Regional Economic and Environmental Impacts of Agricultural Adaptation to a Changing Climate in the United States

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Introduction

Agricultural production has always been closely linked with, and vulnerable to, trends in weather. As a result, agricultural production enterprises and practices have adapted to local climatic conditions, and farmers have developed strategies for responding to local weather variability. Corn farmers in the Corn Belt push back planting dates in response to a wet spring, for example, and may switch to soybean production if persistent wet weather delays corn planting excessively. During extremely dry periods, farmers in the Plains States may increase moisture-conserving tillage practices, such as no-till, ridge-till, and mulch-till (Ding, 2009). Local strategies for weather adaptation are based on years of producer experience and farming-system research specific to regional conditions.

The range of local weather conditions that has shaped the current structure of domestic agricultural production, however, is changing in response to broad shifts in general climatic conditions across the country and around the world. General climatic conditions have adjusted slowly throughout the 20th century, with global average temperature increasing 1.3 degrees Fahrenheit (°F) (IPCC, 2007). As atmospheric concentrations of carbon dioxide (CO_2) have increased, the rate of temperature increase appears to be accelerating, and recent climate models predict further warming trends over time that may have a significant impact on local temperature and precipitation patterns.

Agricultural productivity, and the degree to which other inputs (such as fertilizer, pesticides, and irrigation) are needed to augment production, depend a great deal on local climate conditions. Increases in average temperature, changes in precipitations patterns, and increases in the frequency of extreme weather events would significantly alter local production environment, through the distribution of crop yields, crop acreage planted to different crops, reliance on dryland and irrigated production systems, and the geographic range and severity of pest outbreaks. Changes in water availability for crop production will be an important factor affecting regional agricultural production. Shifting precipitation patterns in combination with warming temperatures may increase water scarcity in some regions, intensifying competition for water currently used in agriculture. In other areas, increased soil-moisture availability may increase opportunities for agricultural production.

Agricultural systems respond to the changing production environment associated with climate change through the process of adaptation. The Intergovernmental Panel on Climate Change (IPCC) defines adaptation as the "adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities" (IPCC, 2007). Agricultural systems can adapt to climate change at a number of levels, from national level investments in agricultural research and development, climate forecasting, or infrastructure to behavioral adjustments of individual farm households. Smit and Skinner (2002) organize agricultural adaptation options within four interdependent categories:

- Technological developments;
- Governmental programs and insurance;
- Farm production practices; and
- Farm financial management.

While adaptation may take many forms throughout the farm economy, this report focuses specifically on the potential for adaptation at the first level of response—farmer behavior. Adapting to changing conditions is nothing new for farmers; they regularly adapt to changes in crop demand, new technological developments, farm policy provisions, land development pressure, and, most significantly, weather variability. The question we address is how changes in climate that affect yield expectations will influence land-use, agricultural markets, producer returns and agriculturally-induced changes to the environment.

Changes in individual farmer behavior in response to climate change may include, but are not limited to, growing different crops or crop varieties; adjusting planting and harvest dates; altering input use, such as applied fertilizers, pesticides, and water; adopting new production methods; expanding planted acreage; or abandoning farming altogether. How individual farmers respond to changing conditions is a function of each farmer's location, resource endowment, economic incentives, and knowledge of alternatives. While farming enterprises are likely to adapt in some way to shifting climate conditions, the costs and benefits of adaptation may vary considerably depending on the farm's location, the crops grown, and other factors that differ across operations.

Similarly, regional impacts of changing climate will not be homogeneous; some regions may see an improvement in crop growth potential, while others may face declining. An analysis that focuses exclusively on the average effect of climate change on national production, commodity and food prices, and agricultural trade would mask important regional differences. Climate change that alters the relative profitability of regional crop production may redistribute production and resource allocations across regions, with significant implications for producer income, resource use, and environmental quality. Assessing the potential impact of climate change on the U.S. agricultural sector requires the ability to differentiate among regional impacts and allow for adaptive behavior that results in shifts within and across production regions in response to changing climate regimes.

Individual farmer decisions, when aggregated to the national level, will have consequences on agriculture markets through production levels, trade, and prices and on resource use that affects environmental quality. Production adjustments may involve changes in aggregate land under cultivation; regional cropping pattern shifts, including movement of crops into areas not historically cultivated; changes in the distribution of regional crop rotations; and changes in tillage practices and fertilizer use. This study explores the regional and national implications of such farm-level adjustments for agricultural markets and environmental quality and the net effect of such adjustments on the projected impact of climate change on U.S. agriculture.

Modeling and measuring the impacts of climate change on agriculture has been an active research topic over the past two decades (Adams and McCarl, 2001; Adams et al., 2001; Reilly at al. 2002). Studies to date have featured the broad aggregate implications to agriculture, and little attention to the specific of crop production in the U.S. This study is among the first to explicitly measure land use change at a regional level and the consequential environmental impacts of adaptation to climate change, and to compare the costs and benefits of adapting to those of failing to adapt.

Scope of the Research

This paper focuses on the following questions:

- How might farmers adjust land-use and land-management decisions when faced with a new production regime shaped by climate change, and what are the implications for regional expansion and contraction of cropland?
- How might negative impacts, such as higher prices to consumers, lower incomes for farmers, and intensification of environmental consequences be reduced or eliminated through adaptation to climate change?
- How might agriculture's response to climate change impact soil and water quality?

We explored climate change’s impacts on agriculture and the potential for, and possible constraints to, adaptive behavior that addresses those impacts. Our quantitative modeling analysis then empirically examined the implication of altered climate regimes on production patterns and market conditions projected to occur by the year 2030. The quantitative methodology consisted of two phases:

- PHASE I: We first established a baseline scenario that assumes the current climate will prevail through 2030. The “no climate change scenario” establishes a baseline pattern of rotation acreages that meets a projected set of yield, production, price, and acreage measures under a set of “current” weather conditions, as measured by an average of weather conditions between 1950 and 2000. The Environmental Productivity and Integrated Climate (EPIC) model linked projections of future climate conditions to crop yields and other biophysical indicators. Since future climate projections are highly uncertain, we employed climate projections from several models to capture a range of possible climate outcomes.
- PHASE II: The Regional Environment and Agriculture Programming (REAP) model was first used to examine regional crop and livestock production, input use, cropping practices, economic returns, and environmental quality based on projected USDA market and production conditions under constant climate conditions (i.e., no climate change). REAP was then used to examine how production, market, and environmental measures behave under the climate change scenarios. To isolate the effect of adaptation, we examined two initial cases assuming climate change: one where farmers are not allowed to adapt by adjusting crop acreage or production practices, and a second where farmers can choose crop acreage, rotation choice, and tillage in response to climate-induced changes in crop yields.

This research focused on agricultural production in the United States. Our purpose was to illustrate possible regional impacts of climate change within the United States and to explore the potential for existing and proposed production technologies both to mitigate negative impacts and to take advantage of beneficial impacts of regional shifts in relative crop yield. We recognize, however, that ecosystems across the globe will be affected by climate change, putting additional pressure on international markets and agricultural production systems worldwide through changes in commodity demand, trade patterns, and broader economic conditions. This study does not explicitly incorporate international market changes into its analysis.

While REAP's strength lies in the specification of crop production detail for major commodity crops, the model's structure also allows for a limited set of adaptation behaviors within the livestock sector. The model permits livestock producers to change what they feed livestock, for instance, by switching between diets to minimize the costs associated with providing for livestock's nutritional needs under the new price regimes associated with climate change. The flexibility of such changes, however, is limited to a pre-existing spectrum of historically observed diet options. New grains, feed meals, and feed combinations that historically have not been used are not included in the set of livestock diet options. Furthermore, the impacts of climate change on the livestock sector are limited to those experienced indirectly through feed markets and increased competition for pasture land; the model does not capture the direct impacts of climate change on livestock productivity and production costs, such as those associated with climate control costs for confined livestock production (Key and Sneeringer, 2011).

Climate Change and Agricultural Impact Analysis

Regional Environment and Agriculture Programming (REAP) Model

The Regional Environment and Agriculture Programming (REAP) Model is a mathematical optimization model that quantifies agricultural production and its associated environmental outcomes for 50 "REAP" regions as defined by the intersection of USDA Farm Production Regions (defined by State boundaries) and Natural Resources Conservation Service (NRCS) Land Resource Regions (defined by predominant soil type and geography) shown in figure 1. REAP solves for regional acreage and production levels for 10 crops and 13 livestock categories and national production levels for 20 processing sectors that rely on crop and livestock inputs. REAP explicitly models regional differences in crop rotations, tillage practices, and input use, such as fertilizer and pesticides. Although crop patterns are solved for at the REAP region level, results are aggregated to USDA's Farm Production Regions (bold lines in fig. 1) for presentation in this study.

Each REAP model region includes a set of available crop rotations that are implemented using one of up to five tillage practices. The combination of region, rotation, and tillage practice is referred to as a production enterprise and represents the basic unit of crop production economic activity in the REAP model. A selection of regionally appropriate production enterprises was derived for each REAP region from 1997 Natural Resources Inventory (NRI) data. When REAP solves for agricultural production patterns under changed climate, technology, or policy conditions, acreage in each region is distributed among production enterprises based on an assessment of relative rates of return arising from differences in yields, costs and returns, and further constrained by acreage distribution parameters that capture historically observed patterns of production.

Baseline Output for 2030

To construct a baseline against which to compare the impacts of climate change, REAP's pattern of production enterprises is calibrated to replicate projected agricultural production conditions for 2030, assuming constant climate conditions based on a monthly average of climate variables calculated as a monthly average over 1950-2000 (Hijmans et al., 2005). This "no climate change baseline" scenario assumes that technology and market conditions will continue to change at historical rates, and holds the suitability of a given region to produce crops constant according to a baseline set of weather conditions.

Technology and market condition projections in 2030 were extrapolated from USDA's annual agricultural production and market indicator projections (USDA, 2010). The USDA projections included estimates of planted and harvested acreage, anticipated crop yields, trade volumes, and market prices over a 15-year planning horizon (table 1). The projections assume that agricultural policies remained constant and that improvements in crop yields grow at a fixed rate. Yield estimates for the baseline case were calculated by first running EPIC under the "current" weather conditions. EPIC yields were then adjusted, using a crop-specific adjustment factor, to meet projected average yields for 2030 to capture assumptions about exogenous increases in crop productivity. The baseline projections do not consider the likelihood of shocks to agricultural production from extreme weather or changes in other economic conditions that might affect exports, imports, or input prices, such as energy prices, incomes, or exchange rates.

Characterizing the Study’s Climate Projections

There are various sources of uncertainty associated with generating estimates of future local weather conditions suitable for agricultural production impact analysis. Most significant among these are:

- The rate at which carbon and other greenhouse gases (GHG) are expected to be emitted into the atmosphere in the coming decades;
- The effects of that GHG accumulation on climate dynamics and core average climate variables, such as temperature, precipitation, and relative humidity; and
- Our capacity to downscale geographically coarse average climate projections into local projections for temperature, precipitation, and other variables that reflect daily weather changes across a finer spatial and temporal scale.

The IPCC Special Report on Emissions Scenarios (IPCC-SRES) addressed the first source of uncertainty. The report defined several emissions scenarios that reflect different sets of assumptions about global population change, technology adoption, energy use, and macroeconomic conditions. The uncertainty surrounding carbon dynamics and climate response is reflected by a wide array of models that attempt to project future climate trends. These models-- general circulation models (GCMs)--differ from one another in the numerical methods used as well as in the spatial resolution at which climate projections are made. As a result, different models may vary considerably with respect to predictions of the magnitude and direction of precipitation and temperature change for given points or regions.

Each of the IPCC scenarios represented an estimated future path of CO_2 emissions that can be used as emissions input data into a GCM. Atmospheric CO_2 levels are an important driver of many long-term climate phenomena, so the various emissions scenarios result in different long-term climate projections. This analysis used climate projections derived from a single emissions scenario–the SRES A1B emissions scenario–which was designed to reflect “very rapid economic growth,” “the rapid introduction of new and more efficient technologies,” and a balanced portfolio of energy sources that included both fossil fuels and renewable energy technologies (IPCC, 2007). The SRES A1B emissions scenario represented a middle ground between other illustrative scenarios. Because this research focuses on an analysis year (2030) that occurs prior to significant divergence in emissions levels across the different scenarios, sensitivity analysis of results across the different emissions scenarios was not considered a high priority. In contrast, the significant variability across GCM results using a single emissions scenario suggested a need to explore climate projections across a number of models to capture a range of possible climate impacts arising from a single projected path of emissions.

“Downscaling” refers to the process of translating the large-scale climate information that emerges from GCMs into finer temporal and spatial resolution. There are several methods available for downscaling GCM output; the downscaled data used in this study were generated by Jones, Thornton, and Heinke (2009). Each of the four datasets represents output from a different GCM running the SRES A1B emissions scenario (table 2).

Figure 2 shows the variation in mean annual maximum temperature and precipitation change between the base period and 2030 for each of the four climate projections across REAP. The Model for Interdisciplinary Research on Climate (MIROC) represented the most extreme change from the base period, in that it demonstrated the largest temperature increase and the most negative precipitation change. The Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Max Planck

Institute’s ECH scenarios represented the mildest change projections; both predicted a similar range of temperature increases across REAP regions, but the ECH scenario predicted slightly wetter conditions relative to the CSIRO projections. The Centre National de Recherches (CNR) projection was highly variable in both temperature increase and precipitation change across the REAP regions and represented a moderate national projection in terms of the severity of climate change predicted among the scenarios considered.

While the magnitudes of shifts in maximum temperatures differed across GCMs, regional patterns of temperature impact were somewhat similar (fig. 3). The models generally projected the most moderate temperature increases in the West and Southeast and more significant temperature impacts in the Midwest and Northeast. That pattern of impact was roughly consistent with a composite of multiple IPCC model simulations generated for North America, which projected temperature increases from approximately 1 degree Celsius (ºC) in the Southeast to more than 2ºC in Northern Canada, with intermediate values over the rest of the contiguous United States (USCCSP, 2008).

In contrast to the consistent pattern of relative temperature impacts, there was little consistency in precipitation-change projections across GCMs (fig. 4). Some regions exhibited an increase in precipitation according to some models and a decrease in precipitation according to others. A few regions demonstrated a consistent direction of impact across models; the Pacific Northwest exhibited an increase in precipitation across all models, while the Texas/Louisiana region exhibited a decline in precipitation across all models. Nevertheless, even regions with a consistent direction of impact exhibited a wide range of estimated magnitudes across GCMs. Because there is no basis with which to assign probabilities to weather outcomes predicted across GCMs, crop yield impacts, adaptation potential, and aggregate system impacts were calculated and presented independently for each of the illustrative climate projections.

Quantifying Climate Change Impacts on Crop Yields

Climate change is expected to impact crop growth and development through a number of pathways. In this analysis, climate change impacts on crop yields were estimated using EPIC – a field-scale biophysical model that uses a daily time step to simulate crop growth, soil impacts, hydrology, nutrient cycling, pesticide fate under various cropping systems (e.g., tillage, crop rotation, soil and nutrient management) and weather scenarios. A random weather generator built into EPIC uses the average monthly climate information derived from the GCMs--minimum daily temperature (TMIN), maximum daily temperature (TMAX), and precipitation (PRCP)--to generate daily temperature and precipitation patterns for simulated crop growth in each REAP region.

To represent a range of possible weather scenarios associated with each GCM's set of average monthly estimates, simulation results were run 10 times for 20 years, using a different random weather seed for each run. Results from the first 10 years of each run (a total of 100 years) were discarded to minimize the impact of initial soil conditions on yield and environmental impact estimates. Results from the remaining 100 years were used to calculate the average yield and environmental impact results associated with each production enterprise. Because variability estimates for future weather cannot be derived from either the original or the downscaled GCM climate output, the weather variability, and therefore the incidence of extreme weather events, was held constant in this analysis across the baseline and future weather scenarios.

For each production enterprise, EPIC was used to calculate a set of yield and environmental impact measures associated with region-specific weather assumptions and four sets of regional soils differentiated by highly erodible, non-highly erodible, with tile drainage, and without tile drainage. To calculate the impact of the climate change scenarios on crop growth in each region, the crop growth parameters and geophysical process parameters used in EPIC's simulations were held constant across the estimates generated using the baseline climate conditions and the projected climate conditions emerging from the GCMs. In moving from the baseline to the climate change projection scenarios, however, we assumed that ground-level CO_2 concentrations increased from 381 parts per million (ppm) in the baseline to 450 ppm across GCM projections. EPIC calculated the impact of the increased atmospheric CO_2 effect using a nonlinear plant response equation with crop-specific parameters. The only other variables that differed between the baseline and the climate change yield estimates were the Minimum Temperature, Maximum Temperature, and Precipitation variables.

Quantifying the Impacts of Climate Change and Adaptation Behavior using REAP

Climate-induced changes in agricultural production were assessed by substituting into REAP the yield and cost estimates for production enterprises that were estimated in EPIC using new, regionally variable climate conditions associated with climate projections. Yield estimates were again adjusted (by the same crop-specific adjustment factor) to account for exogenous increases in productivity up to 2030. Because climate change affects crops and regions differently, the relative productivity and economic value of regional production enterprises will change under the projected climate scenarios. Production enterprises that are economical under one climate regime may not be economical under another.

Our analysis showed that in each climate change scenario, several historically established crop rotations were no longer economical to employ, possibly because the enterprise was marginally economical in the baseline and was sensitive to climate -induced changes in yield or price. Another economic driver may be that changes in other crop yields and/or prices make them more favorable to produce and force out crop rotations that do not experience improved yields or increased prices. Optimizing agricultural production levels and patterns under projected climate conditions produced a new pattern of production enterprises that reflected changes in regional production levels, including shifts among crops, crop rotations, tillage used, and expansion or contraction of cropland.

Quantifying the Agricultural Impact of Climate Change and the Potential for Agricultural Adaptation

Applying information about the yield impact of climate change across projected production patterns in the United States is a straightforward, if naïve, approach to estimating the potential economic impact of climate change. This method assumed an unrealistic future in which farmers' yields and returns are affected by climate change, but farmers fail to adapt their production decisions to changing climate conditions. Nevertheless, illustrating just such a scenario allowed us to visualize regional and crop differences in the biophysical impacts of climate change and, as described later, to differentiate changes that take place in the agricultural sector due to biophysical impacts from dynamic behavioral adaptation.

Previously, we illustrated a "no adaptation" case and then provided the results of a more comprehensive assessment of climate change impacts, incorporating the impacts of farmer adaptation decisions in determining production and price patterns under changed climate conditions. A comparison between the "no adaptation" and "adaptation" cases illustrates the benefits of adaptation.

Climate Impact Analysis: No Adaptation

"No adaptation" case results were derived by inputting new yield numbers into REAP but prohibiting the model from adjusting projected 2030 baseline acreage, tillage, or rotation allocations to crop production activities in response to the new climate-adjusted yields. REAP then used the baseline (i.e., no climate change) production patterns, together with the adjusted yield and environmental impact information, to calculate crop production, farmer income, price impacts, and environmental impacts under each future climate scenario. Note that, for this case, REAP eliminated farmer adaption but retained the flexibility to adjust the livestock sector, most notably with respect to its demand for feed grains, in response to changed production and prices patterns. Changes in national yield by crop due to climate change, assuming no adaptive behavior on the part of farmers, are shown in figure 5.

These crop yield averages reflect the average impact of climate change on individual production enterprises (i.e., region/rotation/tillage combinations) weighted by the amount of crop acreage in that production enterprise, which remained constant across the climate projections in this case. Several interesting climate effects on crop productivity are evident here. Climate change impacts were most negative for corn and soybean productivity, though the least extreme scenario (ECH) produced an increase in crop yields for both. Several other crops experienced crop productivity increases for some or all of the scenarios, though the yield increases associated with the more extreme climate change scenarios (MIROC and CNR) were generally lower than those associated with the milder scenarios (ECH and CSIRO). While the impact of any temperature increase was generally negative, positive crop productivity impacts can arise both from beneficial precipitation changes (increases in water-constrained regions) or from the CO_2 fertilization effect projected when atmospheric carbon concentrations increase from 381 to 450 ppm. For several crops, the latter positive effects outweighed the negative temperature-related losses for some or all of the projected climate projections.

Aggregating crop productivity impacts at the national level, however, masked considerable variability in both crop productivity by region under the baseline and in regional impacts on productivity under the climate change scenarios. Disaggregating the results for corn to the level of the farm production region produced the results shown in figure 6. While the productivity results for the Corn Belt drove the pattern of national averages shown in figure 5 (because the Corn Belt accounted for 53-56 percent of U.S. corn production under these scenarios), there were regional differences in corn’s response under a given climate scenario. In some regions, one or both of the milder climate change scenarios actually increased corn yields. Furthermore, corn production increased under even the extreme climate scenarios in the minor corn-producing regions of the Pacific and Mountain States and the Southern Plains region. A portion of corn production in those regions is irrigated and, therefore, less sensitive to precipitation losses from climate change but also mildly responsive to carbon fertilization gains.

In a situation with fewer interacting parts, price results might mirror productivity results; when national average crop productivity decreases (increases), the price of that crop increases (decreases) (fig. 7). Since crop and livestock markets are integrated, however, this simple dynamic did not play out for several crops and climate scenarios. Because corn prices go up in every scenario, there was always an incentive to substitute away from corn in livestock diets, which has implications for the price of other grains and feed meals. The significant corn price increases in the CNR and MIROC scenarios, in particular, appeared to pull up soybean, oat, sorghum, and barley prices, despite field productivity increases for some of those crops. Productivity, and therefore supply, of oats increased under every scenario, but prices also increased under all but the ECH scenario. Similarly, barley's substitutability with the other feed grains in livestock diets led to increased barley demand and a demand-induced price increase under the MIROC scenario that persisted despite increasing supply.

The productivity impacts illustrated in this section reflect only EPIC's yield-change calculations based on changing climate conditions, while the price impacts reflect a limited set of interacting demand-and-supply forces across agricultural sectors. Projecting potential climate change impacts on the agriculture sector, however, requires a more comprehensive analysis to capture how farmers may respond to biophysical impacts in their crop production decisions. In the following sections, we discuss how farmers might adapt to the biophysical impacts of climate change and the implications of such production adjustments for aggregate crop production, prices, agricultural acreage, and a suite of environmental indicators under changing climate regimes.

Climate Change Impacts When Farmers Adapt Crop Rotations, Tillage, and Land-Use Decisions

The economic value of planting specific crops in each region changed in response to the new production conditions, since yields and costs did not change uniformly in magnitude or direction for all regions in our scenarios. In some regions, adaptation to climate change resulted in reduced planted acreage, while planted acreage in other regions increased. Regional production effects reflected both changes in yield and planted acreage. Differences in production levels, coupled with demand response to substitute crops, in turn drove changes in crop prices. The combination of changes in acreage, yield, and price influenced the degree to which farm revenues responded in a region. In this section, we report results from the REAP model that describe the economic and environmental impacts of the climate change scenarios on U.S. agriculture, taking into account how farmers may adjust their crop and tillage decisions. The results are shown relative to the baseline projection (assuming no climate change) for U.S. agriculture in 2030.

Regional Shifts in Planted Acreage for Selected Crops

Each of the four climate change scenarios demonstrated a small increase in planted acreage compared with baseline acreage levels (fig. 8). The total acreage change, though relatively small compared with the baseline acreage, was composed of changes in the acreage planted to individual crops. The individual crops showed a much wider range across climate change scenarios, following differences in productivity and regional redistribution (table 3). Corn acres increased in all scenarios, reflecting the decline in corn yields illustrated earlier and the need for additional acreage to compensate. Response of other crops varied by scenario, with the ECH and CSIRO scenarios showing a reduction in wheat acres that corresponds to the larger wheat-yield increases in these scenarios. Soybean acres declined in the CNR and MIROC scenarios; despite higher soybean prices, acreage decline likely reflects a decrease in the relative returns to soybean production arising from the significant yield decline under the comparatively warmer climate scenarios. The corresponding corn price increase in the MIROC scenario keeps soybean acres from declining further as soybeans are often produced in rotation with corn, particularly in the Corn Belt.

Even though total U.S. acreage planted increased in all scenarios, no individual region showed an increase in planted acreage across all scenarios. While the variation in total acreage change was small across scenarios from a national perspective, the regions showed different degrees of response. Acreage in the Corn Belt was the least sensitive to climate change, with total changes ranging from -2.7 to 1.4 percent. In contrast, the Delta region showed a range of change between -9.8 and 5.0 percent. The sensitivity to change reflects the capacity of the region to economically shift to a different crop mix, indicating crop and production practice substitution possibilities and the larger regional yield changes relative to the national changes for each crop.

Figures 9 to 11 illustrate the change in planted acreage by climate change scenario for the three major field crops (corn, wheat, and soybeans). As with the national total, corn acreage in the Corn Belt was the least sensitive (-1.3 to 1.1 percent). For each of the other regions, at least one scenario demonstrated at least a +/-10 percent change in acreage from the baseline. The Southern Plains increased corn acreage in all scenarios, with the Delta and Pacific regions reducing corn acres in all scenarios.

The Corn Belt also showed the smallest change in wheat acres (0.4 to 2.4 percent). The Lake States and Corn Belt increased wheat acres in all scenarios; all other regions showed both increases and decreases across scenarios. Climate change induced soybean acres to move into the Northern and Southern Plains (fig. 11). Once again, the Corn Belt showed the smallest range in soybean acreage change (-5.6 to 0.8 percent); by contrast, change in soybean acres in the Delta region ranged from -19.2 to 11.4 percent.

Corn acreage increased in the combined Northern regions (Corn Belt, Lake States, Northern Plains, and Northeast) in all scenarios, while corn acres in the combined Southern regions (Appalachian, Delta, Southeast, and Southern Plains) declined in the ECH and CSIRO scenarios and increased in the CNR and MIROC scenarios. The same relationship holds for wheat acres. Taken as a group, the Southern regions were more sensitive to weather-induced yield change than were the Northern regions. This trend was indicative of the larger range in EPIC-derived yields in the Southern regions under the climate change scenarios.

Changes in Crop Prices and Regional Farm Revenue

Crop price changes were highly scenario-specific, although there were some features common to the results. The CNR and MIROC scenarios led to higher corn and soybean prices than under the baseline, whereas the CSIRO and ECH scenarios generally resulted in lower prices (except for a small price increase in soybeans in CSIRO) (table 4). Corn and soybean yields were lower in the CNR and MIROC scenarios in all regions, while the CSIRO and ECH scenarios showed increased yields in some regions. Wheat prices declined in all scenarios. Wheat and corn prices were generally less sensitive to changes in climate than soybean prices, mainly as a result of smaller projected sensitivity of wheat yields to temperature and rainfall and the poor substitutability between wheat and corn in the diets of livestock within REAP. While REAP's existing diets reflect feed combinations that historically have been used in the livestock sector, significant feed price changes also may induce changes in popular diet combinations as an adaptive response by the livestock sector. Our analysis did not capture that dynamic.

Climate change reduced returns to corn in all scenarios relative to the baseline, although less so in the higher temperature/precipitation change scenario, where price increases helped support producer revenue (table 5). Because of the positive effect of climate change on cotton yields, cotton returns increased significantly in all scenarios. Returns to other crops varied by scenario. Returns in the Corn Belt mimicked changes in precipitation and temperature, whereas returns in other regions did not necessarily mirror the same trend (table 6). The more extreme scenarios generally led to lower returns, but not for all regions. Nationally, the milder scenarios led to an increase in returns, whereas the more extreme scenarios led to a decline in returns. From the perspective of crop returns, the Southern Plains was the most robust, even though the regional change in acreage was large compared with other regions. This result reflects the relatively higher returns to cotton production under climate change, and the ability of agriculture in the Southern Plains region to reallocate production resources to minimize the regional impact on profitability.

Changes in Environmental Outcomes

Shifts in crops and production practices as a result of climate-induced changes in crop yields will have an influence on the environmental impacts associated with agricultural production. Changes in total acreage, in tandem with the redistribution of crop rotation/tillage practices, will affect regional nutrient loss and soil erosion. National increases in nutrient loss caused by acreage expansion in one region may not be offset by an acreage decrease in another region. Table 7 depicts the changes in nitrogen loss (leaching and runoff to ground and surface water) and total soil erosion (wind, sheet, and rill) compared with the baseline, along with the change in U.S. planted acres. Total nitrogen lost to water (measured as nitrogen deep-percolation and runoff at the field edge) increased in all scenarios, which follows from the general increase in acreage nationally. Increased nitrogen loss was not uniform across the country, with the MIROC scenario resulting in the most widespread changes (fig. 12). The Corn Belt, Northern Plains, and Southeast regions all increased nitrogen lost to water in all scenarios.

Soil erosion also increased in all scenarios, and this measure was generally more sensitive to temperature and precipitation change than the measure for nitrogen loss to water. The Corn Belt and Lake States showed a wide range of erosion impacts over the scenarios, largely as a result of crop production practice shifts (fig. 13).

How Farmer Adaptation Affects Measured Impacts of Climate Change

In the no adaptation case, farmers did not adjust production decisions in response to changes in expected yields across crops. As a result, regions may over-plant crops whose returns have declined relative to other potential crops, while under-planting crops that have become relatively more profitable. In the adaptation case, in contrast, farmers adjusted their land use, crop rotations, and tillage decisions in response to both changes in climate and adjustments in market conditions resulting from climate effects. Below, we compare how incorporating farmer adaptive response to climate change affects measured economic and environmental impacts with the model where the potential for such adaptive responses is ignored.

Regional Shifts in Planted Acreage for Selected Crops

Adaptation includes the various strategies farmers use to adjust their production decisions (e.g., shifts in crops or crop rotations) in response to absolute and relative changes in yield and management costs. Figure 14 illustrates the redistribution of planted acreage that resulted from adaptation for this analysis. In most region/scenario combinations, adaptation led to an increase in corn acreage (fig. 15). Failing to adapt (no adaptation case) restricted the supply of corn, which led to higher consumer prices. When farmers are permitted to adapt, they respond to high corn prices by changing production in favor of corn. Thus, farmer behavior can moderate climate change impacts on production by diverting productive resources to crops whose loss most negatively impacts other farm sector stakeholders.

Changes in Crop Prices and Regional Farm Revenue

Although national welfare (the sum of economic benefits to consumers plus benefits to producers) increases when farmers have the flexibility to adapt, the benefits of adaptation differ across regions and between consumers and producers. Consumers generally benefitted from the process of adaptation. Prices (a measure of consumer benefit) were generally lower if all farmers adapted (table 8), which moderated consumer expenditure impacts of climate change and increased consumer welfare measures relative to the case where adaptation was not permitted.

Producers were not necessarily better off as a result of adaptation, however. For some regions, nationwide adaptation led to lower returns relative to not adapting by, for instance, driving down the price of a major crop in that region. Returns to crop production in the Corn Belt did not benefit from nationwide adaptation (table 9); this is the consequence of smaller acreage changes in the Corn Belt relative to other regions combined with the lower prices that resulted from adaptation.

Changes in Environmental Outcomes

Table 10 illustrates the consequences of adaptation with respect to selected environmental measures when compared with the fixed-acreage, no adaptation case. The percent increase in nitrogen loss and soil erosion was greater than the percent change in acreage in all scenarios, suggesting that climate change adaptation induced crop production to shift into areas more vulnerable to soil and water-quality impacts. Climate-change induced crop reallocation, however, significantly reduced nitrogen loss in the Pacific and Mountain regions while resulting in small improvements in the Southern Plains (fig. 16). Even the more extreme scenarios showed regions where nitrogen loss declined, despite a 2- to 4-percent increase in losses nationally. Impacts on soil erosion followed a similar pattern to that of nitrogen loss (fig. 17).

Conclusions

The biophysical impacts from climate change on crop growth are both complex and uncertain. Although temperature increases associated with climate change are widely expected to lower crop yields, shifting regional precipitation patterns may either increase or decrease yields. There has also been considerable debate over the likely impacts of increasing atmospheric CO_2 concentrations on plant growth. Our analysis suggests that the possible negative implications of climate-induced yield effects on crop prices, farm revenue, and food supply can be mitigated somewhat by farmers' ability to adapt to changing climatic conditions through crop production decisions, technologies used, and the regional allocation of land. There also may be increased environmental impacts associated with expansion of cropland.

Nationally, acreage in crop production was fairly robust to climate change in the sense that aggregate acreage changes across scenarios (compared with the baseline projection) tended to be relatively small (less than 3 percent), whereas the range for individual regions was typically greater than the national range. This finding indicates considerable flexibility within the U.S. farm sector to respond to changing resource and market forces, resulting in production reallocations that minimize the aggregate disturbance to commodity supply and demand. In this analysis, available adaptation strategies included changing crops, crop rotations, and tillage types, as well as expansion or contraction of crop production acreage. Mild climate change led to a reduction in crop prices; more extreme climate change resulted in price increases in some crops, most notably for soybeans and corn. Adaptation led to an increase in crop production, in general, though even with adaptation corn and soybean production declined under the more extreme climate projections.

Total acreage in U.S. fieldcrop production increased in all climate change scenarios, although variations in yield changes across scenarios did not necessarily translate into acreage expansion in all regions. Corn and cotton were the only crops that increased acreage in all scenarios. Higher atmospheric carbon concentrations raised cotton yields considerably in every region where cotton was grown. The increase in supply, together with relatively elastic demand, caused cotton prices to drop precipitously, facilitating enough increase in demand to actually expand acreage even though existing acreage was already more productive. The corn yield effect was small relative to other crops across the scenarios, but high demand for corn raised corn acreage to compensate for lost yields. Corn acreage increased relatively more in regions where corn was not the predominant crop. Crop distributions in the Corn Belt and the Northern regions, in general, were less sensitive to climate change than in the Southern regions.

Price and production changes contributed to shifting regional returns to crop production. Returns in the Corn Belt, where much of the Nation’s fieldcrop production is concentrated, declined under all climate change scenarios in proportion to the severity of projected change. Farm returns nationally, however, increased under the two milder climate projections, with losses in the Corn Belt compensated for by increased returns in other regions as a result of changes in price and production patterns. Our findings suggest that, for regions outside the Corn Belt, changes in crop returns did not necessarily correspond to the general magnitude of the temperature and precipitation change of the scenario. Changes in relative productivity both across crops and within crops across regions, together with the resulting market-mediated price impacts, appeared to be the primary determinant of how any given region fared under changing climate conditions.

Under most scenarios, changes in environmental indicators of soil and water quality generally followed acreage changes. Environmental impacts were also sensitive, however, to changes in production practices. Under several scenarios, the shift in soil erosion and nitrogen deposited to water were proportionately larger than the total increase in cropped acreage, indicating an increase in production intensity for regions where more severe environmental impacts were observed.

Analysis Limitations and Future Research

In exploring the implications of climate change for the U.S. farm sector, our analysis focused on the yield-related impacts associated with increased regional average temperatures, varied regional changes in average precipitation, increased carbon concentration in the atmosphere, the expanded incidence of pests, and the market-mediated price impacts that arise as a result of decentralized impacts and adaptive responses. The GCM results used to drive our climate change projections did not allow us to estimate changes in the variability of daily temperature and precipitation, but other studies suggest that changes in volatility of weather parameters—including increased incidence of extreme weather events—may also be a significant driver of yield and impact changes (Isik and Devadoss, 2006). By capturing only changes in average maximum daily temperature, minimum daily temperature, and precipitation, our EPIC results may underestimate the full yield impacts expected from changes in those climate conditions.

Furthermore, direct yield impacts represent only a partial, if important, subset of the climate change elements likely to impact farmers. Other atmospheric factors, such as ground-level ozone, which is expected to increase in tandem with increasing CO_2 emissions, may have significant agricultural impacts and may influence the incentives and constraints that farmers face in responding to a changing climate. The potential impacts of climate change on the supply and costs of agricultural inputs, such as land, energy, fertilizer, water, and labor, would also affect relative returns to different types of production and would possibly create region-specific constraints on the adaptive strategies available to farmers. Such considerations were beyond the scope of this analysis. Moreover, our research focuses on the potential for adaptation within the U.S crop sector, with a particular emphasis on major field crops. We did not consider specialty crops – fruits, vegetables, nursery crops, and other specialty crops – which account for an important share of the value of U.S. agricultural production. We recognize, however, that climate change can have an important bearing on resources supporting specialty crop production as well. The model did consider livestock sector impacts through changes in feedgrain markets, although we did not capture the full range of substitution of feed ingredients that may occur due to climate change. Nor did we explicitly model the effects of climate change on animal productivity and other aspects of livestock management costs.

Our analysis also was limited in the range of adaptation strategies available to farmers that could be examined within the existing modeling framework. REAP evaluates adaptation strategies related to changing crop patterns and practices, but existing production enterprises in the model did not allow for other farm-level adaptation strategies, such as changing harvesting and planting dates or the timing and magnitude of applied irrigation or fertilizer. Such strategies are common responses to weather variability and will be an important element in farmers' adaptation responses. The potential for, and constraints to, expanding irrigated acreage and water use may be a particularly significant factor in adaptation strategies for the Western and the Southeastern regions, where there is already significant competition for water resources. REAP does not currently allow for an analysis of shifting irrigation patterns within U.S. agriculture; however, such modifications are underway and will inform ongoing ERS research related to climate adaptation.

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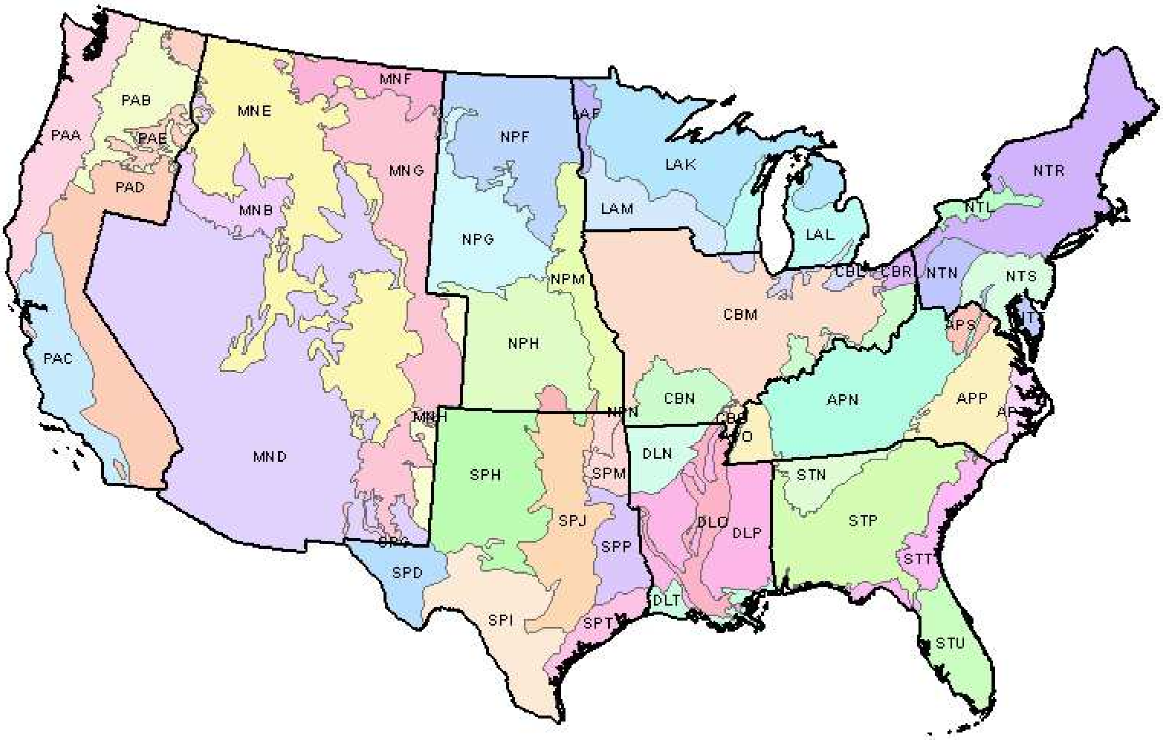
Figure 1
REAP model regions and USDA Farm Production Regions



Note: USDA's Farm Production Regions are outline in bold black line.
Source: USDA Farm Production Regions and the Natural Resources Conservation Service (NRCS) Land Resource Regions

Table 1
Baseline production and market projections for 2030

Crop	Planted acres (million)	Harvested acres (million)	Production (million bushels, except as noted)	Harvested yield	Price (dollars)
Corn	89	81.8	16,400	200.4	3.65
Sorghum	6.7	5.8	370	63.4	3.45
Barley	3.3	2.9	252	78.2	3.93
Oats	3.1	1.3	192	71.5	2.25
Wheat	52.5	44.6	2,371	50	4.7
Rice[1]	3.075	3.057	296.9	84.35	16.76
Soybeans	76	75	3829	51	9.3
Cotton[2]	11.5	10.2	21.495	2.125	333.6

[1] Rice units measured in million cwt, or hundredweight.

[2] Cotton units measured in million 500 pound bales.

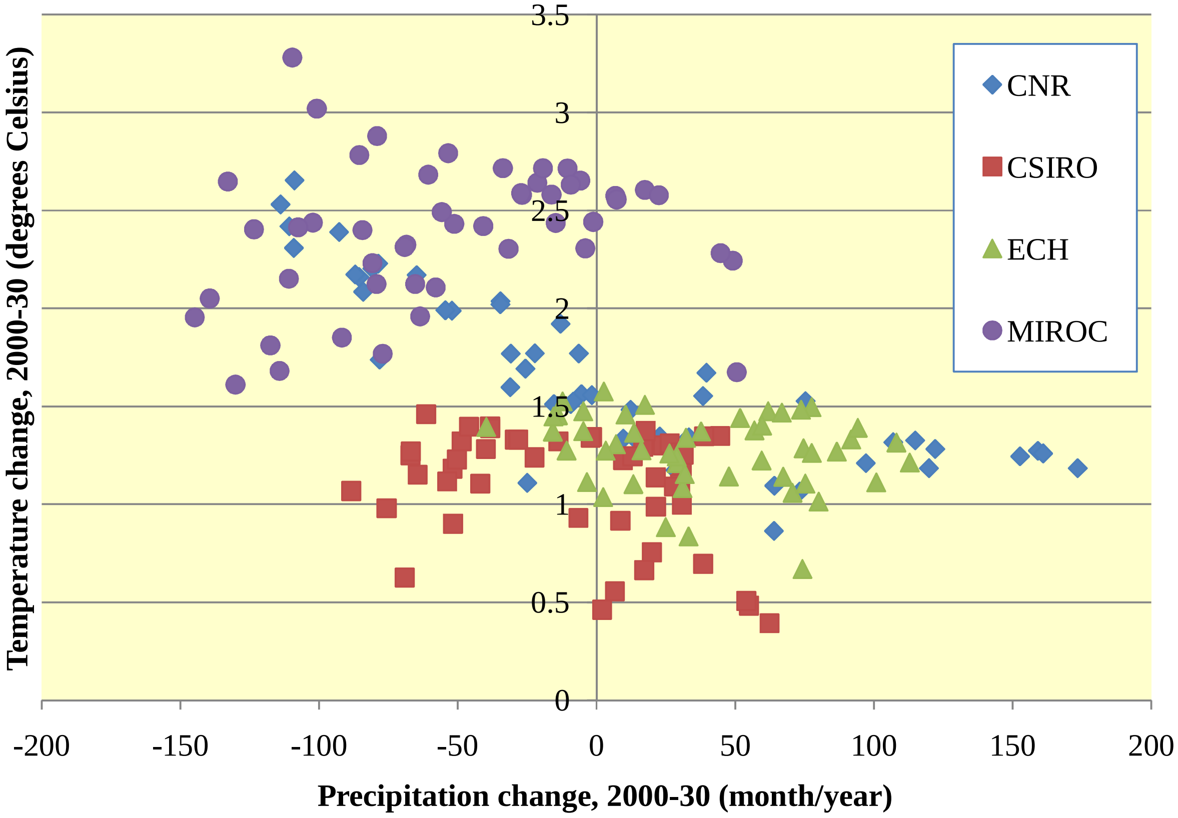
Source: Paul Westcott, personal communication, 2011.

Table 2
General circulation models adopted for use in this study

Model name	Label	Institution	Reference
CNRM-CM3	CNR	Centre National de Recherches Meteorologiques (CNRM), Meteo France, France	Déqué et al. (1994)
CSIRO-Mark 3.0	CSIRO	Commonwealth Scientific and Industrial Research Organisation (CSIRO) Atmospheric Research, Australia	Gordon et al. (2002)
ECHam5	ECH	Max Planck Institute for Meteorology, Germany	Roeckner et al. (2003)
MIROC 3.2	MIROC	Center for Climate System Research (University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC), Japan	K-1 Developers (2004)

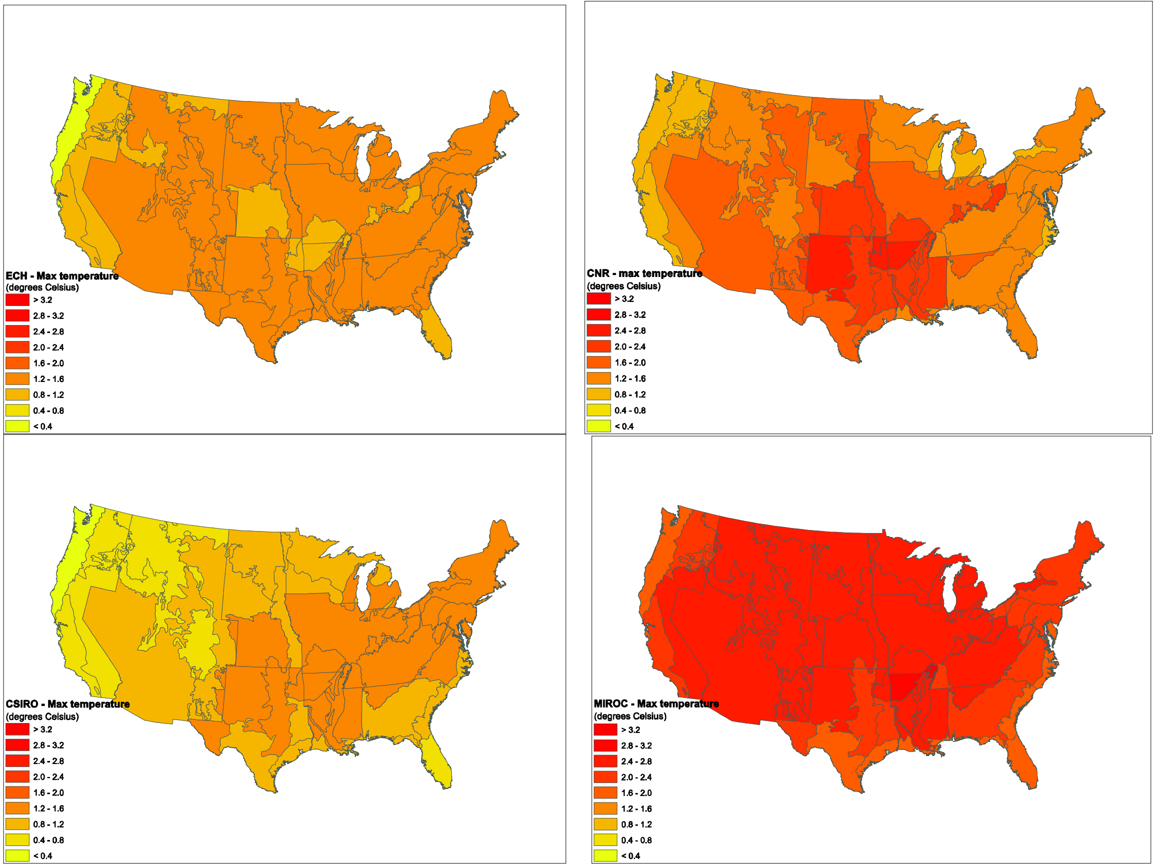
Figure 2

Estimated change in mean annual maximum temperature and precipitation for each REAP production region under the four climate change scenarios



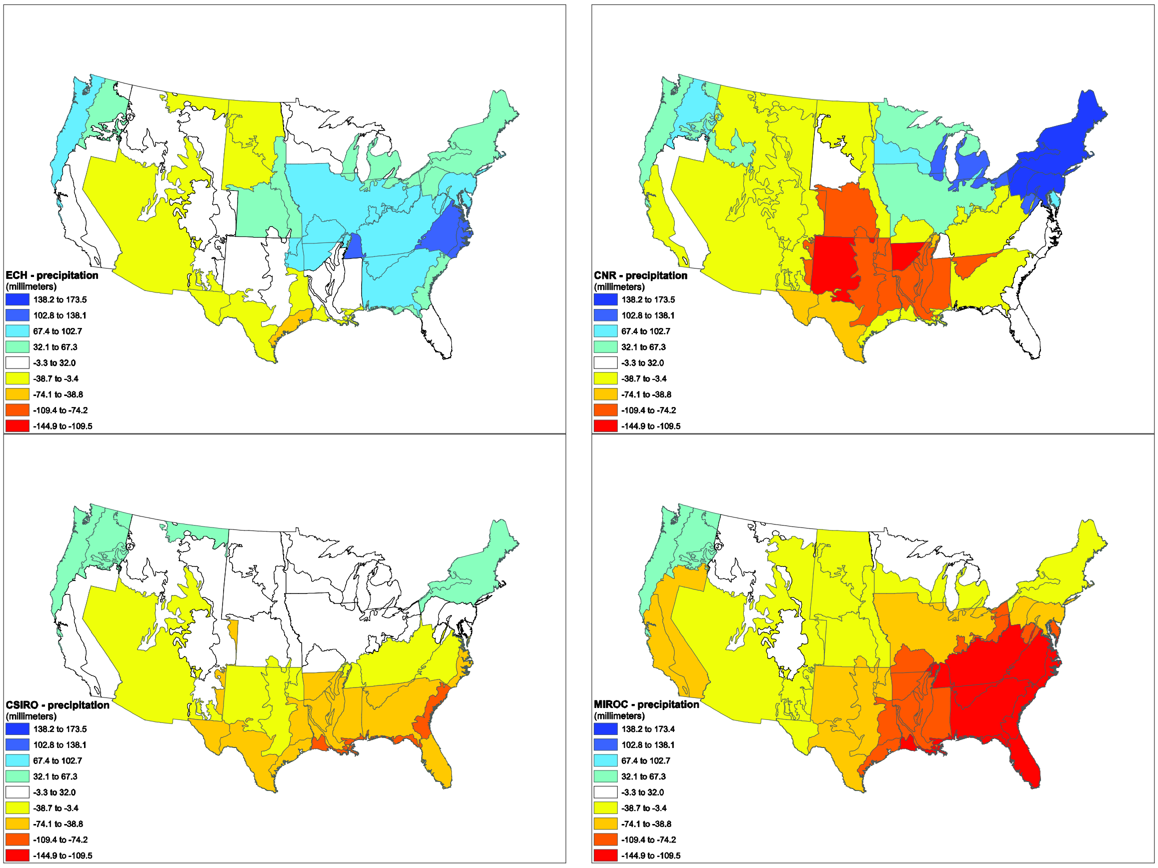
REAP=Regional Environment and Agriculture Programming.
Source: USDA, Economic Research Service calculations and Jones, Thornton, and Heinke, 2010.

Figure 3
Change in mean annual maximum temperature (degrees Celsius), from the baseline under the four climate change scenarios



Source: USDA, Economic Research Service calculations and Jones, Thornton, and Heinke, 2010.

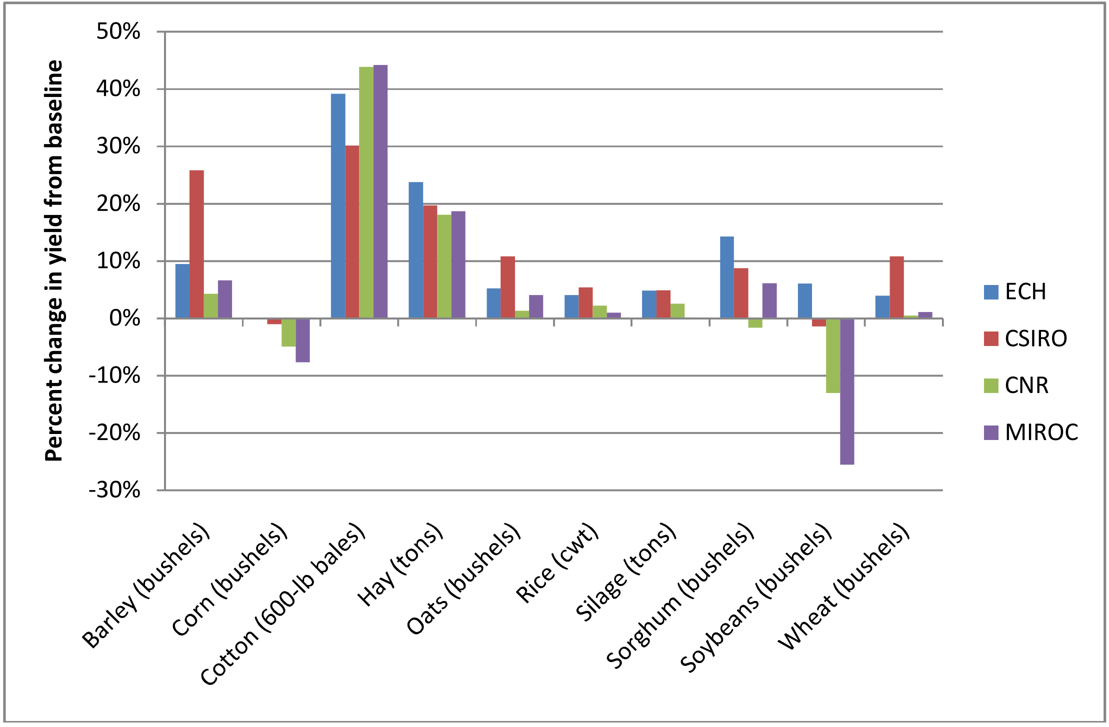
Figure 4
Change in annual precipitation (millimeters), from the baseline under the four climate change scenarios



Source: USDA, Economic Research Service calculations and Jones, Thornton, and Heinke, 2010.

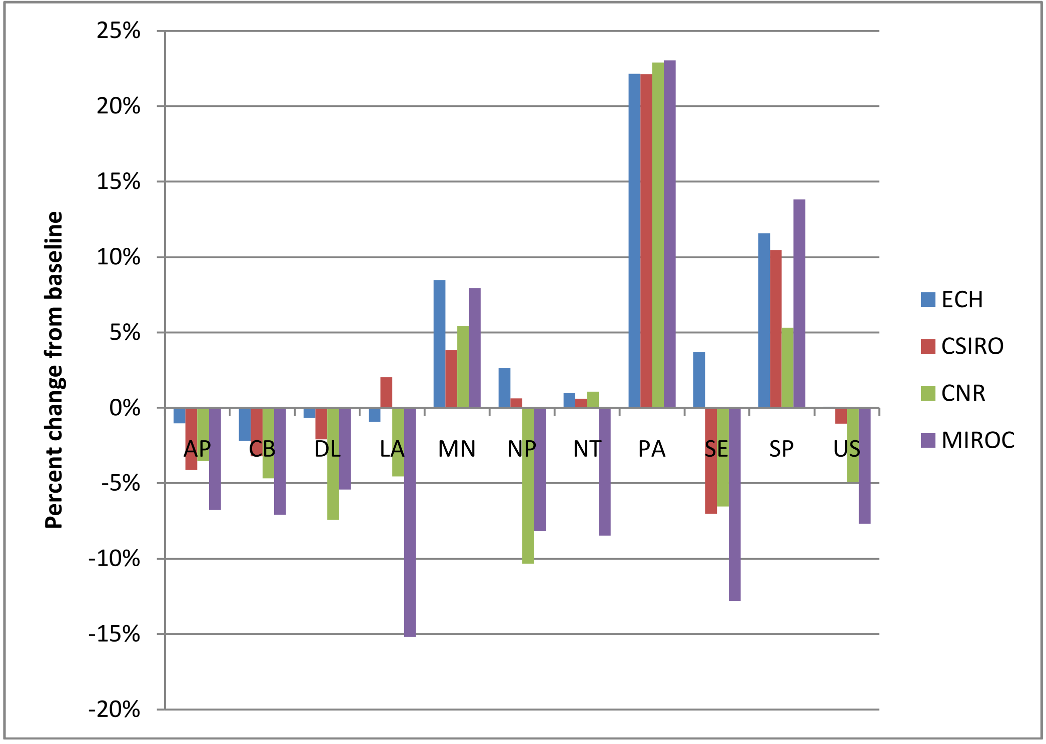
Figure 5

Changes in national average crop yield without adaptation, by climate change scenario



Cwt=Hundredweight.

Figure 6
Regional differences in national average corn yield without adaptation, by farm production region and climate change scenario



AP=Appalachia.
CB=Corn Belt.
DL=Delta.
LA=Lake States.
MN=Mountain.
NP=Northern Plains.
NT=Northeast.
PA=Pacific.
SE=Southeast.
SP=Southern Plains.

Figure 7
Price changes relative to the “no climate change baseline,” by climate change scenario

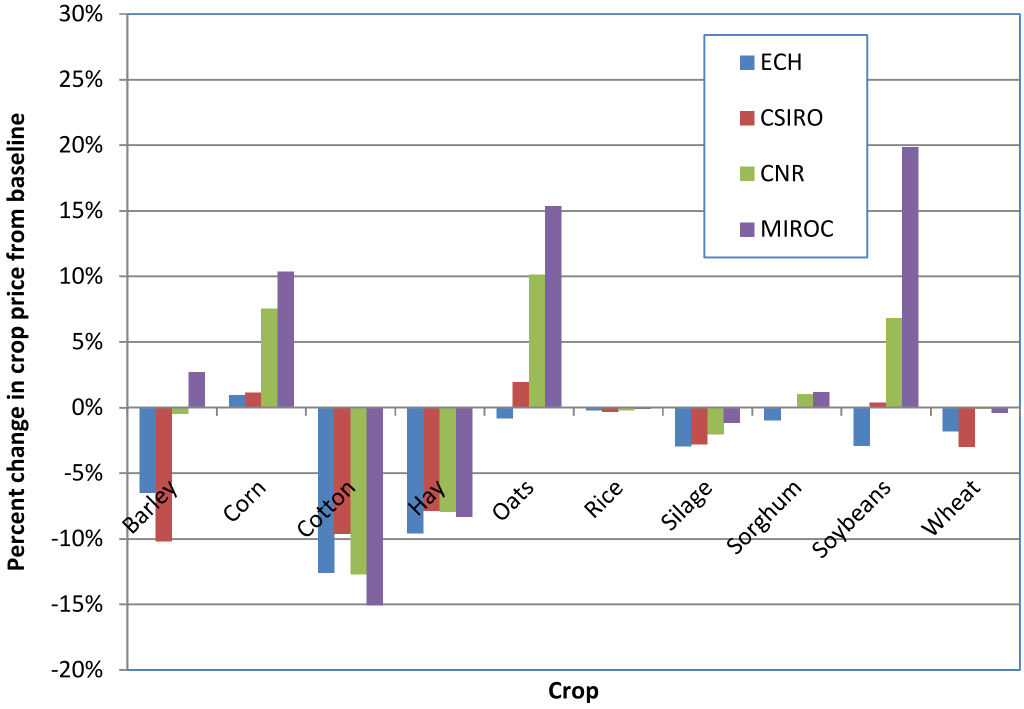


Figure 8
Changes in total regional planted acres from “no climate change baseline”

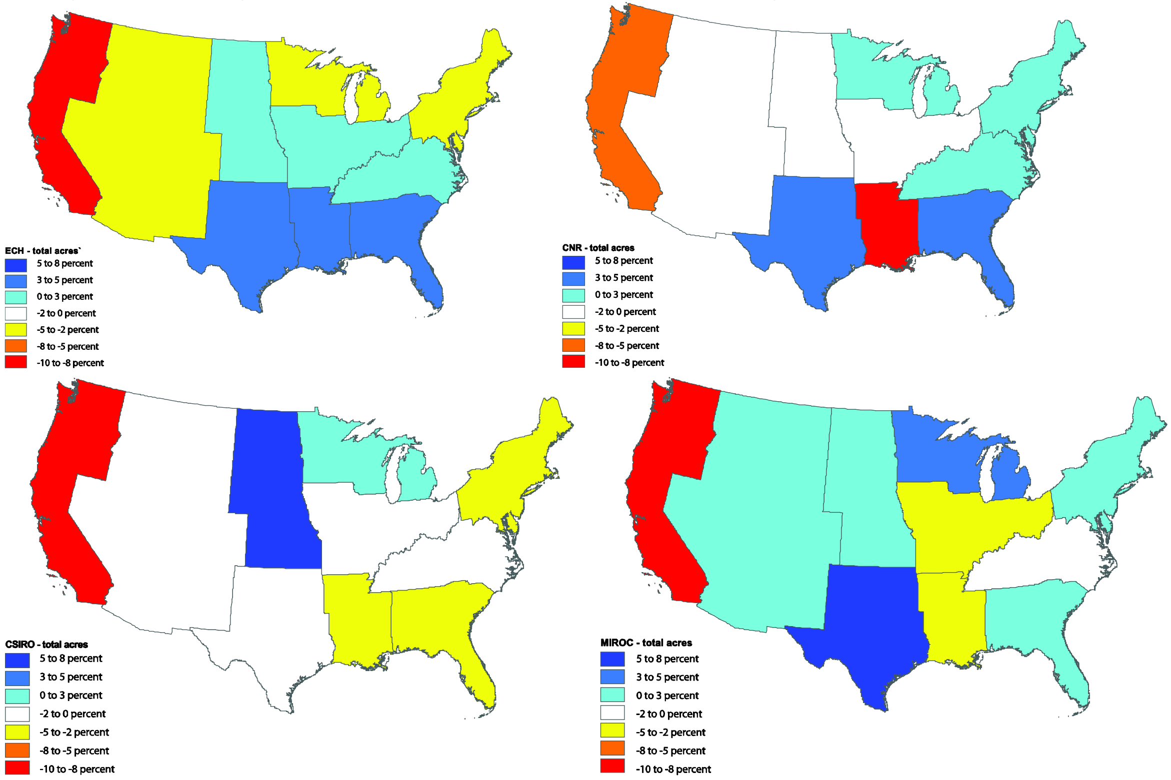


Table 3
Total U.S. acreage change, by climate adaptation scenario

	ECH	CSIRO	CNR	MIROC
	Percent change			
Total	0.6	0.6	0.2	1.0
Corn	1.7	2.8	3.0	4.2
Wheat	-1.1	-0.2	1.0	0.8
Soybeans	1.4	1.0	-2.8	-1.8
Other crops	-0.1	-1.5	-0.2	0.5

Figure 9
Changes in regional planted corn acres from “no climate change baseline”

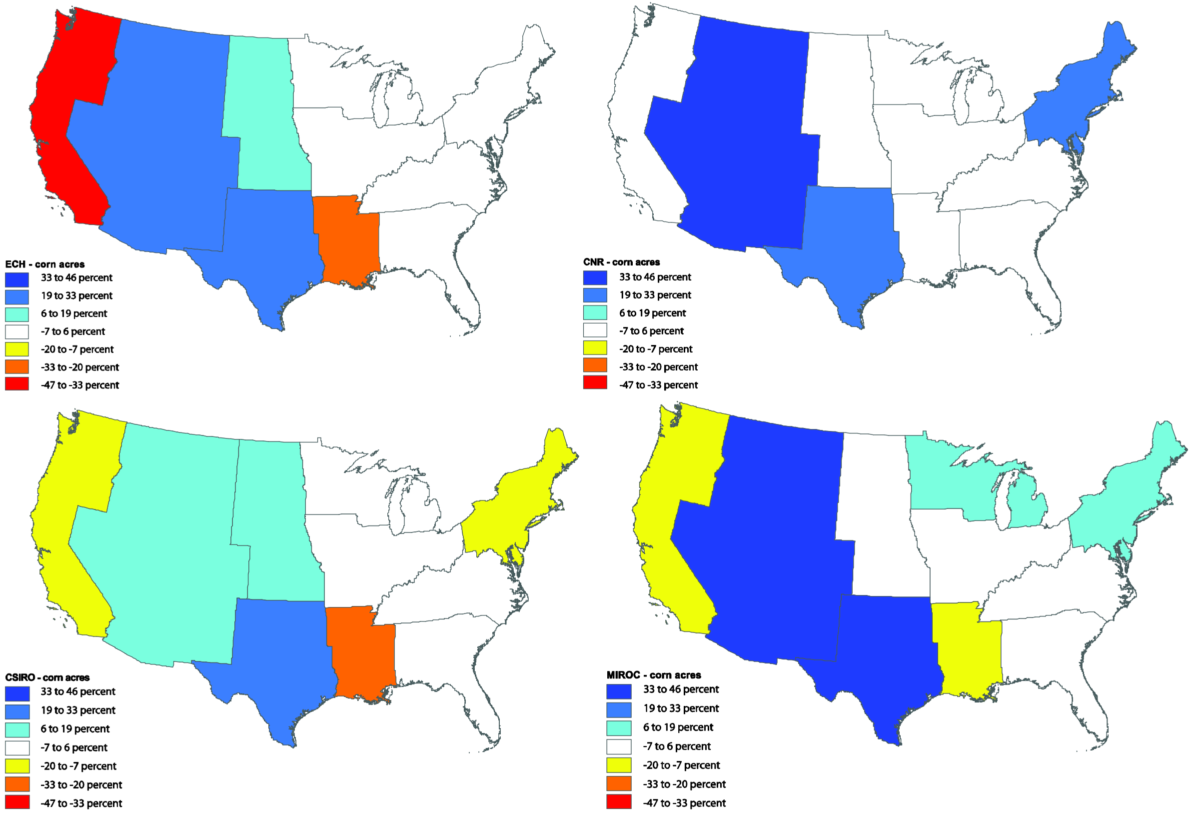


Figure 10
Changes in regional planted wheat acres from “no climate change baseline”

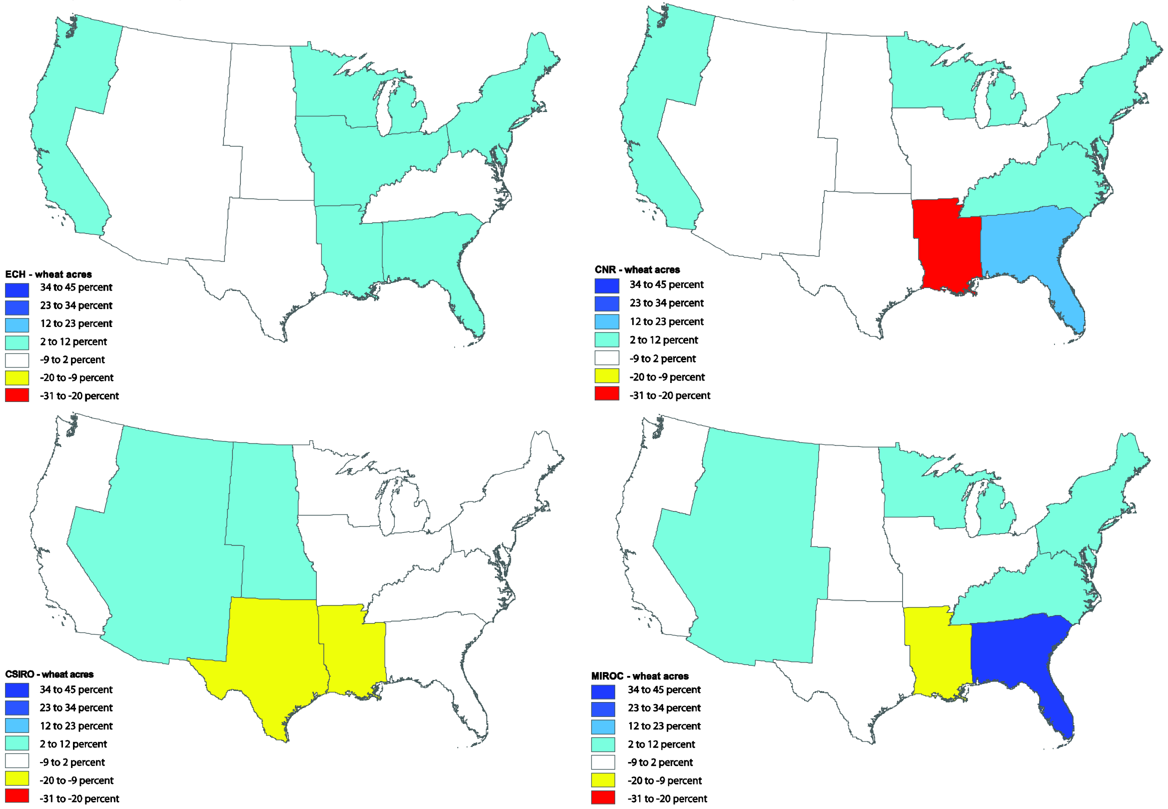
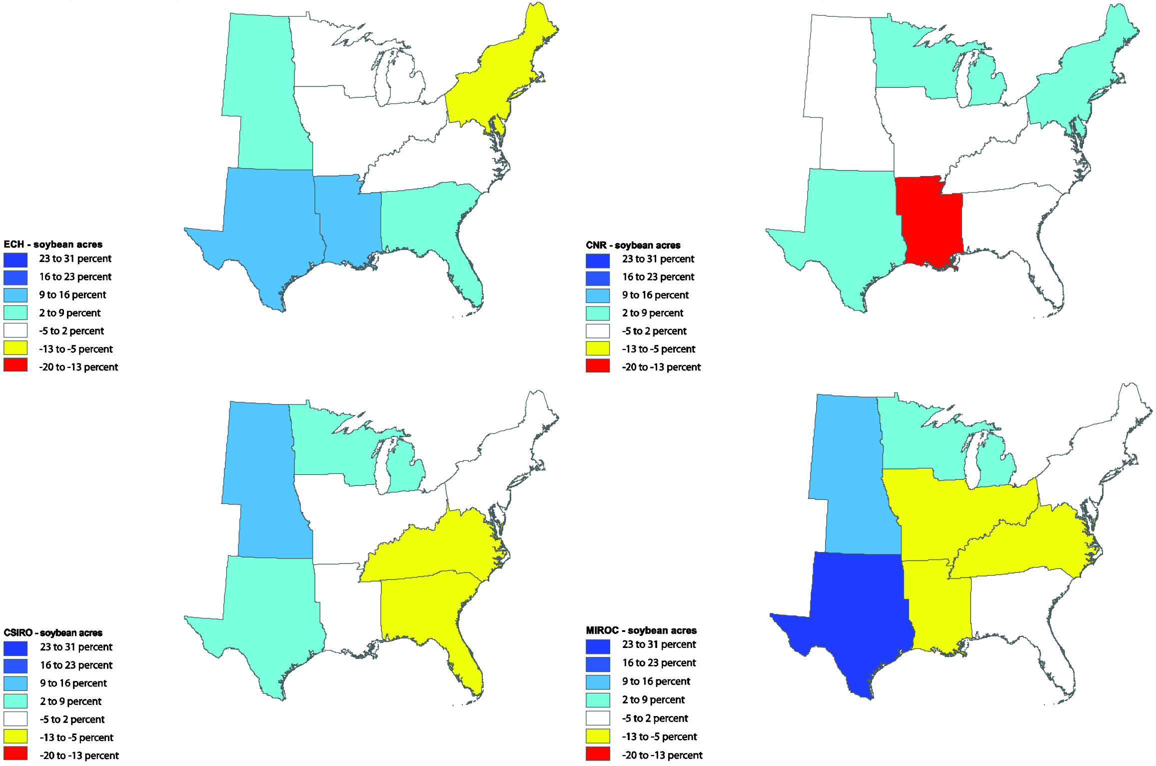


Figure 11
Changes in regional planted soybean acres from "no climate change baseline"



Note: Soybeans not cultivated in Pacific and Mountain regions.

Table 4
Change in crop prices from “no climate change baseline”

	ECH	CSIRO	CNR	MIROC
		Percent change		
Corn	-2.2	-2.1	3.7	6.0
Wheat	-1.6	-5.9	-0.8	-1.0
Soybeans	-3.5	0.3	7.6	22.1

Table 5
Change in returns to crop production from “no climate change baseline”

Crop	ECH	CSIRO	CNR	MIROC
		Million dollars		
Corn	-742	-839	-33	-223
Wheat	-10	332	-265	-456
Soybeans	1361	-180	-2772	-3412
Cotton	1135	1081	1474	1266

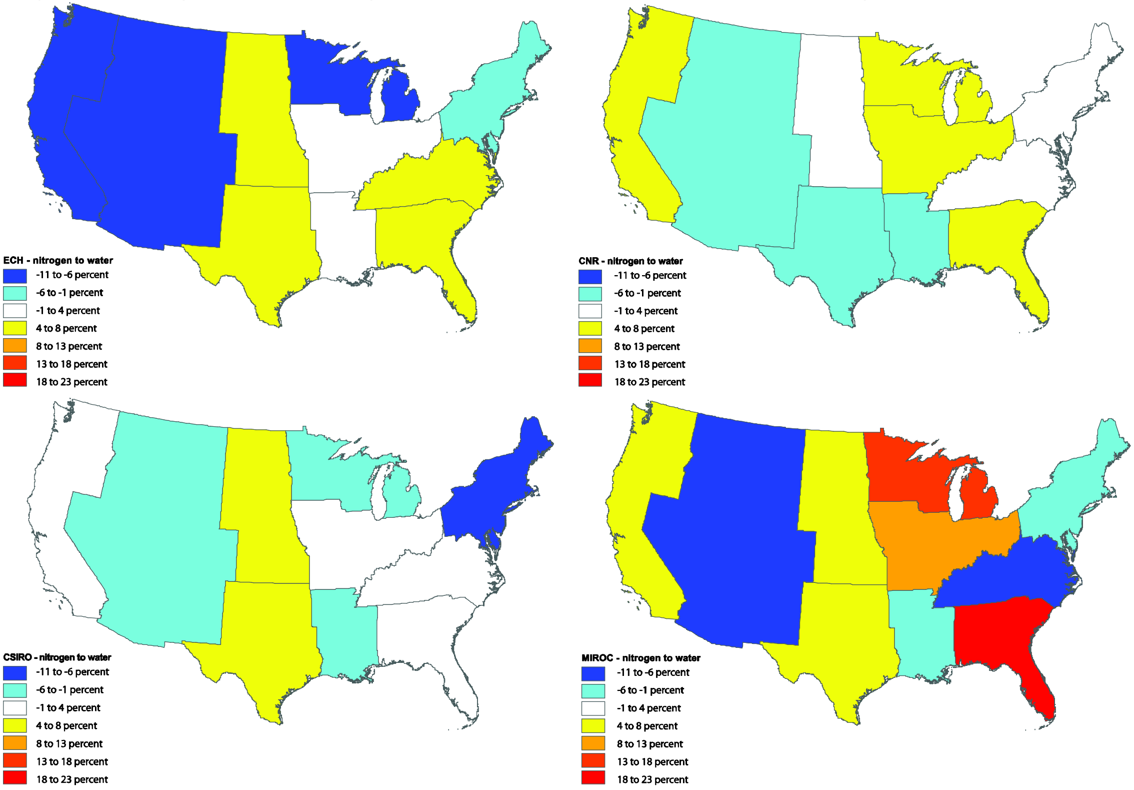
Table 6
Changes in returns to crop production from “no climate change baseline”

Region	ECH	CSIRO	CNR	MIROC
		Million dollars		
Corn Belt	-1114	-2165	-2112	-4053
Delta	904	167	-521	-146
Lake States	41	902	1001	-37
Northern Plains	1256	1671	-914	255
Southern Plains	418	322	7	681
U.S. total	3619	2165	-332	-1465

Table 7
Change in total U.S. planted acreage and select environmental measures from “no climate change baseline”

Environmental measure	ECH	CSIRO	CNR	MIROC
		Percent		
Total acreage	0.6	0.6	0.2	1.0
Nitrogen loss to water	1.4	1.5	2.1	5.0
Soil erosion	0.3	2.2	4.3	7.7

Figure 12
Regional change in total nitrogen loss to water from “no climate change baseline”



See table 4 for the sources of the CNR, CSIRO, ECH, and MIROC models.

Figure 13
Regional change in total soil erosion from “no climate change baseline”

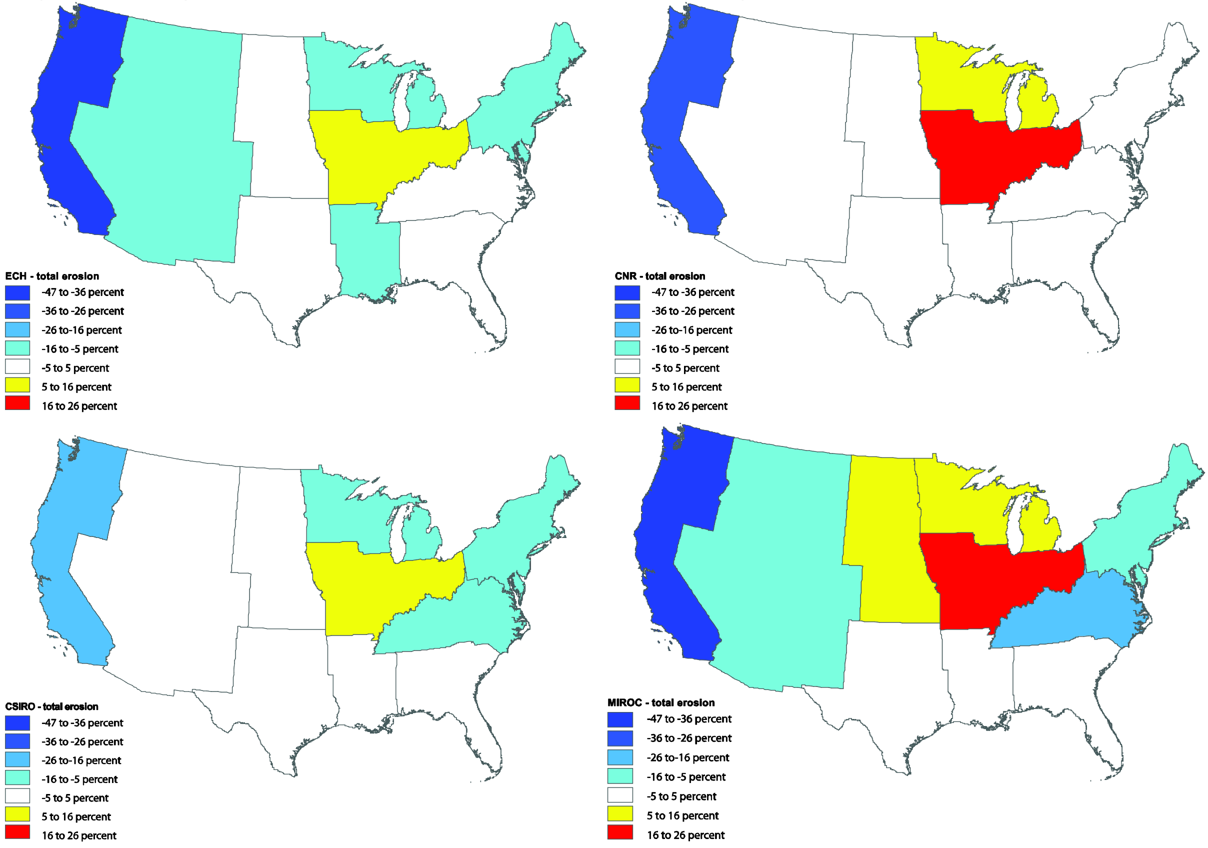


Figure 14
Regional change in total acreage, from “no adaptation case” to “adaptation case”

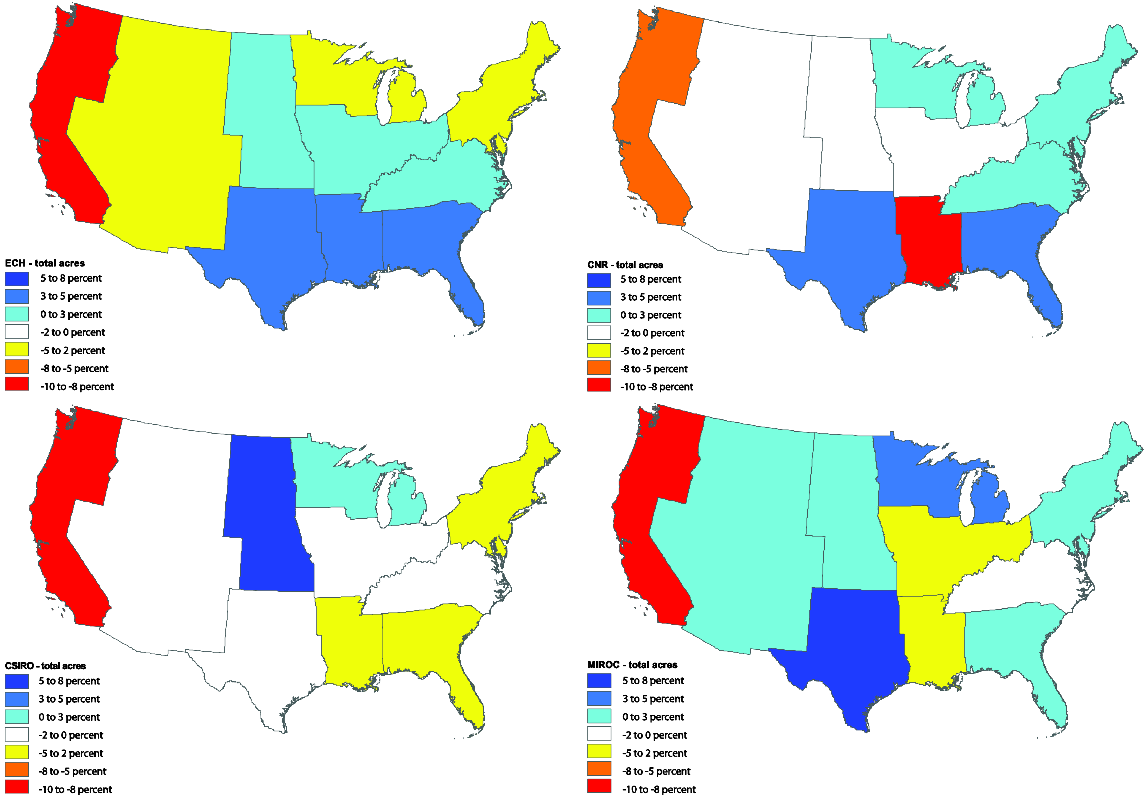


Figure 15
Regional change in corn acreage from “no adaptation case” to “adaptation case”

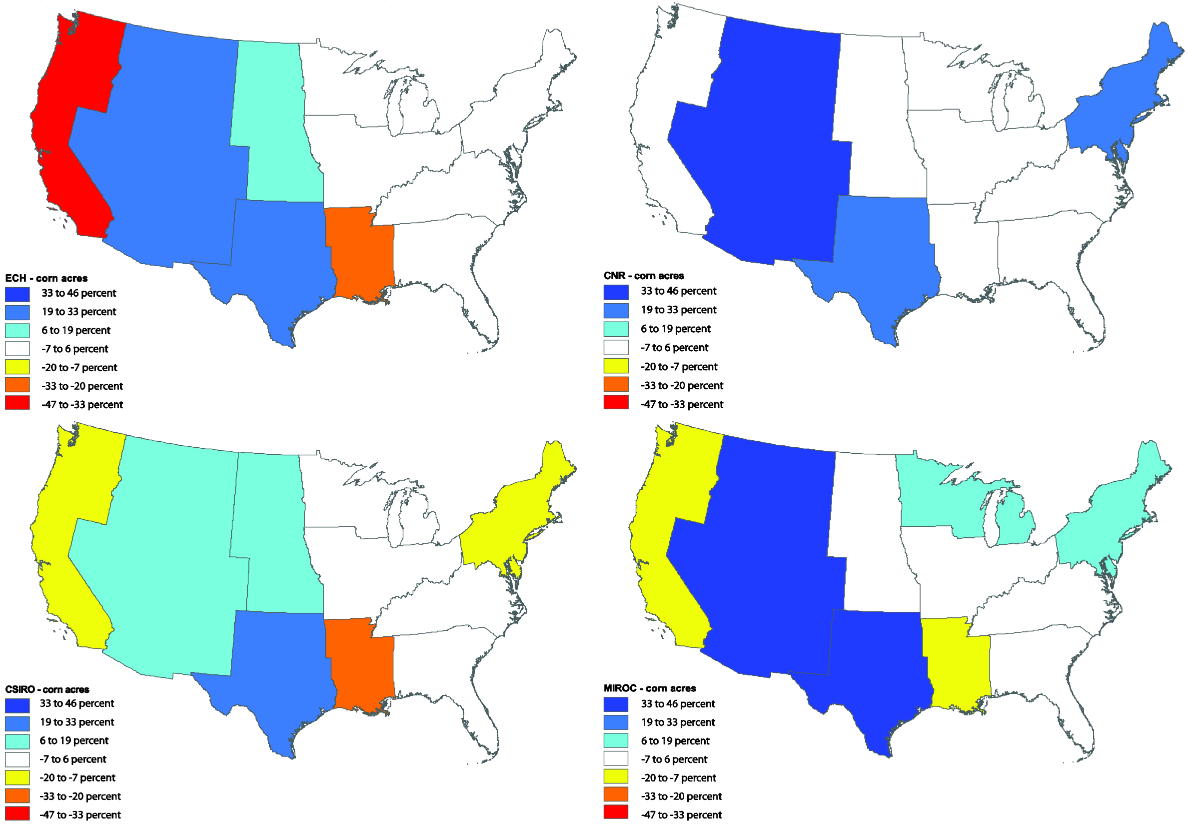


Table 8
Price difference from “no adaptation case” to “adaptation case,” by crop

Crop	ECH	CSIRO	CNR	MIROC
		Percent change		
Corn	-3.2	-3.2	-3.6	-3.9
Sorghum	-1.1	-1.8	-1.1	-1.2
Barley	2.1	2.6	-1.6	-2.9
Oats	-0.6	-0.4	-8.7	-7.1
Wheat	0.2	-3.0	-0.7	-0.6
Rice	0.0	-0.3	-0.4	-0.3
Soybeans	-0.6	-0.1	0.7	1.9
Cotton	-8.2	-5.5	-5.7	-9.0
Silage	0.9	0.7	0.5	0.3
Hay	0.3	0.6	0.5	0.8

Table 9
Direction of change in returns to crop production from “no adaption case” to “adaptation case,” by region

Region	ECH	CSIRO	CNR	MIROC
Appalachian	↑	↑	↑	↑
Corn Belt	↓	↓	↓	↓
Delta	↑	↑	↑	↑
Lake States	↑	↑	↓	↓
Mountain	↑	↑	↑	↑
Northern Plains	↑	↑	↑	↑
Northeast	↓	↓	↓	↓
Pacific	↑	↑	↑	↑
Southeast	↑	↑	↑	↑
Southern Plains	↑	↑	↑	↑
U.S. total	↑	↑	↓	↓

Table 10
Change in total U.S. planted acreage and select environmental measures from “no ddaptation case” to “adaptation case”

Environmental measure	ECH	CSIRO	CNR	MIROC
		Million acres		
Total acreage	1.8	1.8	0.8	3.2
		Percent change		
Total acreage	0.6	0.6	0.2	1.0
Nitrogen loss to water	4.2	4.0	1.7	3.6
Soil erosion	4.4	4.2	3.8	3.4

Figure 16
Regional change in nitrogen loss to water from “no adaptation case” to “adaptation case”

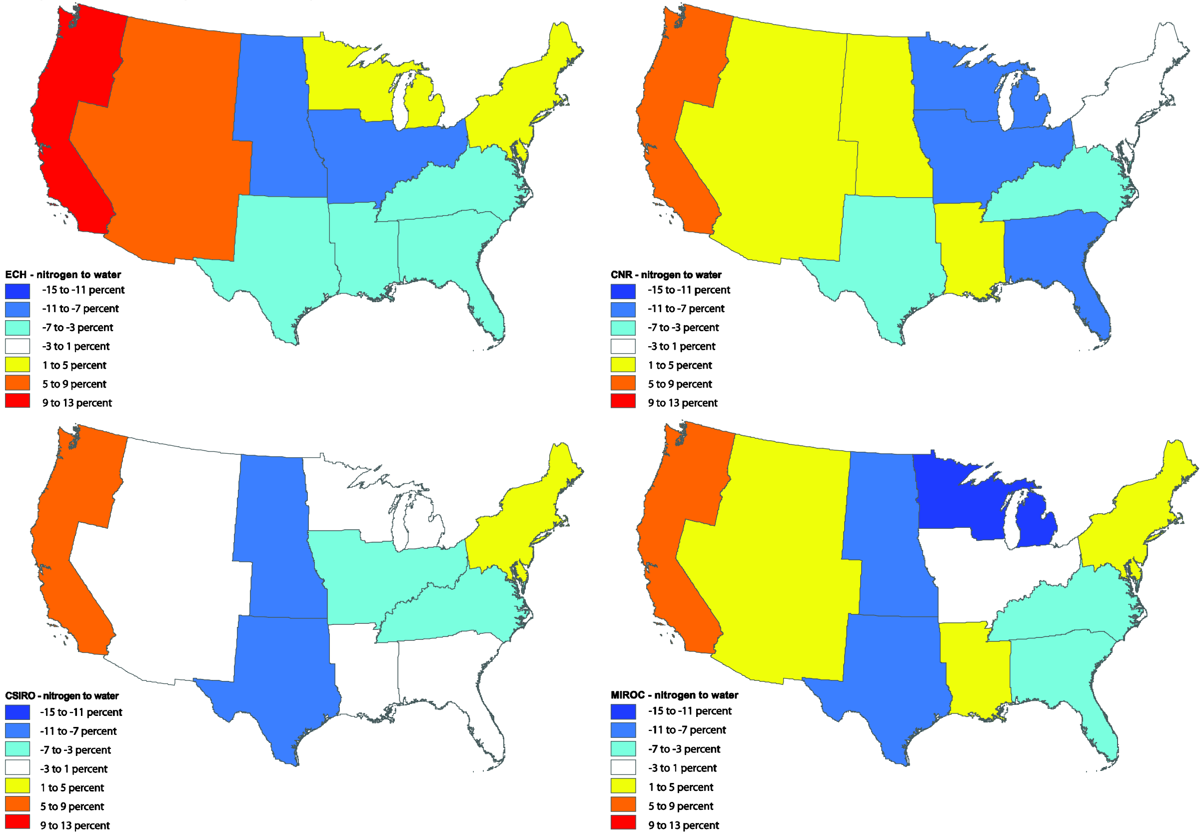


Figure 17
Regional change in total soil erosion from “no adaptation case” to “adaptation case”