Agricultural Production under Climate Change: The Potential Impacts of Shifting Regional Water Balances in the U.S.

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Abstract

General circulation models predict significant and accelerating changes in local patterns of precipitation and temperature over the next century. The vulnerability of agriculture to climate change will depend on both the biophysical impacts of climate change on crop yields and on the agricultural system's ability to adapt to changing production conditions. Shifts in the extent and distribution of irrigated and dryland production are a potentially important adaptation response. Farmer flexibility to adapt may be limited, however, by changing availability of irrigation water under future climate conditions. This study uses a suite of models to explore the biophysical and economic impacts of climate change on U.S. fieldcrop production under several potential future climate projections, and the potential limits and opportunities for adaptation arising from shifting regional water balances. Study findings suggest that the impacts of irrigation shortage on cropland use vary by region but that the net impacts on national production of surface-water irrigation shortages attributable to climate change are small relative to the direct biophysical impacts of climate change on yield.

Key words: climate change, adaptation, agriculture, irrigation shortage, water resources, Regional Environment and Agriculture Programming (REAP) model, regional crop production.

Production enterprises and practices in agriculture are adapted to variability in local climate conditions, as farmers have developed strategies for responding to the weather patterns that have historically prevailed in their region. However, the range of local weather conditions that has shaped the current structure of U.S. agricultural production is itself changing in response to shifts in climatic conditions across the country and around the world. General climate conditions have warmed slowly throughout the 20th century, with an increase in global average temperature of 1.1 degree F (Walthall et al. 2012). The rate of increase appears to be accelerating, however, with rising carbon dioxide (CO_2) concentrations in the atmosphere. Global climate models predict further rapid increases in average temperature that are likely to have significant impacts on local patterns of temperature and precipitation.

The accelerating pace of climate change presents new challenges for farmers as they are forced to respond to conditions that are outside of historical ranges, including the increasing incidence of extreme weather conditions. Producers may adapt to shifting production conditions through various adaptation strategies, including changes in cropland extent, cropping mix and planting/harvest dates, a shifting reliance on irrigation and other applied inputs, and adoption of improved production management technologies and drought-tolerant crop varieties. Agriculture's vulnerability to climate change, or, conversely, its capacity to adapt, is likely to vary regionally, given the heterogeneity in regional resources and projected changes in temperature and precipitation patterns. While some regions face declines in crop growth potential, others may see improvements. Rising temperatures and shifting rainfall patterns will affect seasonal changes in crop-soil moisture and growing season precipitation for dryland production. Furthermore, the impacts of climate change on water availability will also vary regionally (Elliot et al. 2014), with implications for each region’s flexibility to adapt to climate change through shifts in irrigated acreage.

Irrigation adoption has been suggested as an important adaptive response to lessening the adverse effects of climate change on crop production. However, changes in the availability of water supplies may limit potential for irrigation expansion in some areas. Meanwhile, irrigation demand is projected to shift over time in response to changes in precipitation patterns, crop-water requirements, and resulting adjustments in cropping patterns and production technologies. Potential shifts in the distribution of irrigated and dryland acreage will depend on the future viability and relative profitability of irrigated and dryland production systems as well as on regional adjustments in irrigation water supply. Climate changes that alter the relative profitability of regional crop production may drive production migration across regions, with significant implications for local producers. Furthermore, changes in surface-water storage, combined with increasing demands for water by other sectors (eg., municipal and energy sectors) over the next century, may exacerbate water shortages and potentially limit the availability of irrigation water in some regions. Assessing the potential impacts of climate change on the agricultural sector requires the ability to differentiate among regional impacts and allow for shifts within and across production regions in response to changing climate regimes.

A significant body of research has addressed the impacts of climate change on water resources (NWAG 2000; Thomson et al. 2005; IPCC 2007; USCCSP 2008; USDI 2011; Elliot et al. 2014). While global circulation models are fairly consistent in predicting temperature increases under GHG emission assumptions, there remains considerable uncertainty about both future precipitation patterns and regional effects on hydrologic systems. Nonetheless, some general trends in precipitation patterns have emerged from the climate modeling literature.

Annual precipitation is projected to increase across the northern U.S. latitudes, with potential for declining levels in other regions (IPCC 2007; TNC 2009). Changes in annual precipitation may be accompanied by a shift in seasonal precipitation, with a greater share falling in the winter and early spring. Rising temperatures would interact with shifting precipitation regimes, contributing to increased drying conditions during the late-spring and summer growing season across much of the U.S. Climate projections also suggest the potential for more extreme weather events, with greater storm intensity and increased frequency and severity of drought.

A changing water cycle will have differing effects on water availability for dryland and irrigated production systems. Dryland production may be particularly sensitive to shifting climatic factors, as soil moisture available for crop growth is directly affected by changes in precipitation and evaporation during and prior to the growing season. The net change in soil moisture will vary regionally, depending on whether higher evaporative losses with rising temperatures are offset or exacerbated by changes in precipitation. Changes in the seasonality of precipitation may also have differing crop-level effects, reflecting the seasonal timing and duration of crop growing seasons. Projected increases in seasonal and inter-annual variability of precipitation would have particularly important implications for dryland systems. Heightened storm intensity increases field water runoff, reducing the share of precipitation that infiltrates the crop root zone (SWCS 2003). In areas subject to warmer and drier conditions, projected increases in drought frequency and severity may increase annual variability of dryland yields. The capacity of local soils, tillage systems, and crop rotations to retain available moisture during drought will be important factors in the continued viability of dryland production.

In arid areas of the western U.S. where soil moisture reserves are generally low and crop-water demands are high, irrigation provides the primary share of crop-water requirements in most years. While irrigation reduces the risk of uncertain seasonal rainfall associated with dryland production, irrigators may be subject to variability in the availability and cost of purchased water supplies. Surface-water sources account for roughly 58 percent of water withdrawals for irrigated crop production nationally, with the remaining 42 percent supplied by groundwater (Kenny et al. 2009). Sources of irrigation water may be differentially affected by climate change. Climate change is likely to have an especially important impact on surface-water resources, given the importance of regional precipitation on water runoff and surface water flows.

Previous studies have examined potential shifts in U.S. freshwater supplies and crop irrigation requirements under climate change, as well as implications for national and regional irrigated acreage. In an extension of the 2000 National Climate Assessment analysis, Reilly et al. (2003) report a net decrease in national irrigation water demand of approximately 5-12 percent for 2030 and 34-38 percent for 2090, with irrigated acreage declines of 3-10 and 40-50 percent. In general, cropland contracts with temperature stress across the southern tier states, with irrigation declines concentrated in the western states (Reilly et al. 2003). In a study of elevated CO_2 effects on water regimes and implications for U.S. grain production, Thomson et al. (2005) report declines in national water demand for irrigated corn, soybean and winter wheat under all scenarios considered. In the two studies, a potential shift to dryland production reflects both increased precipitation in some areas and the differential effects of climate on irrigated and dryland crop productivity. In a third study of constraints and potentials for global irrigated agriculture, Elliott et al. (2014) suggest significant declines in irrigated area in the western U.S. due to increasing water scarcity; potential for irrigation expansion in the eastern U.S. may be limited by costs of water access. The study highlights the sensitivity of irrigation demand projections to estimated CO2 effects on crop production (Elliott et al, 2014).

This study explores at a relatively fine regional scale the differential impact of climate change on dryland and irrigated production systems under future climate conditions within the United States, focusing on changes in the relative profitability of dryland versus irrigated production arising from yield and production cost impacts under changed climate conditions. This analysis decomposes the potential regional irrigated acreage response under climate change into the effects arising from 1) economic drivers related to changing patterns of comparative advantage across irrigated and dryland production and 2) constraints on the availability of irrigation water supplies. The analysis explores whether constraints to irrigation that arise due to water-supply scarcity will substantially limit farmer adaptation options and how that dynamic varies regionally.

Methodology

In this research, we apply a suite of models and supporting data bases to explore the dynamics of climate change, water resources and producer adaptation (figure 1). Downscaled climate data under several potential climate projections for the period 2000-2090 are used to estimate the regional biophysical impacts of changing climate conditions on yields and crop irrigation requirements. These regional impacts are then used as inputs in an economic model of the U.S. agricultural sector to explore the producer and consumer response to those impacts, and the combined effect on regional and national estimates of production, prices, farm returns, and other measures of producer and consumer welfare.

Downscaled climate data, and the potential regional water shortages associated with each scenario, were developed by Colorado State University and the USFS Rocky Mountain Research

Station (Foti, Ramirez, and Brown 2012). Nine future climate scenarios were explored, which include three different General Circulation Models (GCMs) applied to each of three of the emissions scenarios in the IPCC Special Report on Emission Scenarios (SRES)—the A1B, the A2, and the B2.[1]

The three emissions scenarios considered each represent a distinct storyline about potential future development and resulting carbon emissions. The A1B emissions scenario is considered a "middle of the road" projection characterized by rapid economic growth, the introduction of energy-efficient technologies, and a balanced portfolio of energy sources (IPCC, 2007). The A2 emissions scenario is a higher-emissions scenario characterized by rapid population growth and more fragmented, slower regional growth. The B2 emissions scenario is a lower-emissions scenario representing lower population growth and intermediate economic development.

Because there is large variability in the output climate values across general circulation models (GCMs) for a single emissions scenario, each emissions scenario was run through three separate GCMs to derive a range of possible climate outcomes associated with each future emissions scenario. The climatic implications of the A1B and A2 emissions paths were estimated using the following GCMs: the Canadian Centre for Climate Modeling and Analysis Coupled Global Climate Model, Version 3.1, Medium Resolution (hereafter CGCM), the Australian Commonwealth Scientific and Industrial Research Organization Mark 3.5 Climate System Model (hereafter CSIRO), and the Japanese Center for Climate System Research Model for Interdisciplinary Research on Climate, Version 3.2, Medium Resolution (hereafter MIROC). Results for the SRES B2 emissions path were generated by the following GCMs: The Canadian Centre Model, Version 2 (hereafter CGCM); the Australian Commonwealth model CSIRO Mark

2 (hereafter CSIRO), and the United Kingdom Met Office Hadley climate model (hereafter HADN) (table 1). See Joyce et al. (2011) for more details on development of the climate scenarios.

Surface-water supply and demand under 9 climate scenarios were estimated by Foti, Ramirez, and Brown (2012) for 98 water basins, or Assessment Sub-regions (ASRs), in the contiguous 48 U.S. states. The GCM results were downscaled for use at the ASR level using a two-step downscaling and bias correction process that downscaled GCM output to the 5-km grid resolution used in the water yield estimation model and adjusted for bias using first 30 years and then 8 years of historical data (Foti, Ramirez, and Brown 2012). While our study focuses on climate-induced changes in surface-water supplies, our estimates of irrigation availability under future climate scenarios also include rough projections of groundwater withdrawal reductions for selected basins, which are derived from USGS data series and supporting literature and are assumed to be fixed across climate futures.

Crop production for a given region and soil type is simulated using the biophysical simulation model EPIC (Environmental Policy Integrated Climate model). EPIC is a field-scale crop response model that uses a daily time step to simulate crop growth as well as soil impacts, hydrology, nutrient cycling, and pesticide fate under different tillage, crop rotation, soil and nutrient management, and weather scenarios. For the simulation of crop production, our regional analysis divides crop production in the United States into 267 regions, as defined by an overlay of the ASRs (defined by hydrological boundaries), land resource regions, and farm production regions (figure 2). Climate impact and adaptation analyses were conducted for four future time frames. Climate conditions for the 2020 time frame are calculated as average conditions across projected years 2011-2030, those for 2040 are averaged across 2031-2050, those for 2060 are averaged across 2051-2070, and those for 2080 are averaged across 2071-2090. “Reference” climate conditions are defined by an average over 2001-2008 conditions for the CGCM_A2 estimation scenario.[2] See Foti, Ramirez, and Brown (2012) and Joyce et al. (2011) for more information about the derivation of the underlying climate projections and detailed characteristics of those projections under each climate scenario and year of analysis. Interested readers can find additional, more detailed information on the crop modelling methodology used in this analysis in appendix A.

Regional Environment and Agriculture Programming Model

The Regional Environment and Agriculture Programming Model (REAP) is a mathematical optimization model that quantifies agricultural production and its associated environmental impacts for 267 production regions across the United States. REAP allocates production acreage among a discrete set of crop rotations available to each region and allocates the resulting agricultural products among a set of markets--including feed use, various processing sectors, other domestic use, and exports-- in order to maximize the economic surplus resulting from that production. REAP includes 10 major commodity crops (corn, sorghum, oats, barley, wheat, rice, cotton, soybeans, hay, and silage), a number of livestock enterprises (dairy, swine, poultry, and beef cattle), and a variety of different processing technologies used to produce retail products from agricultural raw materials. Although optimal cropping patterns are determined at the more disaggregated level of the REAP region, results are generally aggregated up to USDA’s Farm Production Regions (blocks of color in figure) for presentation.

Each REAP production region includes a set of available crop rotations that are implemented using one of up to three tillage practices, and are available in either dryland or irrigated production (or both). The combination of rotation, tillage practice, and irrigation practice is referred to as a production enterprise and represents the basic unit of crop production economic activity in the REAP model. The selection of available production enterprises for each region was derived from the 2007 National 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 available production enterprises based on an assessment of relative rates of return arising from differences in yields, costs, and returns, and is further constrained by a nested set of CET constraints representing acreage distribution constraints that are parameterized to capture historically observed patterns of production (see Malcolm et al. (2012) for more information about REAP).

To form a reference against which climate change impacts are measured in future time periods, we designed a set of agricultural production conditions for future time periods that reflect a world in which patterns of production continue to change in response to historically observed dynamics (changing population, diet, demographics, and other socio-economic factors), but without climate change. Conditions for that "reference scenario" are developed for 2020, 2040, 2060, and 2080; the reference scenario reflects one set of plausible expectations about how prices, acreages, and yields might change over the next 70 years in the absence of climate change. This reference scenario was developed based on a combination of expert input, literature, and a modified extrapolation of the USDA's current 10-year baseline forecast.

For each analysis year, REAP's acreage distribution parameters, and the yield output and environmental impact estimates from the EPIC model, are calibrated to the reference scenario such that the portrait of agriculture emerging from the model's reference optimization—average yields, production level, crop production acreage, and prices—matches that specified by the reference projection for that time period. The adjustment to EPIC's yield output corrects for yield biases that existed in the original EPIC outputs and reflects changes in crop technology that are projected to occur between current yield estimates and those of the analysis year. Calibration of REAP's acreage, production, and environmental impact assumptions incorporates information on irrigated cropping rotations from the National Resources Inventory as well as supporting data on irrigated/dryland crop acreage (NASS/AgCensus), irrigation application rates (FRIS/EPIC), irrigated costs (ARMS), water-supply source (USGS), and tillage and fertilizer use (ARMS).

The optimal allocation of acreage in REAP is sensitive to climate through the effect of climate conditions (or, more precisely, the impact of the weather that arises under different sets of long-term climate conditions) on agricultural productivity and yield, as well as on how that impact varies regionally. The impacts of climate change on agricultural production are then assessed by substituting into REAP the regional yield and cost estimates for production enterprises that were derived using the climate change projections. These yield impacts are introduced into REAP to explore how surplus-optimizing production decisions are likely to change under each of the climate change projections with altered patterns of crop productivity and irrigation demand by region and over time. Implications of climate change for acreage allocation and crop production are generated for each of the nine future climate scenarios and four different analysis periods. We first explore acreage allocation in an adaptation scenario that does not include a consideration of future water shortages and then examine how crop production and acreage allocation is likely to be impacted by reductions in irrigation water supply estimated for each of the future climate scenarios and analysis periods.

Analysis of irrigation water availability

The changing availability of water resources under climate change is captured in our second analysis scenario by estimating irrigation shortages for each REAP region, analysis year, and climate scenario that may arise due to changes in precipitation as well as changes in demand from other water-consuming sectors. Irrigation water-supply adjustments under the climate change scenarios reflect projected changes in surface-water availability. When considering irrigation constraints on production, however, the reference scenario against which climate impacts are measured includes estimates of irrigation shortages arising from reduced groundwater withdrawals over time as such shortages are assumed to be independent of climate change projections. Reference levels of irrigation water use by REAP region are then estimated for each analysis year based on reference crop model acreage allocations and EPIC-generated estimates of irrigation water use per acre under the reference climate conditions. Relative to that reference case, irrigation shortages under each climate change projection are calculated as a percent reduction in available irrigation water by REAP region and year.

Groundwater shortages

For purposes of this analysis, fixed declines in irrigation groundwater withdrawals over time were projected for selected REAP regions. To develop groundwater use projections, irrigated acreage was allocated by aquifer system and REAP regions using an overlay of Landsat spatial irrigation data with USGS aquifer delineations and REAP region boundaries. This overlay provides a spatial representation of the groundwater resources for model use and allows for irrigated acreage and groundwater use to be weighted by model region. The change in future withdrawals reflects various factors that are partly influenced by climate factors, including the physical stock of renewable and stored groundwater, the costs of groundwater access, interactions across surface and groundwater (ie., conjunctive systems, water source substitution), and institutional restrictions on groundwater management.

Several sources of information were used in assigning groundwater withdrawals by REAP model region. County-level groundwater withdrawals for irrigation use were obtained from USGS water-sector assessments for 1985, 1990, 1995, 2000 and 2005 (USGS 2013), and used to identify areas where groundwater withdrawals have declined in recent decades. Withdrawals trends were compared against USGS maps highlighting groundwater aquifers where pumping in excess of natural recharge has resulted in significant water-table declines (Konikow 2013; Reilly et al. 2008). Projected declines in groundwater withdrawals for major aquifer systems were also drawn, where available, from the published literature (Steward et al. 2013; Scanlon et al. 2012; UCCHM 2014).

For irrigated regions experiencing both reduced groundwater withdrawals and declining water-tables over much of their land area, groundwater supplies for irrigation were assumed to decline in a roughly linear fashion over the coming decades.[3] In areas of the southern and central High Plains, where groundwater is the predominant water source and overdraft is a serious concern, groundwater withdrawals are assumed to decline by up to 10 percent in 2020 and as high as 50 percent in 2080. Withdrawal reductions of up to 30 percent in 2080 are assumed for California's Central Valley and areas of the lower Colorado River basin. Lesser reductions of up to 10 percent in 2080 are assumed for areas of the Pacific Northwest, eastern Rocky Mountains, southern California, and southern Mississippi Delta regions (figure 3).

Changing climate conditions may affect groundwater supplies through modified rates of aquifer recharge as well as changes in groundwater demand with climate-induced adjustments in surface-water availability. While aquifer dynamics under climate change has received increasing research attention, we do not model changes in groundwater withdrawals under alternative climate futures for this analysis. Groundwater recharge is highly site-specific, based on local soils and hydrologic systems, and comprehensive projections of groundwater recharge under changing climate regimes are not currently available (Taylor et al. 2013).

Surface water shortages

Surface-water supply reductions for irrigated agriculture are based on U.S. Forest Service projections of water yield and water demand developed for climate change scenarios under the 2010 RPA Water Assessment (Foti, Ramirez, and Brown 2012). For each of the ASRs, regional water yield was estimated annually through 2090 based on downscaled estimates of temperature and precipitation. Surface-water flows are simulated in a water-routing model of U.S. river systems that accounts for inter-annual reservoir storage and inter-basin transfers. Water demand, a measure of projected water use (in the absence of annual water-supply shortages), was estimated for multiple use categories—public supply, domestic, industrial, mining, thermoelectric, livestock, aquaculture and irrigation. The estimates draw on historical records of sector-level water withdrawals and consumptive use (based on U.S. Geological Survey's five-year schedule for water assessment reporting), as well as projections of water use drivers and related adjustments in withdrawal rates (Foti, Ramirez, and Brown 2012). Potential regional water shortages are then calculated as the difference between projected water demand and water supply by ASR, after instream flow requirements are met.

Surface-water reductions by REAP model region are based on a 20-year average of reported annual (percent) water-supply shortage by ASR for 2020, 2040, 2060 and 2080. (REAP regions generally follow ASR watershed boundaries.) In using surface-water shortage values directly in our model constraints, we implicitly assume that the full water-supply shortfall by ASR is borne by the irrigated fieldcrop sector. This is believed to be a reasonable assumption as irrigated agriculture is generally the primary water use in areas facing water shortages, while the marginal value of water in irrigation is typically lower than for non-agricultural withdrawals. We also assume that higher-valued specialty crops—including vegetables, orchard and berry crops not currently included in the REAP model—are unaffected by climate-induced shortages in surface-water supplies. We further assume that non-modeled fieldcrops (eg. drybeans, potatoes, sugarbeets, peanuts, grass seed, etc.) and uncultivated pasture share regional water-supply shortfalls with modeled fieldcrops. Thus, water-supply constraints in the REAP analysis reflect net adjustments in the Forest Service's reported supply reductions based on irrigated acreage shares in specialty crops and other non-modeled crops.

Projected surface-water supply reductions range from 20 percent to more than 75 percent across areas of the Mountain, Pacific and Plains regions in 2080. While GCM climate projections suggest differences in the specific location and intensity of water-supply shortfalls, there is broad consistency in projected impacts across larger regions. Most severe declines occur in the Middle and Lower Colorado River Basin under virtually all scenarios, while other river systems with headwaters in the central Rocky Mountains and Sierra Nevada range are affected to varying degrees depending on the scenario. In general, water-supply impacts for irrigated agriculture are increasingly severe over time, with the most significant impacts occurring after 2050. Figure 4 illustrates the surface water supply shortages for the CGCM A2 climate scenario over the four analysis years.

Results

We first explore a case where farmers respond to climate change's impacts without irrigation constraints on their adaptation response; farmers are able to change crops, crop rotations, and move between dryland and irrigated production without additional constraints on available water. This baseline adaptation analysis is used to illustrate the biophysical impacts of climate change on the relative profitability of dry and irrigated production, and the importance of those changes as a driver of change in patterns of irrigated production. In the constrained adaptation scenarios, projected constraints on irrigation water availability are imposed that reflect how changing water demands across water-consuming sectors, together with changing precipitation patterns and rising temperatures, may affect the availability of irrigation water supplies across time and across production regions under future climate projections. In order to isolate the impacts of climate change on irrigated shortages, we first impose the estimated groundwater shortages that are projected over time but that are assumed to be independent of the climate change projections. We then complete our consideration of irrigation shortages by applying climate-sensitive surface water irrigation shortages. Under these final scenarios, we explore how changes in irrigation water supply are likely to physically constrain farmers' ability to adapt to climate change using irrigation and how the impacts of this constraint vary by region and crop.[4]

Because the model optimizes through the allocation of acreage to production, we first explore how irrigated acreage responds to climate change under the scenarios described above. Shifts in the actual volume of applied irrigation water under the various analysis scenarios don't perfectly parallel shifts in acreage because per-acre irrigation levels change with climate projections. Irrigation demand per acre responds to the interacting effects of precipitation changes (which may increase or decrease irrigation demand, depending on direction and timing of change), temperature impacts on yield (which may, for instance, decrease crop water demand by decreasing yields), and carbon dioxide fertilization (which increases plant water use efficiency). We then briefly discuss the implications of those acreage changes for actual applied irrigation levels, and conclude with a synopsis of the overall impacts of climate change on agricultural production and prices.

Baseline Adaptation Analysis

This first analysis presents a case in which farmers can alter their production patterns to suit the new growing conditions experienced under climate change, but no additional constraints on potential irrigation water-supply availability are imposed. In this analysis, farmers can respond to climate change in a myriad of ways: by shifting production among crops, bringing land into production in some areas and retiring it in others, shifting between dryland and irrigated production, and changing the rotations or tillage systems with which crops are produced.

The reference scenario for this analysis is characterized by increases in both the fraction of national fieldcrop acreage that is irrigated and in absolute irrigated fieldcrop acreage levels, from 49.6 million acres in 2020 to 56.2 million acres in 2080. Relative to those reference levels, irrigated acreage under the climate change projections generally increases during the early-century analysis years. By the latter part of the century, however, irrigated acreage often declines as a result of climate change, despite the warmer temperatures. This contraction in irrigated acreage is driven by changes in relative profitability, and notably not by constraints on available irrigation, which have not yet been imposed.

Changes in relative profitability of cropping systems are the primary driver of acreage changes in REAP. If changing climate conditions reduce the yield boost derived from irrigation relative to dryland yields for the same rotation, farmers may opt to switch out of irrigated production to save on irrigation costs, even if it entails a drop in yields. Temperature, CO_2, and precipitation can all affect the relative profitability of irrigated versus dryland production:

- Increased growing-season precipitation increases dryland yields but also decreases irrigation requirements, and therefore decreases the costs of irrigated production. The inverse holds for decreased precipitation.

- Increased temperature affects both dryland and irrigated yields; our results suggest that at sufficiently high temperatures it is not possible to fully mitigate the effects of increased temperature through increased irrigation.[5] Changes in the relative profitability of dryland versus irrigated agriculture will depend on the magnitude of irrigated declines relative to dryland yields, and how irrigation, and irrigations costs, are changed to compensate.
- Increased CO_2 improves the water use efficiency of crops, which can potentially boost both dryland and irrigated yields, since irrigated yields are often not sufficiently irrigated to completely eliminate water stress. Irrigation requirements may decline, which can also reduce the costs and increase the profitability of irrigated production. If dryland yields are sufficiently increased through improved water use efficiency, it is possible that CO_2 changes alone can increase the profitability of dryland production relative to irrigated production.
- Increased CO_2 can also have a positive impact on crop yields by stimulating plant photosynthesis. The carbon dioxide fertilization effect is relatively larger for crops with the C_3 photosynthetic pathway, including crops such as wheat, barley, soybeans and alfalfa hay. For crops with the C_4 photosynthetic pathway (including corn and sorghum in our analysis), the effect is much smaller. (Interested readers can find more detailed information on the differences between C_3 and C_4 crops in appendix A). In western regions, where dryland production is dominated by C_3 crops, such as wheat and alfalfa, and C_4 crops are likely to be irrigated, the carbon dioxide fertilization boost experienced by C_3 plants may favor dryland production systems.

In this analysis, the relative profitability of dryland versus irrigated production is influenced by complex interactions among changes in all three climate factors.[6] The net shift in the ratio of returns to irrigated versus dryland production (aggregated over crops) by farm production region for the year 2060 varies by region (table 2). The measures represent the percentage change in the ratio of irrigated to dryland returns (per acre) for a climate projection relative to the reference scenario, with increasing darkness of fill representing decline in the ratio of irrigated to dryland returns. Only two regions, the Delta region (DL) and the Northeast (NE), generally experience an increase in the relative returns to irrigated production, while the Appalachia (AP), Corn Belt (CB), Mountain (MN), Northern Plains (NP), Pacific (PA), Southeast (SE), and Southern Plains (SP) generally experience a decrease in the relative returns to irrigated production. The Lake states (LA) experience mixed impacts across climate projectionss.

Shifts in the relative profitability of irrigated versus dryland production differ by crop. Tables 3-5 present shifts in the relative returns to irrigated agriculture by farm production region for the year 2060 for the production of wheat, soybeans, and corn. In wheat, the general trend is toward a decline in per-acre irrigated returns relative to dryland returns; under some climate projections that decline occurs over a majority of production regions. Relative returns to irrigated soybean production also decline consistently across climate projections for the Appalachia, Corn Belt, Delta, and Northern Plains regions, while generally increasing in the Southern Plains and Northeast regions. For corn production, the impact on relative irrigation returns is more mixed, though in the heavily irrigated Northern Plains, the impact is predominantly negative.

Within a region, irrigated acreage may also decline if crops that are predominantly produced using dryland methods in that region experience yield boosts as a result of climate change, or are relatively less negatively affected than crops that are produced using irrigated methods within the region. Wheat, alfalfa hay, cotton and barley are produced in more arid regions under dryland production; these C3 crops are projected to benefit from carbon fertilization effects. Corn and sorghum, C4 crops which are often grown as irrigated crops in western regions, may not receive a similar yield boost from atmospheric carbon. Such changes in competitiveness across crops, if correlated with differences in irrigated versus dryland production, change the relative profitability of dryland production systems versus irrigated production systems more generally within a region. Such shifts may result in adjustments in production from irrigated to dryland production that reflect changes in crops produced rather than shifts in profitability within different production types for the same crop. Cropping shifts are more likely to occur in arid regions where irrigation contributes a more significant share of crop-water needs.

Imposing constraints on irrigation water

This analysis modifies the baseline adaptation analysis by imposing in each time period constraints on the availability of irrigation water. The irrigation water constraints are composed of two parts: estimated groundwater withdrawal reductions that are assumed constant across climate change projections (which are reflected in the reference scenario as well as the climate change projections) and estimated surface water shortages that vary by climate change projection. Surface-water shortages reflect shifting patterns of regional precipitation as well as changes in demand from other water use sectors.

Imposing water-supply constraints that reflect increasingly limited water supplies across the arid West results in significant declines in national irrigated acreage under most of the climate change projections for each analysis year (figure 5). Note that irrigated acreage under the reference scenario declines with consideration of irrigation constraints, due to the incorporation of groundwater shortage projections into the new calculation of reference acreage.

The projected decline in U.S. irrigated fieldcrop acreage reflects 1) the decline in relative profitability of irrigated cropping systems where precipitation is sufficient to support dryland production (addressed in the previous section), 2) reduced groundwater irrigation withdrawals due to projected regional groundwater depletion, and 3) reduced surface-water irrigation withdrawals as water supplies become more constraining across much of the arid West under climate change. The contribution of these influences varies locally depending on climate conditions over time, the yield response of irrigated and dryland crops, regional dependence on groundwater versus surface water irrigation supplies, and climate-related scarcity of water supplies for irrigation. Figure 6 illustrates the differential importance of these drivers across regions, through differences in regional patterns of irrigated fieldcrop acreage observed with and without irrigation supply constraints in place for 2060.

In the Pacific States, irrigated acreage declines in the absence of water-supply constraints while dryland acreage increases across all climate projections, suggesting an increase in the relative competitiveness of regional dryland production. Under a warming and generally wetter climate in the Pacific Region, higher yields are projected for dryland wheat, hay and cotton under most scenarios. The introduction of water-supply constraints results in further reductions in irrigated acreage and additional expansion of dryland production. The impacts of groundwater withdrawal reductions are relatively small, however; most of the decline in irrigated acreage reflects surface-water shortages under climate change.

Irrigated acreage in the Mountain States also declines under most climate projections, reflecting the dual effect of declining relative returns to irrigation and increasingly limited water supplies. The decline in irrigated acreage is reflected across all irrigated crops, with the exception of irrigated hay which expands in response to generally higher irrigated yields under climate change. The introduction of water-supply constraints results in a significant decline in irrigated acreage across all climate projections, with the vast majority of that acreage coming out of water-intensive irrigated hay production. Again, the impacts of groundwater withdrawal reductions are generally small relative to the effects of surface-water constraints arising from climate change.

The Southern Plains show mixed impacts on irrigated acreage in response to climate projections. In the absence of water-supply constraints, an expansion in irrigated acreage displaces dryland production under 4 climate projections, with declines in irrigated acreage occurring under the remaining 5 projections. Nevertheless, a general increase in the acreage of irrigated corn, wheat, and hay suggest those production systems gain a comparative advantage under changing climate conditions. The introduction of water-supply constraints—reflecting reductions in groundwater withdrawals primarily—results in a net decrease in irrigated acreage across all crops under all climate projections. The fraction of irrigated acreage allocated to corn, hay, and rice, however, increases at the expense of wheat, soybeans, and barley. While declining relative returns to irrigation drive some irrigated acreage declines for crops other than corn, wheat and hay, increasingly limited groundwater supplies represents the primary driver of future acreage changes in the Southern Plains.

The Northern Plains show declining irrigated acreage under most climate change scenarios, even in the absence of water-supply constraints. Dryland acreage also declines across several scenarios, however, reflecting declining yields in corn and soybean production. The introduction of water-supply constraints has a relatively small incremental effect on model results, as acreage declines are attributable primarily to shifts in the profitability of irrigated and dryland production.

In the Delta States, irrigated acreage expands under the majority of climate projections (7) in the absence of water-supply constraints, with dryland acres declining in all but one scenario. Irrigated acreage increases across all major irrigated crops (corn, cotton, rice and soybeans), despite a general decline in irrigated yields. That expansion is likely driven by the even larger declines in regional dryland yields, which shifts the relative profitability toward irrigated production. When water-supply constraints are imposed, both irrigated and total acreage in production generally decline. The impact of water-supply constraints is entirely due to groundwater withdrawal reductions; no additional surface water shortages are projected for this region under any of the climate projections.

In the remaining production regions—the Corn Belt, Appalachian, Lake States, Southeast and Northeast—irrigated acreage accounts for a limited share of the cropland base. A warming climate is projected to increase levels of irrigated acreage for the Corn Belt, Appalachia, and Northeast regions, with mixed impacts on the Lake States and the Southeast. In some cases, the proportional expansion of irrigated acreage is large in those regions, with irrigated acreage under some projections more than doubling in the Corn Belt and under one climate projection increasing five-fold in the Appalachia region. When constraints are imposed on available irrigation water, even regions with no projected shortages are limited to a 10% increase in applied irrigation volume, so such large, cost-free expansions of irrigation are not permitted, though the absolute level of acreage change in those regions is often not substantial. The impact of imposing constraints on available irrigation water is therefore to contract irrigated acreage across all these regions; given the 10% constraint on irrigation expansion, even those regions with no irrigation shortages under the reference scenario can experience shortages relative to what their optimal pattern of production would be under climate change.

Regional shifts in applied irrigation water in fieldcrop production roughly correspond to the shifts in acreage, though differences arise due to changes in per-acre irrigation levels under each of the climate projections (figure 7). In the Mountain States, for instance, under several climate projections, applied irrigation increases under the adaptation scenario without irrigation constraints, despite a decline in irrigated acreage. Under those climate change projections in that region, average irrigation demand per irrigated acre increases as a result of changing growing conditions, increasing per-acre irrigation costs which can contribute to a decline in the relative profitability of irrigated production (and drive the contraction of irrigated acreage under that scenario). The converse holds true under a couple of climate change projections in the Northern Plains, where applied irrigation declines under the scenario without constraints, despite an increase in total irrigated acreage. Even with irrigation constraints in place, the Delta states generally increase their applied irrigation levels slightly under the climate change projections despite a reduction in irrigated acreage; under the climate change projections, average per acre irrigation demand generally increases in that region.

Production and Prices under Climate Change Projections

Declines in irrigated fieldcrop acreage are often accompanied by increases in fieldcrop acreage nationally, as dryland production is generally expanded to offset the decline in national irrigated production. Production on expanded dryland acreage is generally not sufficient, however, to offset yield declines on dryland and irrigated acreage and the accompanying decline in irrigated production acreage. As a result of changing yields and increasing water scarcity under climate change, and resulting shifts in regional cropping patterns, national production of corn, soybeans, oats, rice, silage and sorghum generally declines relative to the reference production levels in each analysis period, while wheat production generally increases (beyond 2040). The national production impact on barley, cotton and hay is mixed across the climate projections, though on average hay production increases while production of the other crops declines. Impacts averaged over the nine climate projections for each crop and analysis year are shown in figure 8.

Each bar in figure 8 represents the incremental imposition of an additional driver of cropping pattern change. The first column reflects the biophysical impacts of climate change in the case where farmers are assumed to adapt to biophysical yield changes without any additional limitations on production due to irrigation supply scarcity. The next column considers groundwater shortages that are unrelated to climate change, and the final column adds the effects of climate-change related surface water shortages. For most crops, the largest production changes arise as a result of biophysical impacts of climate change on crop yields and the resulting farmer response to changes in relative profitability of production. Relative to those initial changes in production levels, the marginal impact of irrigation shortages are generally small.

It's possible to isolate the impacts of climate change on crop prices by comparing prices across climate projections (with and without irrigation constraints) to a reference scenario that incorporates the effects of groundwater depletion (assumed independent of climate change). With the exception of the CGCM_A1B scenario across all time periods (and the CGCM_B2 results for 2060), the climate projections result in increases in a production-weighted price index calculated across the 10 fieldcrop commodities (figure 9). Under most climate projections, with a few exceptions, commodity prices rise with climate change. The marginal impacts of irrigation shortages are insignificant compared with the impacts on prices of changes in temperature and precipitation, given the predominance of dryland fieldcrop production and limited effect of regional water shortfalls on national commodity markets. In 2080, the price impacts of climate change range from a decline in indexed price levels of 7% for the CGCM_A1B scenario to an increase of 41% under the MIROC_A2 scenario.

The price index masks variability across fieldcrops. Prices of corn and sorghum, the two C_4 crops in the analysis, generally increase relative to the reference price, together with those of soybeans, cotton and rice. National average yields and total production of these crops generally drop under the projected climate projections, which drives up national prices, though impacts vary across regions as well as across production methods. Prices of hay and, to a more mixed extent, wheat are more likely to decline relative to the reference price, as both production and average yields of those crops tend to increase under the climate change projections.

Conclusions

The U.S. agricultural sector is expected to face significant changes in crop productivity and resource availability under climate projections through the 21st century. Climate change is projected to have important implications for water resources in particular, involving changes in precipitation and soil moisture reserves for dryland crop production as well as water supplies for irrigated production. To a certain extent, farmers are able to adapt to altered growing conditions and changes in the relative profitability among production enterprises that arise by changing crops, rotations and production methods used as well as the amount of land in production (Malcolm et al. 2012). Irrigation, which offsets natural water-deficits through applied water, is viewed as an important adaptation to mitigating higher crop evapotranspiration losses and potential changes in effective growing-season rainfall under climate change. This article was motivated by concerns that irrigation water shortages may limit the ability of farmers to adapt to climate change through expansion and intensification of irrigated production.

Our results suggest that farm-level economic considerations may limit the potential for increased irrigated expansion as a climate adaptation strategy to particular regions. We find that the differential impact of climate change on dryland versus irrigated yields decreases the relative profitability of irrigated production and causes a contraction in irrigated acreage despite warmer temperatures. This decline is in some areas coincident with increases in precipitation that increase dryland yields, but in others arises from disproportionately large yield declines on irrigated acreage under increased growing temperatures and the resulting effect on irrigation returns, given the high cost of irrigation inputs. Evidence of declining relative profitability of irrigated production is inconsistent with the suggestion that increased irrigation can help mitigate increased growing season temperatures, and in fact suggests that changing climate conditions may lower the marginal productivity of irrigation water in such a way that the yield premium achievable through irrigation declines.

As a result of such shifts in relative profitability, which drive the projected contraction in irrigated acreage and declining demand for irrigation in many regions, the impacts of irrigation shortages on agricultural prices and production are projected to be small relative to the direct impacts of climate change on yields. Underlying such aggregate price and productivity impacts is a set of yield impacts, irrigation shortage and land-use change results that are highly variable across regions. Declines in irrigated acreage in the Northern Plains and the Southern Plains are driven by a combination of reduced returns to irrigation arising from differential biophysical impacts on irrigated and dryland yields and projected groundwater shortages due to aquifer depletion. Declines in irrigated acreage in the Delta, on the other hand, arise almost entirely from more limited groundwater shortages; in this analysis the Delta is the one aggregate region where the relative profitability of irrigated production is consistently maintained or increased under the climate change projections. In all three regions, the marginal impacts of surface-water shortages arising from changes in climate patterns are relatively small. Across the Pacific and Mountain regions, our analysis attributes projected declines in irrigated acreage to a combination of reduced relative profitability of irrigated production and projected surface-water shortages that are largely driven by climate change.

While such broad generalizations may hold on average for production within a region, certain crops within the region may diverge from the pattern. In the Mountain states, for instance, increased returns to irrigated hay production result in projected increases in irrigated hay acreage that are constrained only when surface-water shortage assumptions are imposed. In addition, projected relative returns to irrigation may vary within aggregate regions due to spatial heterogeneity in resources and climate/weather patterns across the smaller REAP production regions. The importance of the different drivers of irrigated-acreage change under the future climate projections therefore vary by region and climate change projection, as well as by crops and production areas within a region.

In evaluating irrigation's potential as a climate adaptation strategy, this study estimates the effect of two important drivers of irrigated acreage response that are climate driven: declines in the relative profitability of irrigation returns, and increasingly limited water supplies for irrigation. However, other factors beyond the scope of the current study will certainly influence the future extent and distribution of U.S. irrigated production. Such factors may include increasing costs of surface-water and groundwater access, regional shifts in farmland markets, farm asset-fixity considerations, water demands for emerging uses, potentials for water-supply enhancement, and institutional adaptations in water resource management. Climate studies suggest an increase in the frequency and severity of extreme weather events, and irrigation may be used increasingly to mitigate periodic drought under both arid and temperate growing conditions. We plan to address some of these concerns in future research extensions.

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Footnotes

1. The SRES emissions scenarios were used in the IPCC Third and Fourth Assessment Reports (2001 and 2007) to represent a standardized set of potential emissions pathways into the future as well as a plausible set of economic, technological, and social development assumptions underlying those pathways.

2. Because there are very small differences across estimation scenarios for the 2001-2008 time frame, “reference” climate conditions were anchored to a single estimation scenario (CGCM_A2). To adjust for small differences in what each estimation scenario considered “reference” conditions, results generated for each projection are calculated as shifts from that estimation scenario’s 2001-2008 values. Those shifts are then applied to the CGCM_A2 “reference” values to generate the projections associated with each of the other climate scenarios.

3. In reality, groundwater withdrawals tend to increase in drought years, as higher-cost groundwater substitutes for a share of the surface-water shortfall due to drought. This analysis examines long-term water-supply trends, and does not allow for periodic substitution across water sources in drought years.

4. Because of the complex institutional structure of water markets, and because our analysis does not include estimates of the impacts of water shortages on water price, we are unable to explicitly account for the marginal impacts of irrigation water shortages on production costs and profitability under climate change. Thus, water shortages create a physical constraint to adaptation, but not an economic constraint through increased costs of water inputs.

5. Irrigated production is not immune to the impacts of climate change because irrigation is not able to completely offset the impacts of a warmer growing season on crop growth. Temperature changes do not simply increase plant water demand, they completely alter the phenology of crop development, including the rate of biomass accumulation and grain set (Walthall et al., 2012).

6. Several other factors not included in this analysis, including changes in tropospheric ozone and solar radiation, may also differentially impact irrigated versus dryland production.

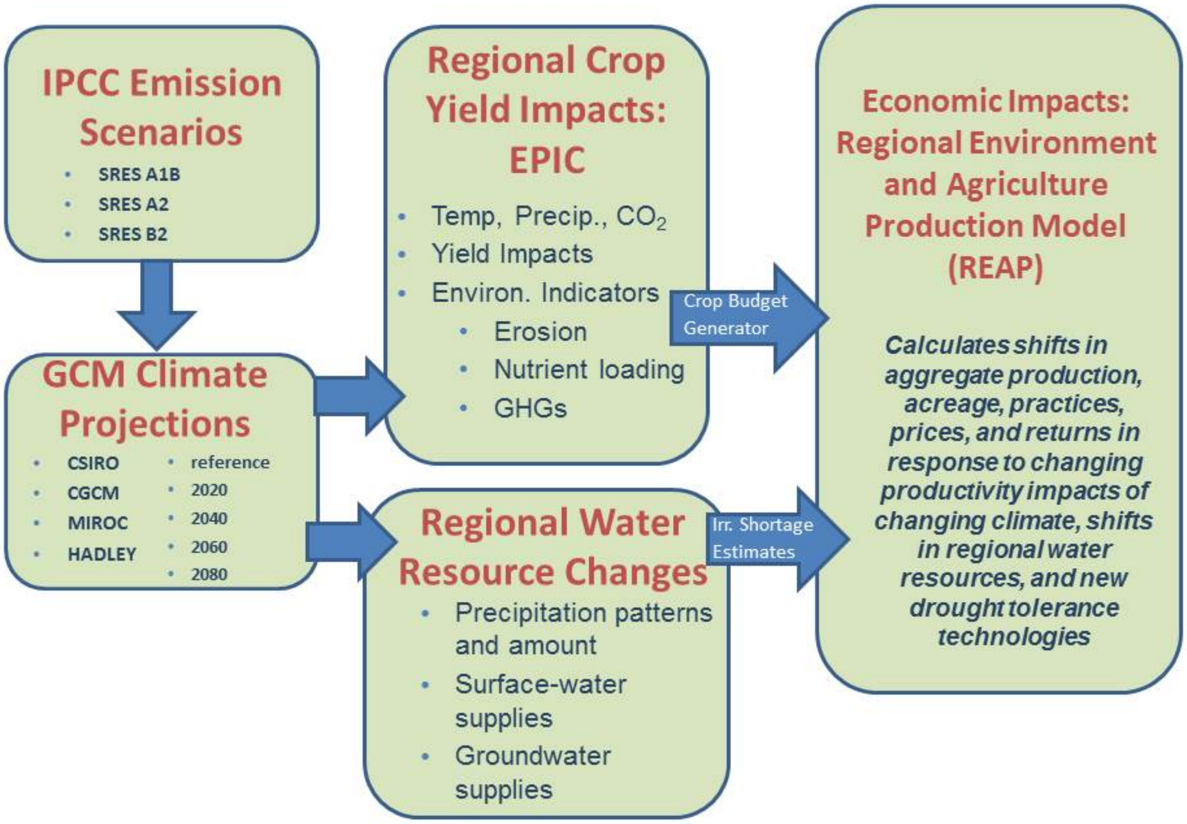


Figure 1: Analytic framework for examining climate change, water resources, and agricultural adaptation

Table 1: General Circulation Model (GCM) Projections Used in this Study for Each SRES Scenario.

A1B	A2	B2
CGCM31 MR CSIROMK3 MIROC32 MR	CGCM31 MR CSIROMK3 MIROC32 MR	CGCM2 MR CSIROMK2 filtered HADCM3

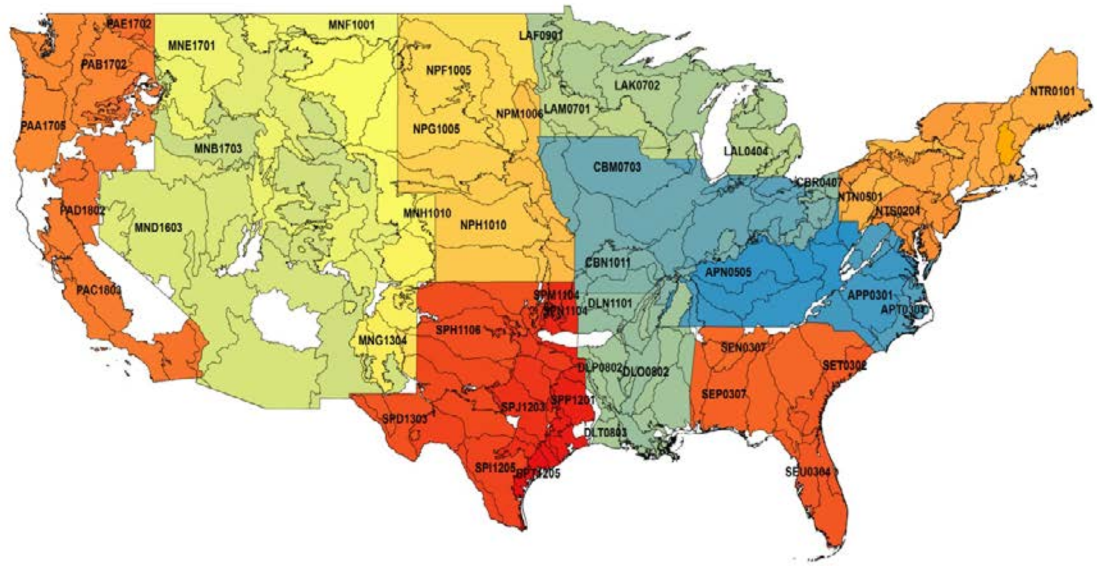


Figure 2: Lines delineate the 267 analytical regions used in the EPIC calculations and REAP optimization. Regions with insignificant crop area in REAP crops (excluding hay) are shown in white and are not included in the analysis. Blocks of similar colors correspond to the ten USDA Farm Production Regions used in reporting out results.

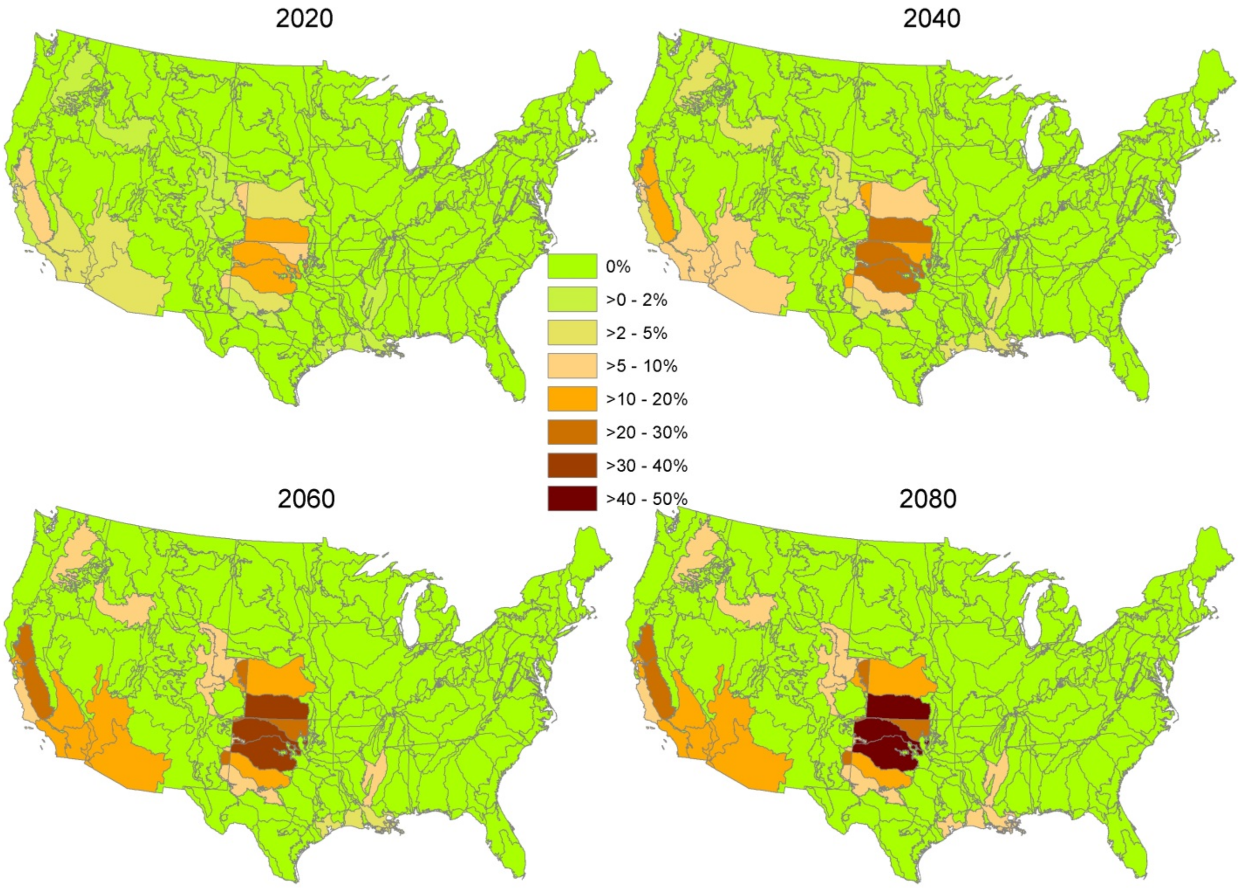


Figure 3: Groundwater supply reductions, 2020-2080

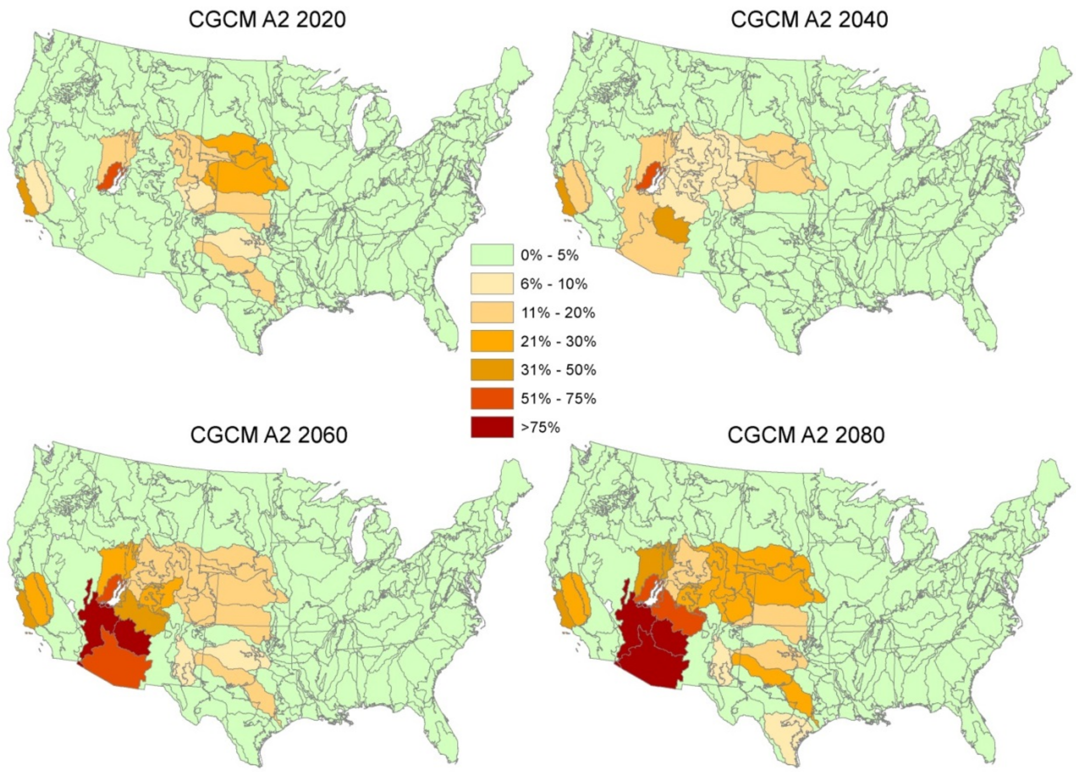


Figure 4: Surface-water supply reductions for all climate projections, 2020 – 2080

Table 2: Percent Change in the Ratio of Returns to Irrigated Production Versus Returns to Dryland Production by Region (2060)

FPR	CGCM_B2	CSIRO_B2	HADN_B2	CGCM_A1B	CSIRO_A1B	MIROC_A1B	CGCM_A2	CSIRO_A2	MIROC_A2
AP	1.6	0.8	-2.6	-3.2	-0.6	-2.5	-8.7	1.4	-2.9
CB	-4.3	-2.9	0.4	-1.9	4	-8.3	-10.9	-6.3	-1.9
DL	4.5	-2.3	13.5	21.4	17	41.5	41.3	16.1	65.2
LA	-5.5	1.8	6.6	-8.1	-0.2	1.1	-6	-1.9	6.9
MN	-35	-21.9	96.9	-43.8	-11.2	-14.7	-27.1	-26.2	-9.9
NP	-7.2	36.5	16.4	-22.4	2.6	-4.1	-26.4	-16.1	-10.3
NE	-3.9	0.8	1.9	-4.9	0.1	4.4	0.7	4.1	11.8
PA	-2.1	-17.9	1.3	-1.2	-19	-20.4	-1.2	-7.8	1.2
SE	17.5	3	-17.6	-18.3	-1.3	-27.3	-7	-8.2	34.2
SP	-8.5	-27.2	-6.3	-22.3	-32.9	32.5	-19.9	5.4	17.4

Table 3: Percent Change in the Ratio of Returns to Irrigated Production Versus Returns to Dryland Production for Wheat (2060)

WHEAT, 2060									
FPR	CGCM_B2	CSIRO_B2	HADN_B2	CGCM_A1B	CSIRO_A1B	MIROC_A1B	CGCM_A2	CSIRO_A2	MIROC_A2
AP	8.4	3.8	-5.1	23	9.9	0.2	8.9	11.2	-9.3
CB	-14	9.2	15.3	-14.5	15.8	9.6	-5.6	-5.2	12.3
DL	-10.1	13.9	-0.7	-18.8	7.3	-13.4	-29.6	-7.4	-3.1
LA	-0.6	3.6	-0.5	-8.9	19.3	9.4	-11.9	-6.9	6.2
MN	-9.4	-6.7	13.3	-21.8	15.3	-5.7	-36.3	-21.4	-0.9
NP	-3.8	18.3	14.4	-12.2	35.5	29.4	-18.2	-8	5.4
NE	-9.2	0.3	1.9	5.9	-7.1	-6.8	-16.1	-9.9	-17.3
PA	-12	-14.2	-2.8	-19	-13.3	-30.9	-42.3	-23.2	-20
SE	-49.9	21.3	-12	-27.5	-4.6	-5.6	-26.2	-0.3	21.2
SP	-42.2	-3.3	30.5	-44.1	11	45.6	-72.9	1.4	48.4

Table 4: Percent Change in the Ratio of Returns to Irrigated Production Versus Returns to Dryland Production for Soybeans (2060)

Soybeans, 2060									
	CGCM_B2	CSIRO_B2	HADN_B2	CGCM_A1B	CSIRO_A1B	MIROC_A1B	CGCM_A2	CSIRO_A2	MIROC_A2
AP	-11.5	-10.7	-12.5	-11.2	-8.7	-5.8	-24.5	-8.8	-19.1
CB	-5.5	-3.8	-2.4	-9	5.2	-12.6	-15.8	-5.9	-5.8
DL	-3.5	-5.8	-2.1	-8.4	-4.6	-11	-16.4	-9.5	-17.3
LA	-5.5	2.9	8.6	-8.3	-0.6	1.4	-8.3	-5.7	5.5
NP	-9.2	26.5	3.8	-19.4	-1.3	-6.8	-30.6	-21.6	-10.5
NE	-0.4	4	3.1	-2.6	6.9	9.7	2.2	7.5	16.5
SE	1	-0.7	-7.8	-13	4.9	40.6	-9.5	8.5	29.9
SP	9.2	26.2	51.6	-14.9	20.2	67.6	10	7	156.7

Table 5: Percent Change in the Ratio of Returns to Irrigated Production Versus Returns to Dryland Production for Corn (2060)

CORN, 2060									
dim7	CGCM_B2	CSIRO_B2	HADN_B2	CGCM_A1B	CSIRO_A1B	MIROC_A1B	CGCM_A2	CSIRO_A2	MIROC_A2
AP	0.9	1.4	0.1	-3.2	0.4	1.2	-7.3	-0.6	1.6
CB	-4.7	-3.2	-1.1	-10.3	0.7	-9.9	-14.5	-7.4	-1.4
DL	4.3	1.9	12.3	1.4	21	25.3	12.3	10.7	38.6
LA	-4.1	3.6	10	-5.7	1.6	3.4	-4.8	-1.6	8.1
MN	-13.8	1.8	33.6	-34.8	-0.7	1.7	-10	-11	10.8
NP	-6.5	29.7	11.7	-15	2.9	-2.6	-21.2	-15	-6.3
NE	-0.5	3.5	3.3	-5.3	4	6.3	0.8	6.9	11.6
PA	5.1	-34.2	60.4	-6.6	7.8	-27.5	-31.5	-2.7	-27.1
SE	0.8	2	-5.2	-4.9	0.4	-8.3	-9.8	-3.6	12.8
SP	-10.5	-12.8	2.2	-7.4	0.1	28.2	1.4	9.5	22.9

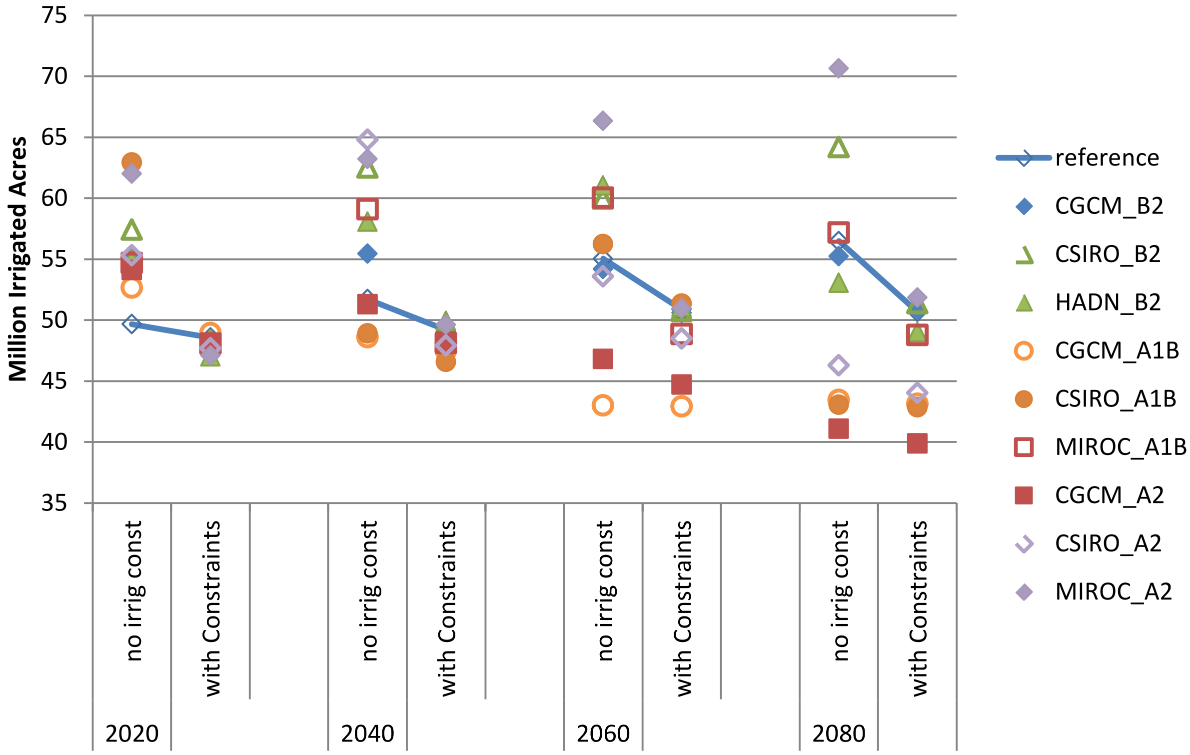


Figure 5: Contraction in national irrigated acreage arising from constraints on availability of irrigation water

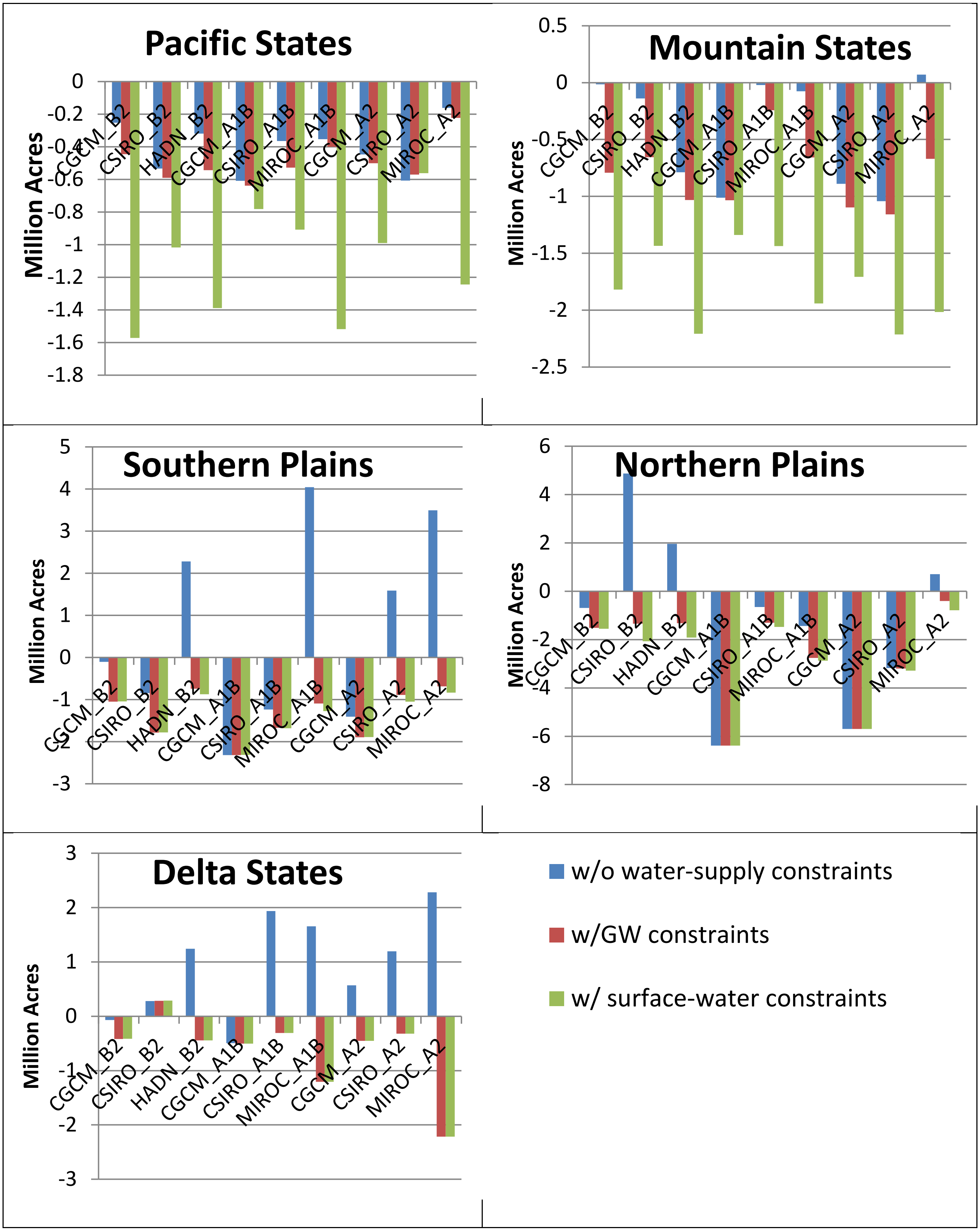


Figure 6: Change in irrigated acreage relative to reference case by climate scenario for major irrigated regions in 2060

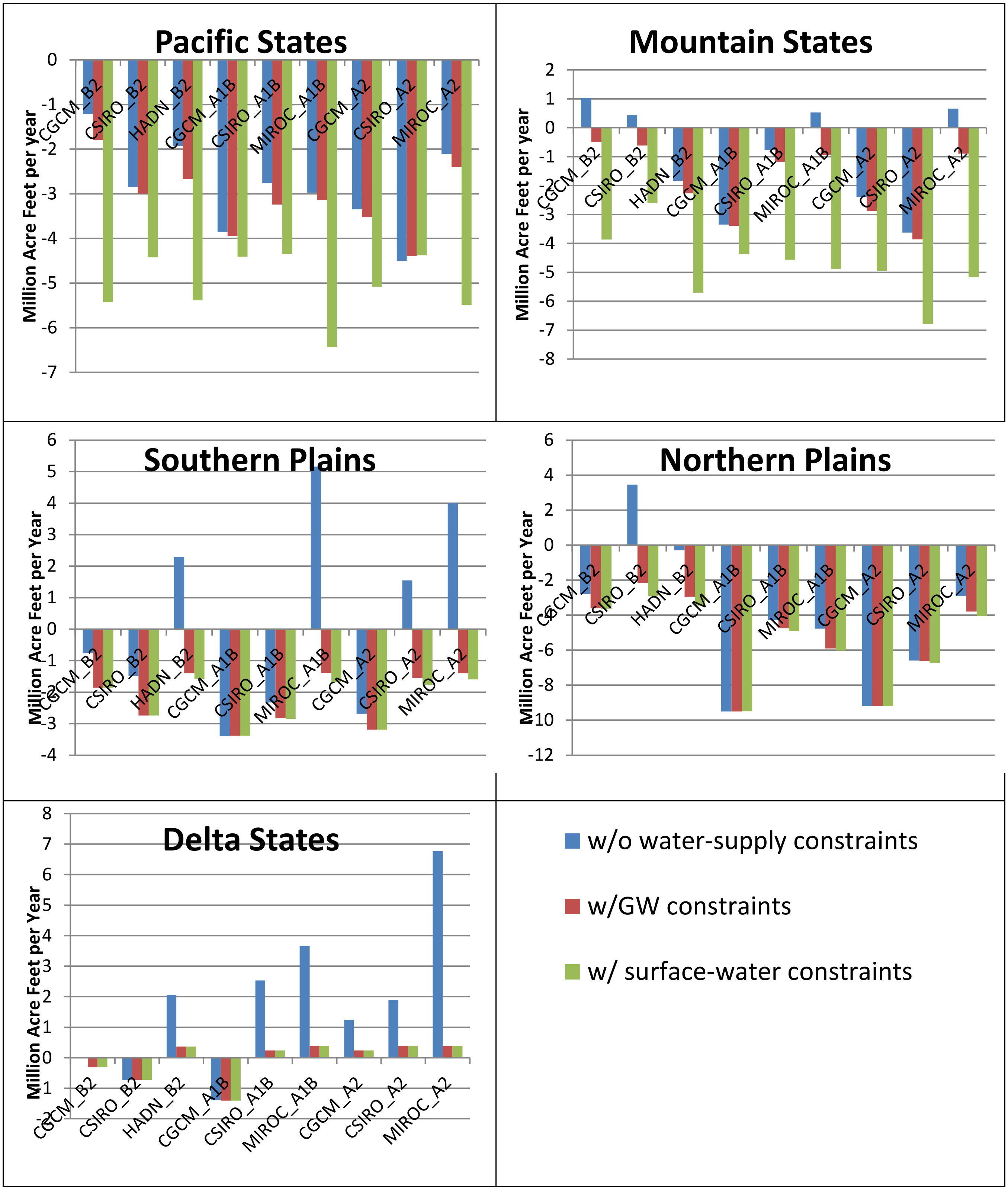


Figure 7: Change in applied irrigated volume relative to reference case by climate scenario for major irrigated regions in 2060

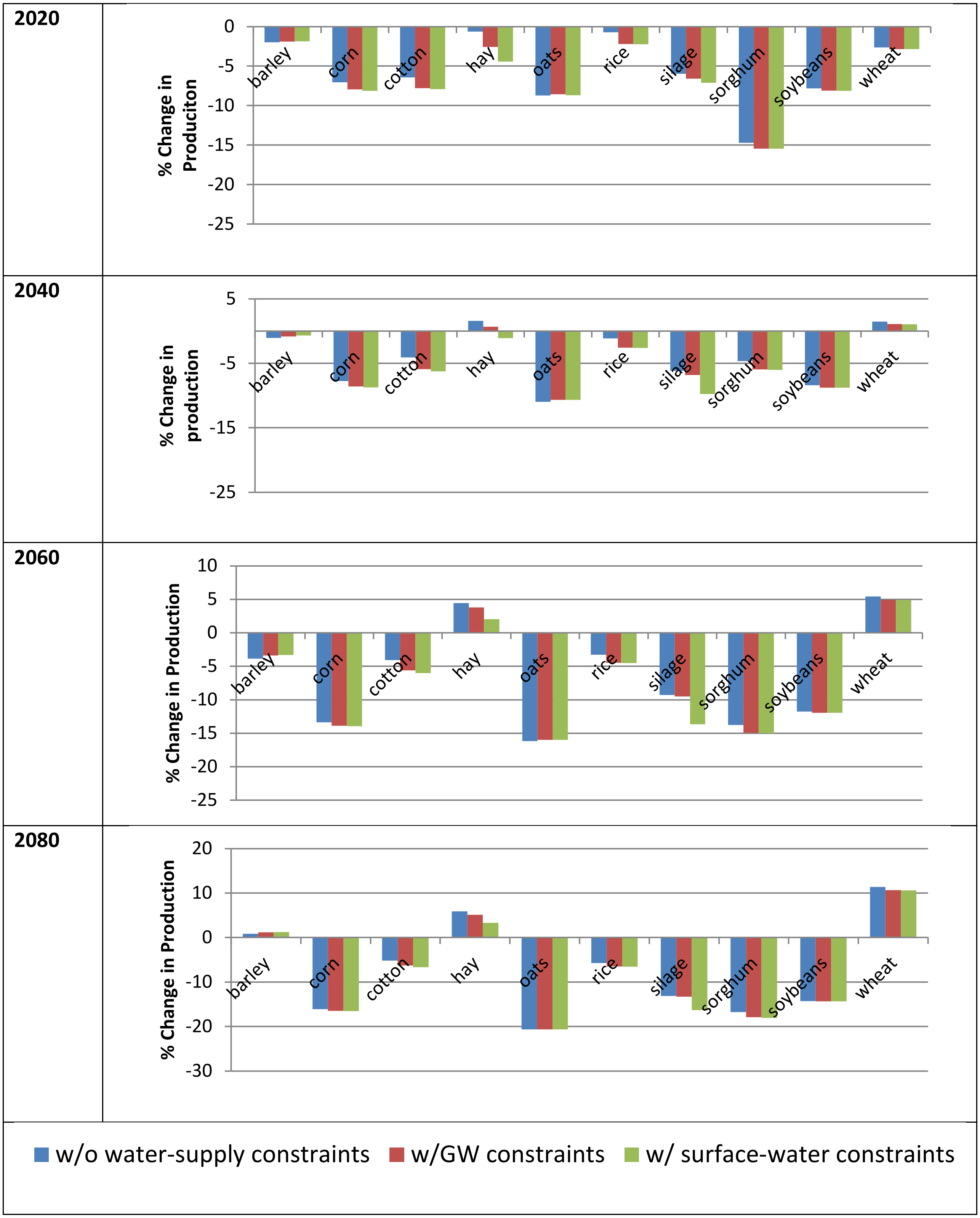


Figure 8: Percent change in national production relative to reference production levels averaged over all climate futures for each analysis period

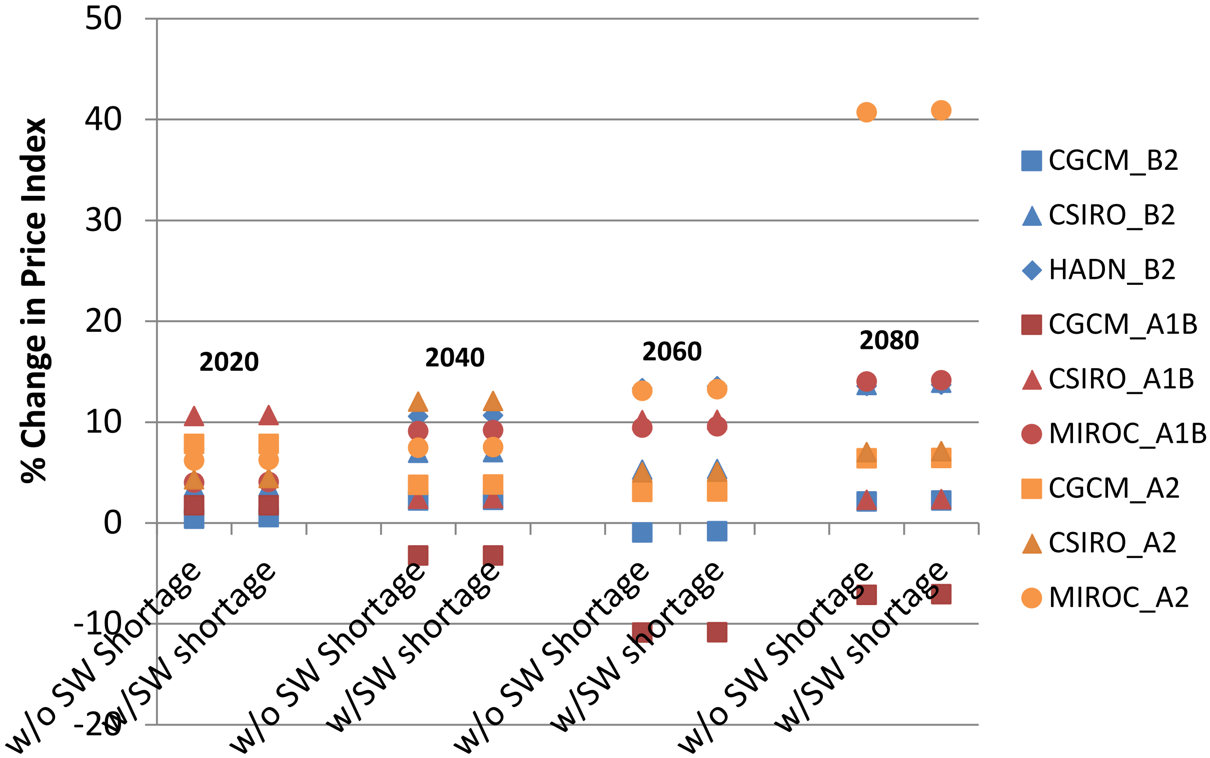


Figure 9: Change in aggregate price index for each analysis year relative to the reference price index for that year

Appendix A

Each crop production region is divided into production on highly erodible land (HEL) and non-highly-erodible land (NHEL), and each land type (HEL or NHEL) is represented by one or more soil series, depending on the amount of cropland in that region and land type. Regions with less than one million acres of cropland in a land type are generally represented by a single soil for that land type. An additional soil type is brought in for (roughly) every additional million acres of cropland on a specific land type (HEL or NHEL). Production in each region is represented by a set of production enterprises that capture the rotations and field production methods used to produce crops in that region. Each production enterprise is simulated across all the soils selected to represent a given region; soil-specific yields and environmental impacts estimated at the field scale are then averaged, using acreage weighting based on soil extent within that region, and those average yields and environmental impact measures are used as representative regional results—i.e., yield and environmental impact measures—for that production enterprise.

Soil properties for each region and soil type are calculated using an overlay of the NASS cropland data layer and the SSURGO database (USDA NASS CDL 2012, SSURGO 2013). The cropland data layer identifies cropland within each REAP region, and the SSURGO database is used to divide that regional acreage into highly erodible (HEL) and non-highly-erodible (NHEL) map units and to characterize the soil types underlying those map units and the crops within them. Soils series chosen to represent each region are based on a consideration of soil coverage as well as importance for predominant crops within the region. Soil properties for each region are calculated by area weighting the individual soil properties by soil map unit (SMU), soil series name (aspatial), Cropland Data Layer (CDL) crop class, and erodibility status (highly erodible land or non-highly erodible land) for each REAP region to estimate representative soil properties by region. This exercise is done for the selected set of soil series described above. The weights are calculated as the area in each REAP region in each unique combination of SMU, crop class, and erodibility status multiplied by the SMU representative component percent of each soil series. A second set of weights is calculated for those properties that are described throughout the various horizons of the soil profile as the SMU average representative horizon width. Properties described at the soil map unit level, and not described in the horizons, are weighed by the first weight only, and properties described in the soil horizons are multiplied by both weights. The weighted soil properties are finally aggregated to each of the soil series in each REAP region.

EPIC crop growth modeling

Projected crop yield response to temperature change in a region depends on where the new temperature conditions fall relative to the range of optimal growing conditions for specific crops. EPIC users may specify both the minimal temperature and optimal temperature for crop growth; growth rate declines on either side of the optimal temperature. Estimates of crop yield response to climate change are therefore highly sensitive to the specification of crop-specific temperature thresholds. The crop-specific critical temperature thresholds used in this analysis are shown in

Appendix Table 1. While the development of heat-tolerant crops may result in altered ranges of optimal growing conditions in the longer term, this analysis assumes that these critical thresholds remain constant across all analysis periods.

Appendix Table 1: Optimal and minimum temperatures for growth for REAP crops

Name	Optimal Temperature (°C)	Minimum Temperature (°C)
Soybeans	25	10
Corn	25	8
Grain Sorghum	27.5	10
Cotton	27.5	10
Winter Wheat	15	0
Spring Wheat	15	0
Barley	15	0
Oats	13	2
Rice	25	10
Corn Silage	25	8
Sorghum Hay	27.5	10
Hay- Alfalfa	15	1
Hay- Timothy	25	8

Changes in carbon dioxide are also entered into EPIC in accordance with expected CO_2 concentrations for each emissions scenario for each time period (Appendix Table 2).

Appendix Table 2: Atmospheric CO_2 concentration used for each SRES emissions scenario (ppm).

	Current	2020	2040	2060	2080
B2	381	408	453	504	559
A1B	381	420	491	572	649
A2	381	417	490	580	698

Changes in carbon dioxide concentration are expected to affect crop yields through two different pathways—first, through its impact on the efficiency of the photosynthetic pathway (radiation use efficiency), and second through its impact on the efficiency of crop respiration, or transpiration. Crops have two different metabolic pathways for photosynthesis, labeled C_3 and C_4. Of the major field crops included in the REAP model, only corn and sorghum are C_4 crops. CO_2's impact on transpiration, which depends to a large extent on soil moisture levels, can operate in both C_3 and C_4 crops; the photosynthesis effect, on the other hand, is generally thought to affect only C_3 crops such as wheat, soybeans and cotton (Lobell and Burke 2010). C_3 crops are therefore projected to have a higher yield response to carbon fertilization than C_4 crops.

There is considerable uncertainty in the literature surrounding potential carbon dioxide fertilization impacts on crop yields under realistic field growing conditions. Based on an extensive review of research, the USCCSP (2008) reports estimated percent changes in yield due to a doubling of CO_2 ranging from 4% in corn, 0-8% in sorghum, 44% in cotton, and 34-38% in soybeans. Actual responses to carbon enrichment will depend upon the extent to which crop growth is constrained by other stressors such as nitrogen or water limitations (Walthall et al, 2012).

EPIC allows CO_2 to impact plant growth through both pathways. The first pathway accounts for carbon dioxide's impact on plant photosynthesis by adjusting the crop's radiation use efficiency as carbon dioxide concentrations change, based on crop-specific CO_2 response parameters. To represent the relationship between CO_2 and radiation use efficiency (represented in EPIC by the "Biomass Energy Ratio"), EPIC fits an s-curve to two points describing radiation use efficiency at different CO_2 concentrations. Carbon dioxide is assumed to have a negligible impact on the radiation use efficiency of C_4 plants, while for the remaining C_3 plants radiation use efficiency change is as shown in Appendix Table 3.

When the Penman-Monteith evapotranspiration estimation method is used, EPIC also reduces evapotranspiration demand as carbon dioxide concentrations increase, making plants more water-use-efficient and drought tolerant in response to increased ambient carbon dioxide. In order to capture the important potential effects of carbon dioxide concentration on water use efficiency, and because the Penman-Monteith method is widely regarded as the "gold standard" in evapotranspiration estimation, we used the Penman-Monteith evapotranspiration estimation method in our crop yield modeling.

Appendix Table 3: Impact of CO_2 concentration on biomass energy ratio for each REAP crop.

Name	CO_2 Concentration	Biomass Energy Ratio
Soybeans	330	17
	700	20
Corn	330	35
	700	37
Sorghum	330	30
	700	32
Cotton	330	15
	700	18
Winter Wheat	330	25
	700	30

Spring Wheat	330	25
	700	30
Barley	330	20
	700	24
Oats	330	20
	700	24
Rice	330	35
	700	42
Corn Silage	330	35
	700	37
Sorghum Hay	330	30
	700	32
Hay- Alfalfa	330	20
	700	24
Hay- Timothy	330	15
	700	18

Changes in crop yields resulting from future climate conditions in the EPIC simulations are therefore directly attributable to differences in average temperature, precipitation and atmospheric carbon dioxide concentration. They are also indirectly attributable to changes in soil conditions arising from farm production enterprises and practices under the altered climate condition. To capture the effect of a range of different weather patterns on yield, each regional rotation for a given soil is run through EPIC five times under five different random weather regimes. Each EPIC run is modeled over 30 years; estimates of yield and observed environmental indicators for the first 20 years are discarded to allow soil conditions to settle from their initial values. Each EPIC run thus results in 10 years of yield estimates with changed weather conditions each year; because each run is replicated 5 times, final average yield and environmental impact estimates are calculated by rotation based on observed results for 50 years of simulated weather conditions for each crop.

Because estimates of the variability of future weather cannot be derived from either the original or the downscaled GCM climate data used in this analysis, the variability of weather, and therefore the relative incidence of extreme weather events, is held constant in this analysis between the baseline and future weather scenarios. Average climate conditions shift, however, so the conditions associated with an extreme event (temperatures and precipitation occurring at a specific deviation from the average) shift as well in our analysis.

Sensitivity of Crop Yield Results to Climate Change Elements

EPIC's calculation of the yield impacts of simultaneously changing values of temperature, precipitation, and carbon concentration drives REAP's analysis of the impacts of future climate scenarios relative to a baseline scenario. EPIC's results are in turn driven by a large set of technical parameter assumptions that are held constant across climate scenarios but that, through their influence on the relative impact of temperature, precipitation, and carbon fertilization on crop yields, can subsequently influence differences in impact across future climate scenarios. Examples of such assumptions include the minimal and optimal growth temperatures for each crop, the parameters of the relationship between carbon fertilization and crop growth, and water-related parameters such as maximum stomatal conductance and assumptions about the rate of decline in radiation use efficiency with increasing vapor pressure deficits.[1]

Because there is ongoing debate about the expected magnitude of dynamics such as carbon fertilization, and to understand how each element of the climate change impact behaves individually in EPIC's results, it's helpful to present disaggregated climate change impact results for each of the climate elements that vary. This section presents results for scenarios in which temperature, precipitation, and carbon concentration are varied independently of one another in the combinations shown in Appendix Table 4. Note that due to interaction effects, the impacts of the combined changes are not a strict sum of the impacts of the individual effects. The impact of temperature on evapotranspiration rates, for example, can alter the sensitivity of precipitation impact results to temperature changes. The sensitivity analysis is presented for crop yields calculated in 2060 varying the elements of the CSIRO_A1B projections.

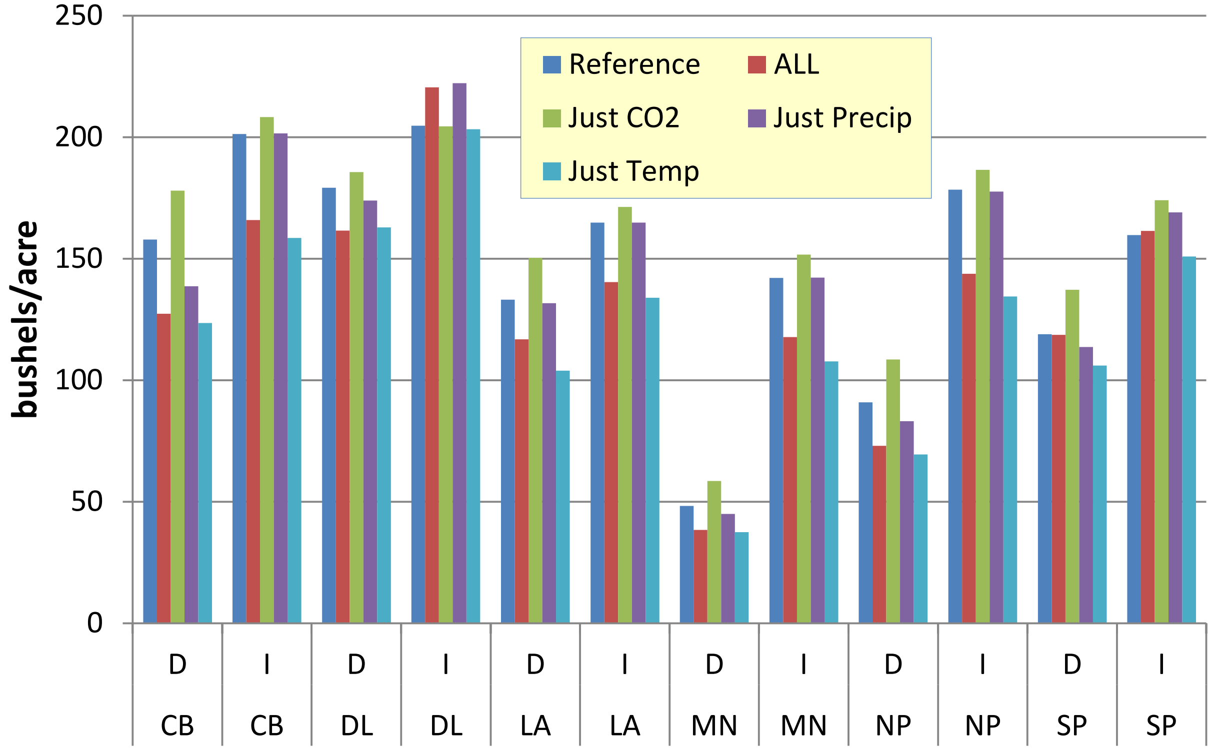
Appendix Table 4: Scenarios used for exploring sensitivity of yield impacts to climate change elements.

	Reference	ALL	Just CO_2	Just Precip	Just Temp
temperature	Reference	CSIRO_A1B_2060	Reference	Reference	CSIRO_A1B_2060
precipitation	Reference	CSIRO_A1B_2060	Reference	CSIRO_A1B_2060	Reference
CO_2 concentration	385	572	572	385	385

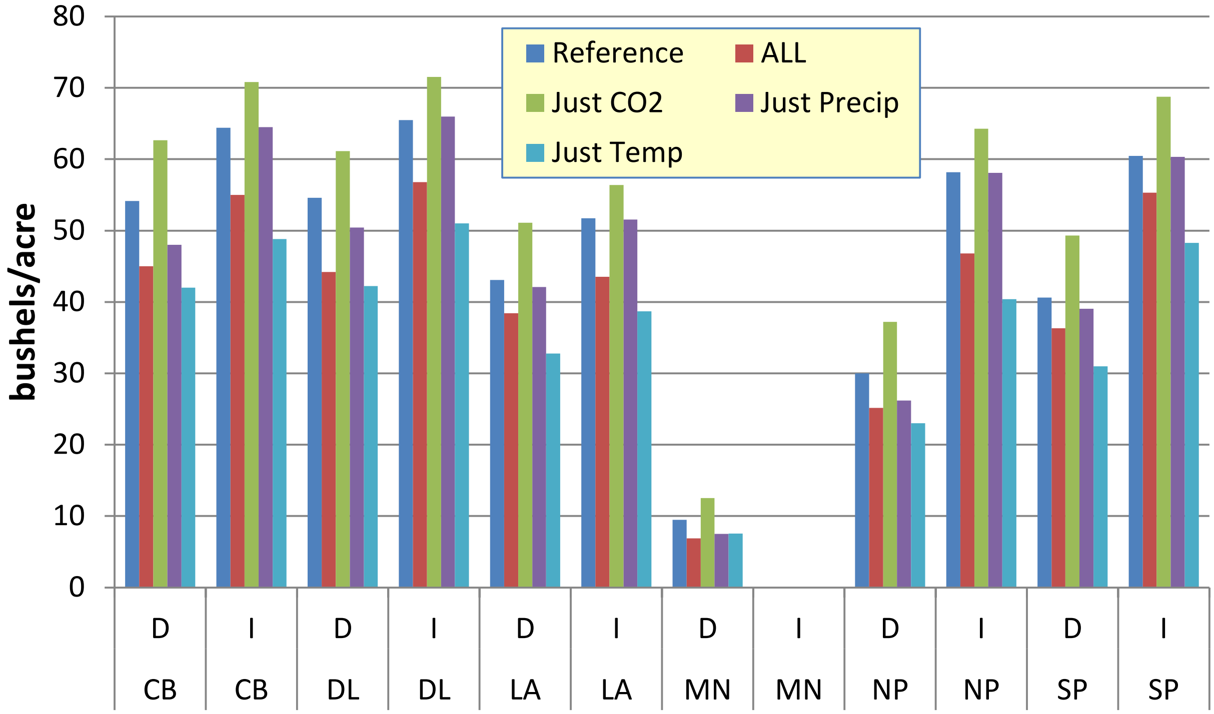
To isolate the biophysical impacts from the behavioral impacts in this analysis, production acreage is held fixed across all the scenarios; the only elements varying are the per-acre yield calculations generated by EPIC for the given combination of climate element adjustments. The changes in productivity illustrated are therefore due exclusively to the changes in biophysical impact simulated by EPIC. Regional changes in productivity reflect changes in productivity at the rotation level that are then weighted by rotation acreage in aggregating up to the regional level.

Impacts on yields of corn, soybean, and wheat for select regions are shown in Appendix Figure 1 to Appendix Figure 3 for the scenarios described above. Note that these yields, which directly reflect EPIC output, have not yet been calibrated by REAP to meet either current observed yields or expectations of technological change, and are therefore generally lower than the yields used in the economic analysis for the year 2060.

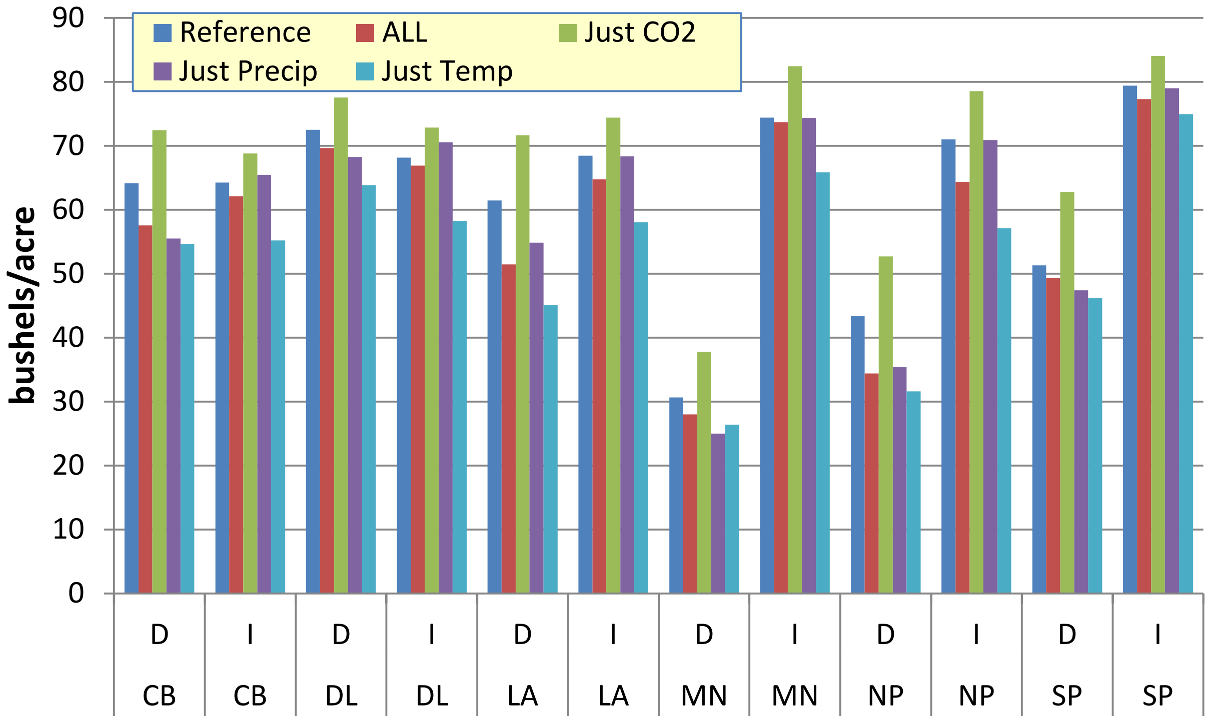
[1] For a complete list of EPIC's parameters, see the EPIC documentation at http://epicapex.brc.tamus.edu/media/23015/epic0509usermanualupdated.pdf



Appendix Figure 1: Impacts on corn yields of individual elements of climate change for the CSIRO_A1B projection in 2060.



Appendix Figure 2: Impacts on soybean yields of individual elements of climate change for the CSIRO_A1B projection in 2060.



Appendix Figure 3: Impacts on wheat yields of individual elements of climate change for the CSIRO_A1B projection in 2060.

The figures illustrate the magnitude of the carbon dioxide fertilization effect as well as the relative impacts of the effects of temperature change versus precipitation change. The impact of carbon fertilization is variable across crops and regions (revealed by third column relative to first column). Corn, a C_4 crop, experiences a negligible CO_2 impact when irrigated, but a more substantial impact under dryland production, which benefits from the improved water use efficiency associated with increased CO_2 concentrations. Wheat and soybeans experience substantial yields gains on both dryland and irrigated production due to the combined impacts of improved water use efficiency and changes in radiation use efficiency. In all cases, yield impacts very by region and irrigation method.

The effects of temperature on yields are generally negative across regions for corn, soybeans, and wheat, though there are increased yields experienced in dryland corn and wheat production in the Pacific region (not shown in figure). Precipitation impacts vary and generally are not as significant as those attributable to other elements of climate change. In those cases where significant impacts occur, they are often consistent across crops; in the Northern Plains, for instance, all three crops experience declines in dryland yields as a result of decreased precipitation in those regions.

The net effect of climate change on yields depends on how the impacts of these elements balance or exacerbate one another. Corn yields, which lack a CO_2 boost to radiation use efficiency, often decline significantly; that drop is almost entirely driven by increased temperature. Under the climate scenario illustrated, soybean and wheat yields also always decline (there are climate scenarios where that is not the case in 2060).

Although crop growth parameters, and the dynamics of the relationship between climate elements and crop growth, are consistent across time periods and climate scenarios, the net effect on yields changes over time and scenario, as the balance between different elements of climate change varies. Furthermore, the aggregate yield impacts, illustrated here at the regional level, are weighted averages of what is occurring at the field scale for each of REAP's production enterprises, so the magnitude of change is not necessarily representative of what is happening for any single rotation. The results for corn growing in the corn belt, for instance, are an average of what is happening to corn yields in a continuous corn rotation and in a corn/soybean rotation (among others). Because the yield impacts of any single element of climate change are dependent on other factors in the crop production system, in particular water and nutrient constraints, those impacts can vary significantly across production enterprises for the same crop within a single region.

Dryland and irrigated production enterprises

EPIC calculates the yield and environmental implications of a set of field operations representing a specific crop rotation using defined tillage and production practices, which include irrigation, fertilizer application rates, and planting and harvest dates. Each of those combinations of rotation/tillage/input use is called a "production enterprise," and each analytical region is characterized by a set of production enterprises that define the choice set for cropland production in that region. A selection of regionally appropriate production enterprises has been derived for each analytical region using the 2007 National Resources Inventory (NRI) data. Estimates of acreage in each region under specific rotation and irrigation practice were extracted from that data, and production enterprises were designed to reflect that set of production choices. Given the diversity of farming practices, we did not attempt to comprehensively represent production in each region; production enterprises observed on fewer than 25,000 acres within a region, for instance, were not included unless that rotation had historically been more predominant in the region or for other reasons was pre-existing as a production enterprise in our EPIC database. We also focus our analysis on major fieldcrops included in our national model of agricultural production (see model discussion below), although specialty crops and minor fieldcrops may account for significant land and water resources in some regions. The list of fieldcrop rotations by analytical region used in this analysis can be found in Appendix C.

The creation of irrigated production enterprises for inclusion in the analysis required several simplifying assumptions. Rotations were defined as either dryland or fully irrigated, in which case all crops in that rotation were irrigated; there are no partially irrigated rotations included within the analysis. The amount of irrigation applied to irrigated rotations is calculated by EPIC. A small amount of plant water stress is allowed; when water stress exceeds the permitted threshold, an irrigation application is triggered. Irrigated rotations are generally fertilized at a higher rate than dryland rotations; in creating irrigated rotations we adjusted nitrogen and phosphorus application according to Agricultural Resource Management Survey (ARMS) data based on the average ratio of irrigated to dryland applications reported by Farm Production Region.[2]

[2] Applied irrigation water can vary substantially across years, depending on that year's precipitation. The fact that the fertilizer application rate on irrigated production enterprises is held fixed and does not vary with weather outcomes or applied irrigation levels is a limitation of the analysis.