains, and parts of the Southwest and Great Lakes regions experience increases in summer precipitation under these model simulations.

CGCM3.1 and MRI-CGCM2.2 project wetter spring months overall, although there is drying in the West, Northeast, and Southcentral regions in the CGCM3.1 model and primarily in Texas and Oklahoma in the MRI-CGCM2.2 model. During the summer growing months,

there are relatively small changes in precipitation in either direction for most of the country in the CGCM3.1 projections, though Texas, along with parts of the Southeast and Northern Great Plains, see increases in precipitation. The MRI-CGCM2.2 model has more extremes in its summer precipitation projections, with relatively large increases in the Carolinas and the Midwest and relatively large decreases in the most southern regions of states along the Gulf Coast from Texas to Florida.

These data were incorporated into the EPIC model to estimate impacts of alternative climate scenarios on crop yields for barley, corn, cotton, hay, potatoes, rice, sorghum, soybeans, and wheat. The EPIC model is a single-farm biophysical process model that can simulate crop/biomass production, soil evolution, and their mutual interaction given detailed farm management practices and input climate data (Williams, 1995). Crop growth is simulated by calculating the potential daily photosynthetic production of biomass.

Daily potential growth is decreased by stresses caused by shortages of radiation, water, and nutrients, by temperature extremes and by inadequate soil aeration. Thus, EPIC can account for the effects of climate-induced changes in temperature, precipitation, and other variables, including episodic events affecting agriculture, on potential yields. The model also includes a nonlinear equation accounting for plant response to CO₂ concentration. As the EPIC model simulates plant growth on a daily time step, when run with daily weather input the changes in frequency and intensity of rainfall events, and changes in temperature extremes are captured by the model simulation. These dynamics are also inherent in the statistical distribution of the monthly weather input.

These crop yields were then used as inputs into the stochastic version of the Forest and Agricultural Sector Optimization Model (FASOM) to assess market outcomes given climate-induced shifts in yields that vary by crop and region. The stochastic version of the model is used to model crop allocation decisions based on the relative returns and risk associated with

alternative cropping patterns under each of the modelled scenarios. FASOM (Adams et al., 2005) was developed to model economic decisions and assess agricultural market outcomes under alternative policies. FASOM and related models (e.g., the Agricultural Sector Model) have been used extensively in numerous forest and agricultural policy applications, including a large number of climate change–related studies for the IPCC, CCSP, U.S. Department of Agriculture, U.S. Department of Energy, U.S. Environmental Protection Agency, and others.

In this study, the stochastic version of FASOM is used to model crop allocation decisions by crop and management categories based on the relative returns and variability of returns under alternative cropping patterns under the yield distributions associated with the climate scenarios modeled. FASOM also generates market equilibrium outcomes under each scenario examined. Previous versions of the model have been applied in applications assessing producer response to changes in production risk (Chen and McCarl, 2000; Chen, McCarl, and Adams, 2001; Chen, Gillig, and McCarl, 2001). The current analysis uses an updated version of the stochastic model to explore potential implications of climate change impacts consistent with AR4 scenarios based on detailed EPIC model simulations.

Results

Yields were simulated for hydrologic unit code regions within the current and potential production range defined for each crop. Yield potential was simulated for each of these crops for both dryland (non-irrigated) and irrigated production conditions with the exception of potatoes and rice, which were assumed to be irrigated. Yields for both irrigated and non-irrigated production were simulated for the entire crop production region even if only or the other has historically been used in a region. This was done to provide inputs to FASOM on what potential yields would be if irrigation status were changed for a crop within a region. This introduces the possibility that producers could either begin irrigating or stop irrigating if the changes in relative yields and production costs resulted in changes in relative profitability.

All yields were simulated holding everything constant except for climate conditions to generate values under both baseline climate and alternative climate scenario conditions. Using input from the GFDL-CM2.0, GFDL-CM2.1, MRI-CGCM2.2 and CGCM3.1 GCMs, we compare the potential yield changes in dryland and irrigated cropping for the 2045-2055 period as modelled using EPIC. We find large effects on crop yields under the climate change scenarios modelled, both positive and negative. There is considerable regional variation in simulated changes in yields across scenarios and cropping practices. Generally, yields increase in northern areas relative to southern areas for major crops other than wheat, but the patterns of simulated yield changes for a given climate scenario are complex and depend heavily on the individual crop, irrigation status, interactions with changes in precipitation that affect water availability, regional soils, and many other factors.

Irrigated crops tend to be less affected under the climate scenarios in our simulations, primarily because they are not facing the water limitations that impact the dryland crops. The EPIC simulations assume that crops can be irrigated to a level that eliminates water stress. A particular concern for climate change is that in areas where the need for irrigation is greatest due to a reduction in precipitation, the supply of water for irrigation will also be reduced. Therefore, locations with large increases in irrigated crop and reductions in precipitation may be vulnerable to production losses as well. To fully consider this risk requires integration of crop modelling with hydrologic modelling for projections of future water supply, which is outside the scope of the current study. In addition, there are cases where dryland yields increase due to greater water availability while non-water limited irrigated crop yields decrease due to the net impacts of higher temperatures. As a result, changes in yields are often larger in absolute value for dryland production than irrigated.

For example, Figure 1 shows simulated percentage changes in dryland and irrigated corn yields across potential production regions in the U.S. EPIC simulated corn yields differ

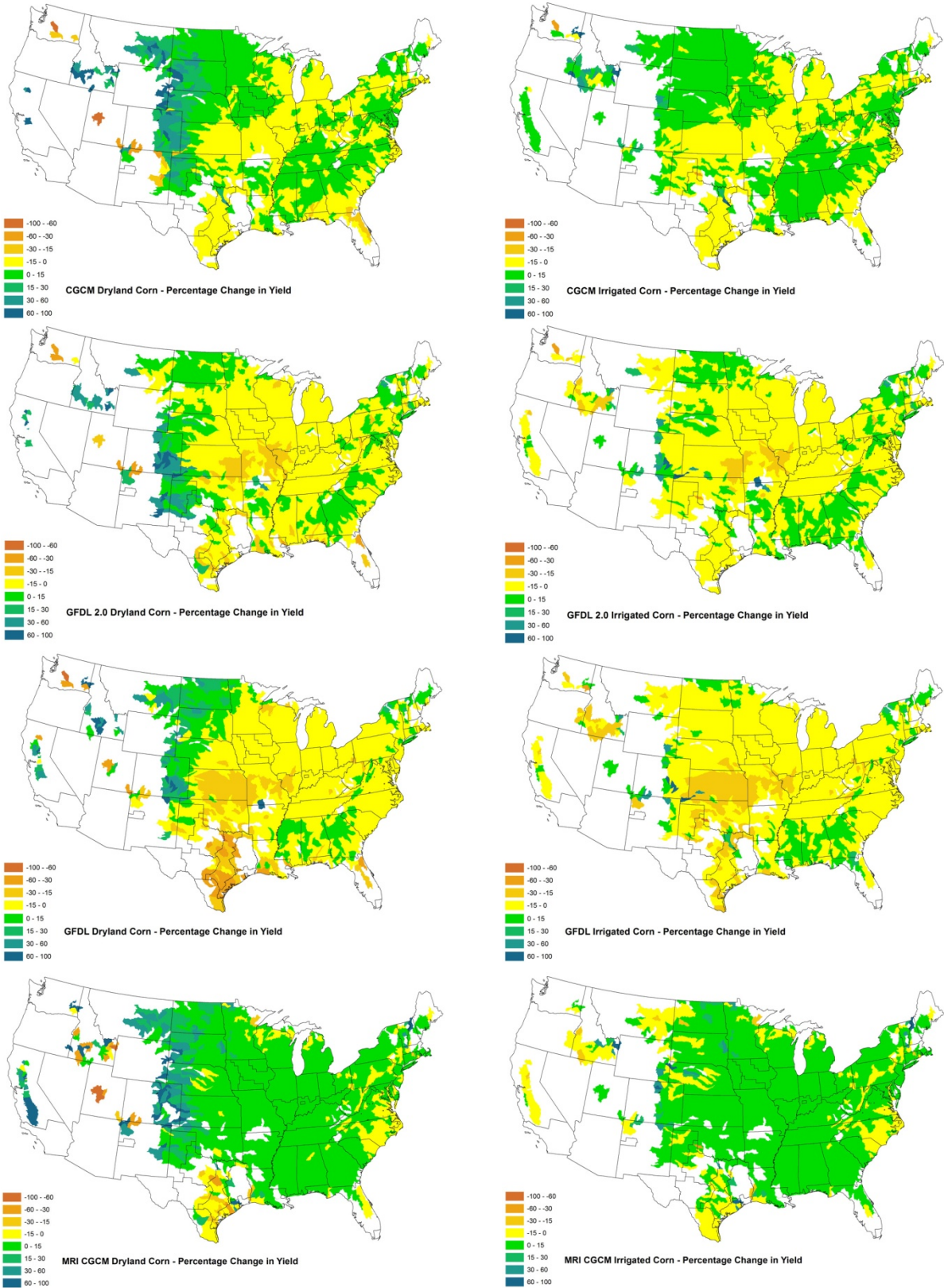
considerably based on the GCM scenario being modeled. Two of the GCMs, CGCM3.1 and MRI-CGCM2.2, predict flat to increasing yields in dryland and irrigated corn throughout the Midwest and Southern U.S., while GFDL-GCM2.0 and GFDL-CM2.1 predict flat to decreasing yields in the Midwest. In all four scenarios, dryland corn yields tend to experience larger changes, with both greater yield increases in some regions and larger declines in others. As mentioned previously, this is consistent with dryland yields being more sensitive to changes in precipitation in these simulations. Projected corn yields vary across each GCM scenario, and the variation is considerable in the Corn Belt. In all the scenarios, the Rockies region experiences the largest increase in simulated yields.

Simulated yields for irrigated barley are projected to increase across the majority of the production region, with fairly large increases in simulated potential yields. Simulation results for dryland barley yields, on the other hand, tend to show increases in the eastern half of the U.S. and decreases in the western half. Simulated potential yields decline by 30% or more in parts of the Dakotas and the Rockies region, areas that are presently home to substantial barley production.

EPIC simulation results tend to show cotton yields that are increasing in the eastern and western portions of the cotton production range and declining in between. Each of the models except GCM3.1 indicate that some of the largest simulated yield reductions would occur in southern Texas and Arizona. Generally, there tend to be reductions in yield in several of the major cotton belt states under these simulations.

Simulated hay yields tend to be increasing in the western and eastern portions of the production range, except for portions of the Southeast, whereas they tend to be decreasing in much of the Midwest and Southcentral regions as well as more southern portions of the Southeast. Yield impacts are relatively consistent across scenarios, with the primary difference being how far north yield reductions extend in the central U.S.

Figure 1. Percentage Change in Dryland and Irrigated Corn Yields Simulated Using EPIC, 2045-2055



All potato production we model in EPIC is assumed to be irrigated. The simulation results for potatoes show substantial variation across climate scenarios. Simulation based on the MRI-CGCM2.2 climate projections shows increasing yields throughout much of the U.S. (with the exception of the most southern regions). Simulations with CGCM2.2 have yields increasing in the most northern portions of the production regions with decreases in most other areas. The GFDL-2.0 and GFDL-2.1 simulation results show large reduction in potato yields across most areas in the U.S.

Rice production (also assumed to be all irrigated) is concentrated in the Lower Mississippi River basin and in Central California. Under all four scenarios, simulated rice yields in Central California generally increase across the region. Simulated rice yields in the Lower Mississippi River basin are generally declining over much of the region under the two GFDL GCMs, while there is a mixture of negative and positive yield effects under CGCM3.1 and generally increasing yields under MRI-CGCM2.2. There is considerable variation in the projected yield changes in rice producing regions of eastern and central Texas across scenarios.

Generally, simulated sorghum yields fall in the Midwest, South Central, and Southeastern U.S. in the climate scenarios other than MRI-CGCM2.2, which shows increases over much of the country with the exception of Texas, Florida, and some small regions scattered about the eastern half of the U.S. Northern and western regions of the sorghum production range simulated, as well as Mid-Atlantic states, tend to show increasing yields across all scenarios for both dryland and irrigated production.

Simulated yields for soybeans show very similar patterns overall to those found for sorghum. As for sorghum, simulated yields are generally falling in the Midwest, South Central, and Southeastern U.S. with increases to the north and west and in the Mid-Atlantic States for the CGCM3.1, GFDL-2.0, and GFDL-2.1 scenarios. The simulations based on the

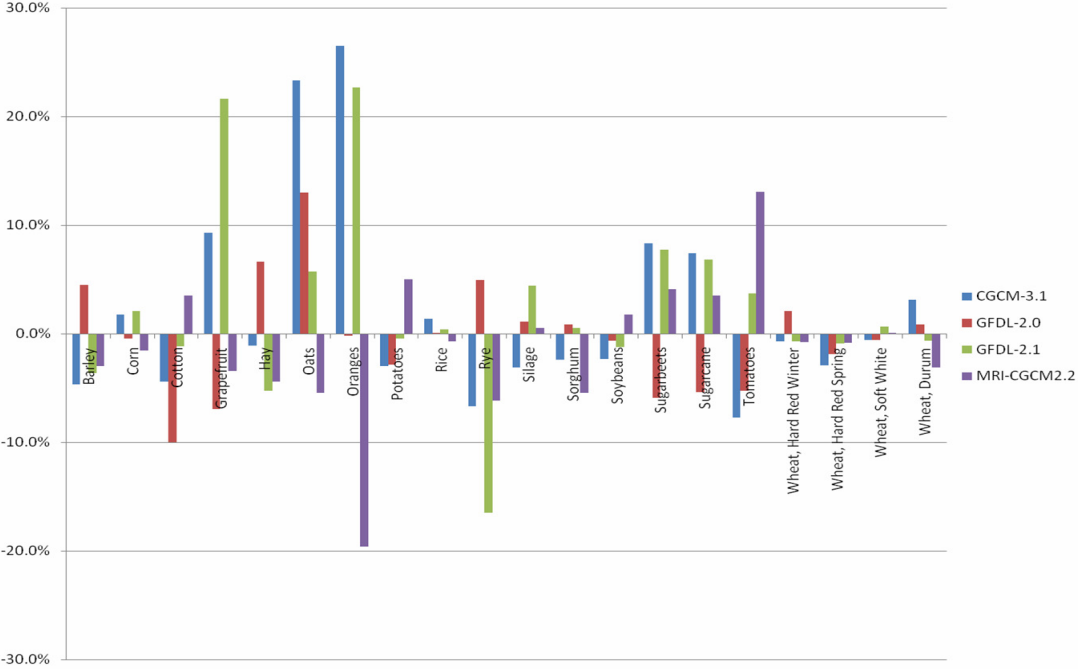
MRI-CGCM2.2 climate projections, on the other hand, show yields increasing across the majority of the U.S.

Finally, simulated wheat yields show a different pattern than any of the other crops simulated using EPIC. For wheat, yields tend to be increasing throughout most of the U.S. except for the most northern portions of the production range. In this case, it is the Dakotas, Lake States, Mid-Atlantic, and Northeast states that tend to have declining simulated yields, with increasing yields predominating throughout the majority of the rest of the U.S.

We then used weighted averages of the finer-scale simulation data to construct average values consistent with the 63 state and sub-state regions included in FASOM. Information on both shifts in mean yields and changes in the standard deviation of yields were included for each of the nine crops for which EPIC simulations were conducted. In addition to the major crops simulated using EPIC, we calculated percentage changes in mean yield and variability for additional crops as well. We used proxy crops and regions to define the potential changes in yield distribution for grapefruit, oats, oranges, silage, sugarbeets, sugarcane, and tomatoes for use in the FASOM model.

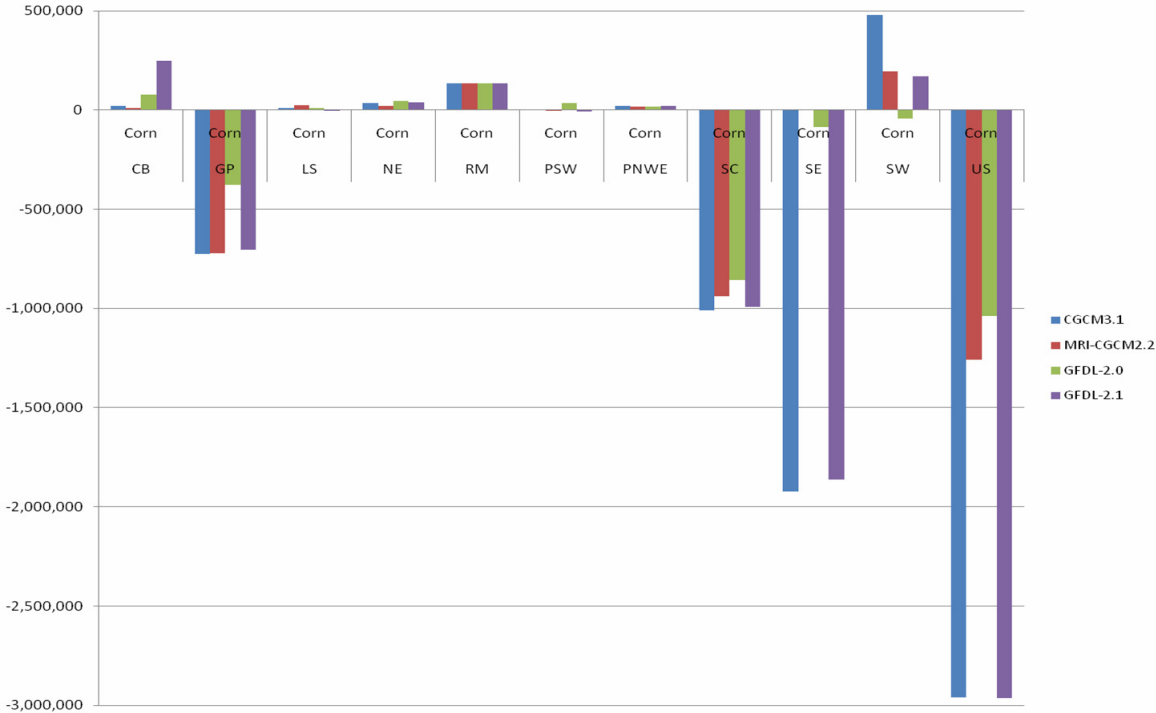
Incorporating the simulated changes in mean yield and standard deviation for each of crops with EPIC-simulated values or values calculated based on proxy crops and regions into FASOM, we generated simulated changes in equilibrium market conditions associated with these shifts in yield distributions that affect expected returns and variability of returns associated with alternative production activities. Figure 2 shows the simulated changes in average market prices under each climate scenario relative to the simulated baseline price levels. There are a mixture of increasing and decreasing mean prices for each crop across the scenarios simulated. In general, minor crops concentrated in particular geographic regions tend to have larger simulated changes in average price as well as price variability.

Figure 2. Simulated Changes in Average Market Price Relative to the Baseline



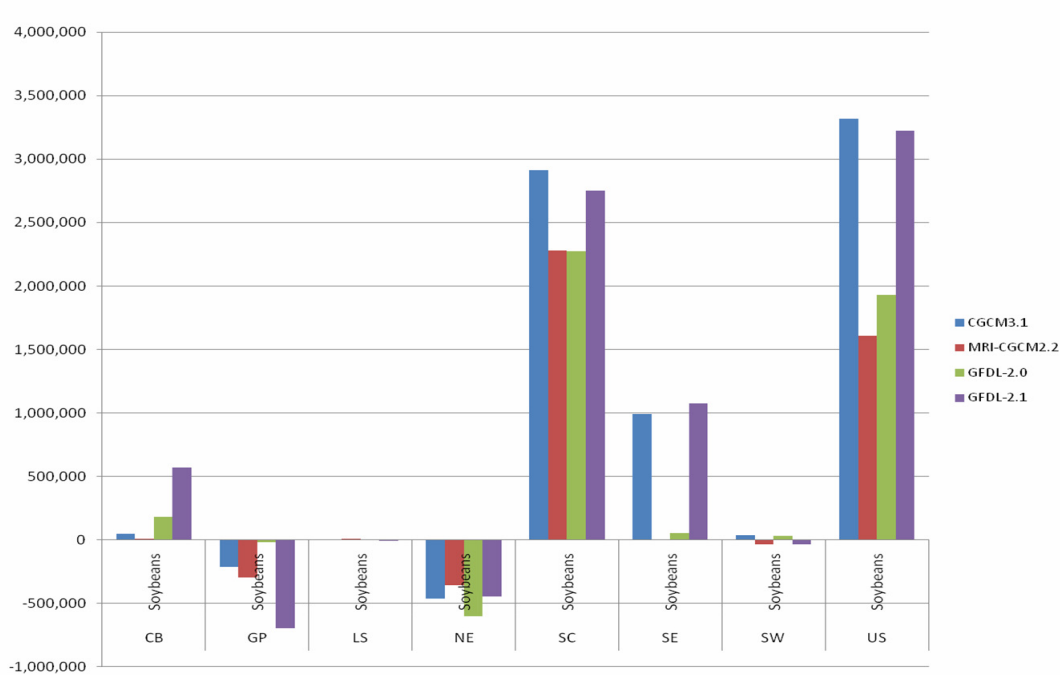
The changes in expected yields and prices as well as in yield and price variability result in changes in acreage allocation. Figures 3 through 5 present the simulated changes in regional (presented by FASOM market region) and national acreage for selected major crops under each of the climate scenarios examined. These results indicate substantial potential shifts in regional as well as national crop mix.

Figure 3. Simulated Changes in Regional Acreage Relative to the Baseline, Corn (Acres)



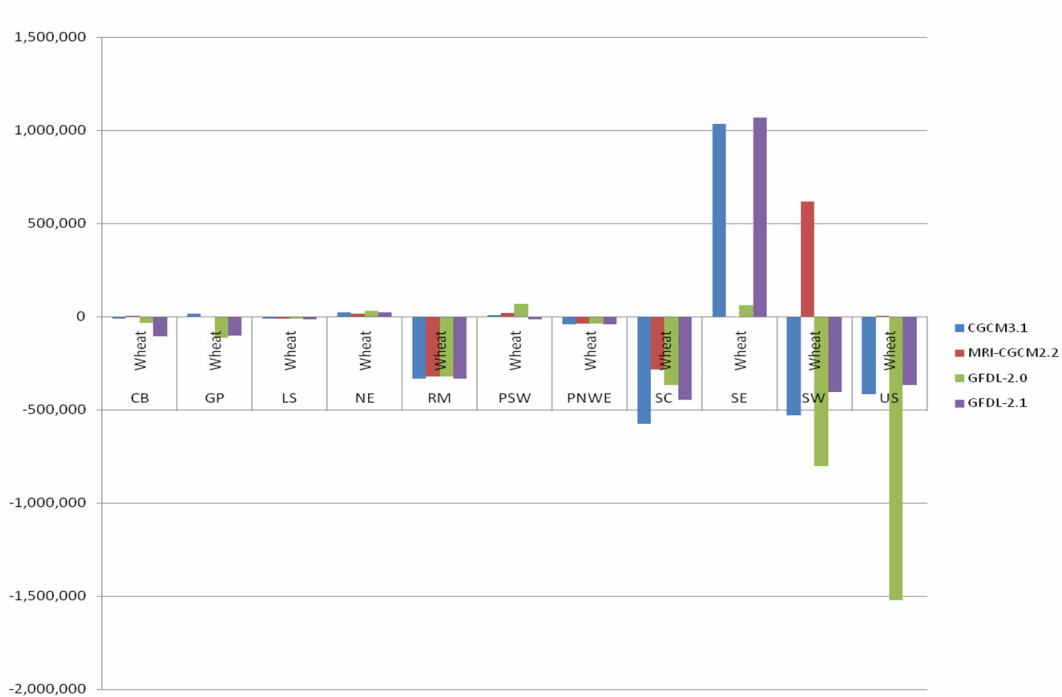
Note: CB=Corn Belt, GP=Great Plains, LS=Lake States, NE=New England, RM=Rocky Mountains, PSW=Pacific Southwest, PNWE=Pacific Northwest East Side, SC=Southcentral, SE=Southeast, SW=Southwest

Figure 4. Simulated Changes in Regional Acreage Relative to the Baseline, Soybeans (Acres)



Note: CB=Corn Belt, GP=Great Plains, LS=Lake States, NE=New England, SC=Southcentral, SE=Southeast, SW=Southwest. These are the only FASOM regions in which soybean production takes place.

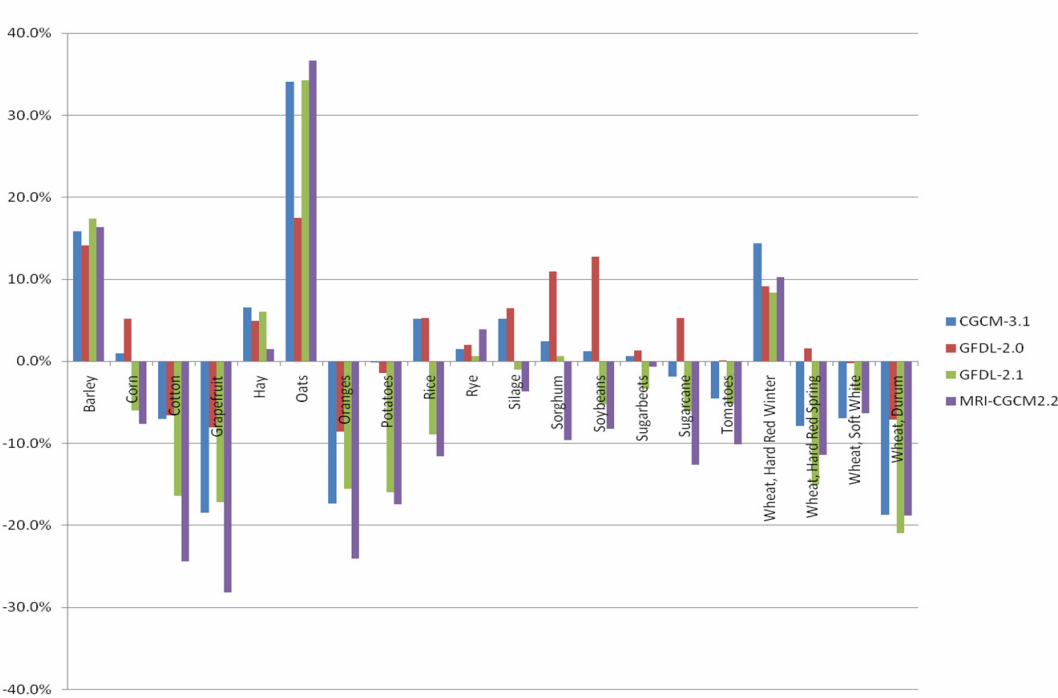
Figure 5. Simulated Changes in Regional Acreage Relative to the Baseline, Wheat (Acres)



Note: CB=Corn Belt, GP=Great Plains, LS=Lake States, NE=New England, RM=Rocky Mountains, PSW=Pacific Southwest, PNWE=Pacific Northwest East Side, SC=Southcentral, SE=Southeast, SW=Southwest

The combination of yield effects for crop/region/irrigation status combinations associated with each climate scenario with the regional shifts in crop acreage and changes in irrigation practices as producers react to changing market conditions lead to the simulated changes in national average crop yields shown in Figure 6. Barley, hay, oats, rye, and hard red winter wheat yields increase under all four climate scenarios examined. Simulated average national yields for cotton, grapefruit, oranges, potatoes, soft white wheat, and durum wheat, on the other hand, decrease under all four scenarios. For the remainder of the crops examined (corn, rice, silage, sorghum, soybeans, sugarbeets, sugarcane, tomatoes, and hard red spring wheat), the direction of the change in yield varies by scenario. Generally, simulated yield effects for these crops were more likely to be positive under the CGCM-3.1 and GFDL-2.0 scenarios and more likely to be negative under the GFDL-2.1 and MRI-CGCM2.2 scenarios.

Figure 6. Simulated Equilibrium Changes in National Average Yield Relative to the Baseline



Conclusions

As a result of changing yields, equilibrium crop acreage allocation and production patterns change as producers switch crops in response to changes in relative expected profitability and risk. While there are reductions in net gains in some regions, there are also increases in other regions that largely offset at the national level. This is consistent with previous studies finding that agricultural impacts of climate change in the U.S. may be relatively small at the national level, but that this obscures important distributional effects.

Although the modeling system applied builds on existing models that have been used for climate change assessments and reflects what we consider reasonable and appropriate assumptions, it is very important to recognize the considerable uncertainties surrounding the results of this study or any study assessing the potential impacts of climate change on agricultural production. There is considerable variation in the publicly available climate projections data between GCMs, including both differences in the magnitude of temperature

changes as well as in the magnitude and direction of changes in precipitation for regions of the U.S. These differences in projected climate conditions lead to differences in simulated changes in crop yields, with many cases where crop yields and yield variability simulated by EPIC for a given crop/region combination may be increasing or decreasing depending on the GCM used.

In addition, this study does not reflect climate change impacts on domestic forests or on international forests and agriculture, both of which will affect relative returns to different uses of land and therefore impact land use decisions. Also, there remain numerous uncertainties regarding issues such as future changes in crop technology, energy policy, climate policy, and other interactions that will substantially affect market outcomes. Additional research is necessary to further explore the potential impacts of climate change on domestic and international agriculture, forests, and land use under alternative climate and policy scenarios.

References

- Adams, D., R. Alig, B.A. McCarl, and B.C. Murray. 2005. "FASOMGHG Conceptual Structure and Specification: Documentation." Available at http://agecon2.tamu.edu/people/faculty/mccarl-bruce/papers/1212FASOMGHG_doc.pdf.
- Boote, K.J., J.W. Jones, and N.B. Pickering. 1996. "Potential Uses and Limitations of Crop Models." *Agronomy Journal* 88:704–716.
- Boote, K.J., N.B. Pickering, and L.H. Allen, Jr. 1997. "Plant Modeling: Advances and Gaps in Our Capability to Project Future Crop Growth and Yield in Response to Global Climate Change." In *Advances in Carbon Dioxide Effects Research*. [L.H. Allen, Jr., M.B. Kirkman, D.M. Olszyk, and C.E. Whitman (eds.)]. ASA Special Publication No. 61. ASA-CSSA-SSSA: Madison, WI.
- Carbone, G.J., W. Kiechle, C. Locke, L.O. Mearns, L. McDaniel, and M.W. Downton. 2003. "Responses of Soybean and Sorghum to Varying Spatial Scales of Climate Change Scenarios in the Southeastern United States." *Climatic Change* 60:73–98.
- Chen, C.C. and B.A. McCarl. 2000. "The Value of ENSO Information to Agriculture: Consideration of Event Strength and Trade." *Journal of Agricultural and Resource Economics* 25(2):368-385.
- Chen, C.C. and B.A. McCarl. 2009. "Hurricanes and Possible Intensity Increases: Effects on and Reactions from U.S. Agriculture." *Journal of Agricultural and Applied Economics* 41(1):125-144.
- Chen, C.C., B.A. McCarl, and R.M. Adams. 2001. "Economic Implications of Potential Climate Change Induced ENSO Frequency and Strength Shifts." *Climatic Change* 49:147-159.
- Chen, C.C., D. Gillig, and B.A. McCarl. 2001. "Effects of Climatic Change on a Water Dependent Regional Economy: A Study of the Texas Edwards Aquifer." *Climatic Change* 49:397-409.
- Glecker, P.J., K.E. Taylor, and C. Doutriaux. 2008. "Performance Metrics for Climate Models." *Journal of Geophysical Research* 113:D06104. doi:10.1029/2007JD008972
- Greenstone, M. and O. Deschenes. 2007. "The Economic Impacts of Climate Change: Evidence from Agricultural Output and Random Fluctuations in Weather." *American Economic Review* 97(1): 354-385.
- Intergovernmental Panel on Climate Change (IPCC). 2007. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.). Cambridge, UK: Cambridge University Press.
- Isik, M., and S. Devadoss. 2006. "An Analysis of the Impact of Climate Change on Crop Yields and Yield Variability." *Applied Economics* 38(7):835-844.
- Kimball, B.A. 1983. "Carbon Dioxide and Agricultural Yield: An Assemblage of Analysis of 430 Prior Observations." *Agronomy Journal* 75:779-788.
- Long, S.P., E.A. Ainsworth, A.D.B. Leakey, J. Nösberger, and D.R. Ort. 2006. "Food for Thought: Lower-Than-Expected Crop Yield Stimulation with Rising CO₂ Concentrations." *Science* 312(5782):1918-1921.

- McCarl, B. and J. Reilly. 2006. "US Agriculture in the Climate Change Squeeze: Part 1: Sectoral Sensitivity and Vulnerability." College Station, TX: Texas A&M University.
- Mendelsohn, R., W. Nordhaus, and D. Shaw. 1994. "The Impact of Global Warming on Agriculture: A Ricardian Analysis." *American Economic Review* 84(4):753-771.
- Morgan, P.B., T.A. Mies, G.A. Bollero, R.L. Nelson, and S.P. Long. 2006. "Season-long Elevation of Ozone Concentration to Projected 2050 levels under Fully Open-air Conditions Substantially Decreases the Growth and Production of Soybean." *New Phytologist* 170:333-343.
- Reilly, J., F. Tubiello, B. McCarl, D. Abler, R. Darwin, K. Fuglie, S. Hollinger, C. Izaurralde, S. Jagtap, J. Jones, L. Mearns, D. Ojima, E. Paul, K. Paustian, S. Riha, N. Rosenberg, and C. Rosenzweig. 2003. "U.S. Agriculture and Climate Change: New Results." *Climatic Change* 57:43-69.
- Rosenzweig, C., A. Iglesias, X.B. Yang, P.R. Epstein, and E. Chivian. 2000. "Climate Change and U.S. Agriculture: The Impacts of Warming and Extreme Weather Events on Productivity, Plant Diseases, and Pests." Center for Health and the Global Environment, Harvard Medical School.
- Schlenker, W., M. Hanneman, and A.C. Fisher. 2005. "Will U.S. Agriculture Really Benefit From Global Warming? Accounting for Irrigation in the Hedonic Approach." *American Economic Review* 95(1):395-406.
- Schlenker, W., M. Hanneman, and A.C. Fisher. 2007. "Water Availability, Degree Days, and the Potential Impact of Climate Change on Irrigated Agriculture in California." *Climatic Change* 81:19-38.
- Schlenker, W. and M. Roberts. 2006. "Estimating the Impact of Climate Change on Crop Yields: Non-linear Effects of Weather on Corn Yields." *Review of Agricultural Economics* 28(3):391-398.
- U.S. Climate Change Science Program (CCSP). 2008. *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. P. Backlund, A. Janetos, D. Schimel, J. Hatfield, K. Boote, P. Fay, L. Hahn, C. Izaurralde, B.A. Kimball, T. Mader, J. Morgan, D. Ort, W. Polley, A. Thomson, D. Wolfe, M. Ryan, S. Archer, R. Birdsey, C. Dahm, L. Heath, J. Hicke, D. Hollinger, T. Huxman, G. Okin, R. Oren, J. Randerson, W. Schlesinger, D. Lettenmaier, D. Major, L. Poff, S. Running, L. Hansen, D. Inouye, B.P. Kelly, L. Meyerson, B. Peterson, R. Shaw. Washington, DC: U.S. Department of Agriculture.
- Van Vuuren, D and K Riahi. 2008. "Do Recent Emissions Trends Imply Higher Emissions Forever?" *Climatic Change* 91:237-248. doi: 10.1007/s10584-008-9485-y
- Williams, J.R. 1995. "The EPIC Model." In *Computer Models in Watershed Hydrology*, V.P. Singh (ed.), pp. 909-1000. Highlands Ranch, CO: Water Resources Publication.