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November 2015

Climate Change, Water Scarcity, and Adaptation in the U.S. Fieldcrop Sector

Elizabeth Marshall, Marcel Aillery, Scott Malcolm, and Ryan Williams

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Abstract

U.S. agriculture faces significant changes in local patterns of precipitation and temperature over the next century, with implications for regional water cycling and water availability. The effects of climate change on food production, farmer livelihoods, and consumer welfare will depend on the direction, magnitude, and rate of change in local weather conditions, as well as on the ability of the agricultural sector to adapt to changing yield and productivity patterns, production costs, and resource availability. Of particular interest is whether producer adaptation is limited, or even enhanced, by regional changes in water availability for irrigation. This analysis focuses on cropping allocations and shifts in irrigated and dryland crop area as two potential responses to climate change in U.S. fieldcrop production. Despite higher temperatures and much regional variation in production response, U.S. irrigated fieldcrop acreage and water used for irrigation tend to decline with long-term climate change. Driving the decline in water use are changes in crop growth due to temperature stress, changes in growing-season precipitation, and shifts in surface-water supply availability. Changes in the relative profitability of dryland and irrigated agriculture will increase irrigation demand in some major irrigated regions and reduce demand in others.

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

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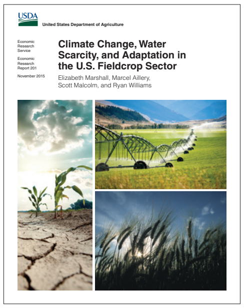
A report summary from the Economic Research Service November 2015



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Climate Change, Water Scarcity, and Adaptation in the U.S. Fieldcrop Sector

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What Is the Issue?

U.S. agriculture faces a changing production environment due to shifts in global climatic conditions. Climate models predict wide-ranging impacts on local temperature and precipitation patterns, with broad implications for crop yields, crop-water demand, water-supply availability, farmer livelihoods, and consumer welfare.

Adaptive farming strategies can help producers reduce the costs of climate change. Farmers can respond to climate-induced shifts in relative profitability by changing crops, rotations, production methods, and amount of cropland cultivated. Shifts in the extent and intensity of irrigation have also been widely proposed as a response to warmer conditions. The reallocation of production acreage and methods in response to climate change may be constrained, however, by limits on the regional availability of cropland and water resources. This report explores regional patterns of change in fieldcrop production and in the intensity and extent of irrigation under various climate projections of future temperature and precipitation patterns. We look specifically at changes in growing conditions and crop yields, changes in profitability due to shifting comparative advantages, and constraints on irrigation water supply.

What Did the Study Find?

Projected changes in climate are likely to alter growing conditions across important agricultural regions in the United States. Key findings of this study at the national level include:

- Average yields are projected to decline as a result of climate change for corn, soybeans, rice, sorghum, cotton, oats, and silage under both irrigated and dryland production as early as 2020, relative to projected yields assuming no climate change.

- Changing climate conditions generally increase the profitability of irrigated production relative to dryland production before midcentury. After that, the premium received by irrigated crops declines across several climate projections and crops. The declining benefits of irrigation are driven by: shifting patterns of precipitation, which affect both costs of irrigation (through volume of water applied) and the yield premium achievable through irrigation; temperature-related crop yield impacts for both irrigated and dryland production; and differences in carbon fertilization impacts on crops grown under dryland production versus those that are predominantly irrigated.

- Future irrigated crop acreage declines as a result of climate change across analysis years 2020 through 2080. Before midcentury, the decline is largely driven by regional constraints on surface-water availability for irrigation. Beyond midcentury, the decline reflects a combination of regional surface-water shortages and declining relative profitability of irrigated production.

- Averaged across climate projections, production drops for all crops due to climate change in 2020, relative to baseline production levels for that year. In 2040 and beyond, wheat, hay, and barley production levels increase as average yields increase, resulting in above-reference production levels for all three by 2080.

Summary table

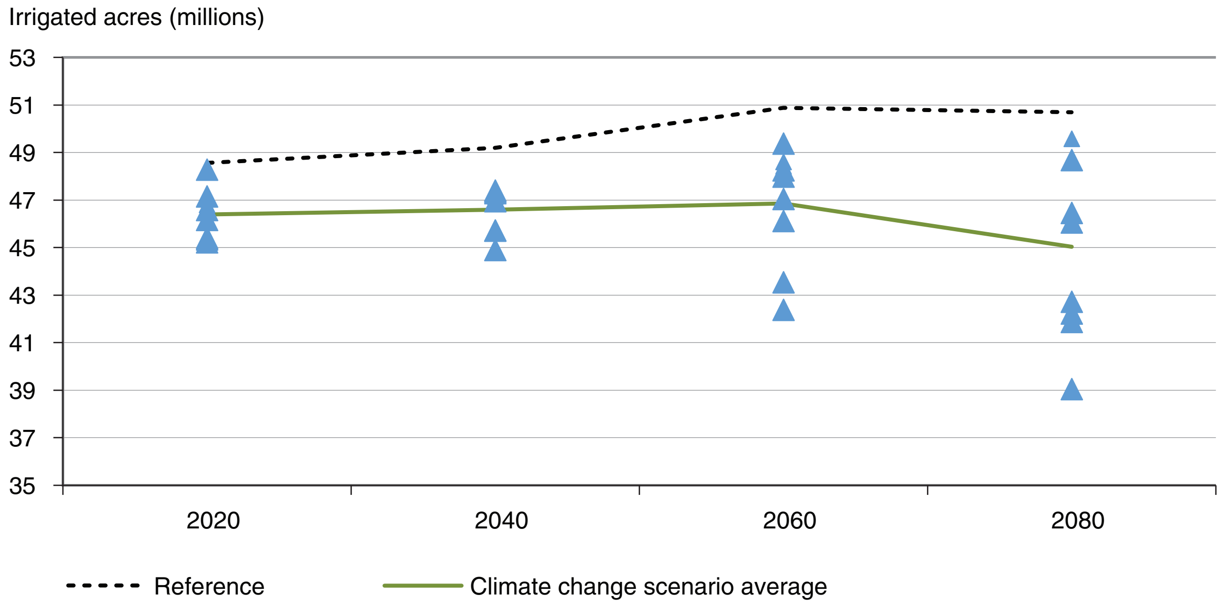
Percent change in U.S. production (averaged across climate scenarios) relative to reference conditions

	Average % change in production			
	2020	**2040**	**2060**	**2080**
Barley (bushels)	-1.9	-0.6	-3.5	1.0
Corn (bushels)	-8.1	-8.7	-13.8	-16.2
Cotton (bales)	-7.9	-6.1	-5.6	-5.9
Hay (dry tons)	-4.0	-0.6	2.7	4.2
Oats (bushels)	-8.7	-10.7	-16.1	-20.8
Rice (cwt)	-2.2	-2.5	-4.2	-6.1
Silage (dry tons)	-6.9	-9.5	-13.1	-14.4
Sorghum (bushels)	-15.1	-5.4	-14.0	-17.0
Soybeans (bushels)	-8.1	-8.8	-11.9	-14.3
Wheat (bushels)	-2.8	1.3	5.6	11.6

Source: USDA, Economic Research Service

Summary figure

Extent of irrigated fieldcrop acreage under reference weather and under climate change projections



Note: This is a simplified version of figure 7. Markers represent irrigated acreage under nine possible climate futures representing growing conditions derived from multiple general circulation climate models under multiple carbon emissions assumptions between 2020 and 2080. Reference line represents irrigated acreage assuming a continuation of growing conditions averaged over 2001-2008.
Source: USDA, Economic Research Service.

Commodity prices rise as a result of climate change under most climate projections. Despite higher prices, producer welfare (aggregated across fieldcrop sectors) also declines due to declining yields and crop returns.

Climate-induced impacts on relative profitability of cropping systems, farm returns, irrigated acreage, and production levels vary regionally. These differences reflect regional variation in cropping patterns, reliance on irrigation, and the direction and magnitude of climate change impacts. Key regional findings include:

- Production returns decline in the ***Corn Belt*** across all climate projections, reflecting the sensitivity of corn yields to increasing temperature stress.
- Agriculture faces increased water scarcity in major irrigated areas, with projected surface-water reductions (relative to reference use levels) ranging from 20 percent to more than 50 percent across areas of the ***central and southern Mountain, Pacific, and Plains*** regions by 2060.
- Across the ***northern tier of the Pacific, Mountain, and Northern Plains*** regions, projected reductions in irrigated area are driven by increased precipitation and declines in the relative profitability of irrigated cropping systems. In the ***southern Pacific and Mountain*** regions, climate-induced surface-water shortages combine with declining irrigation returns to reduce irrigated area under most climate scenarios.
- In the ***Southern Plains***, increasingly limited water supplies reduce irrigated acreage, although climate effects on surface-water supplies are dwarfed by projected reductions in groundwater withdrawals from the Ogallala aquifer.
- In the ***Delta*** region, the relative profitability of irrigated production generally increases under climate change, creating an incentive for expanding irrigated acreage. Water-supply constraints, however—primarily limits on groundwater availability—prevent that expansion.

How Was the Study Conducted?

This analysis draws on downscaled projections of temperature and precipitation under reference climate conditions as well as nine climate change scenarios for 2020, 2040, 2060, and 2080. Climate data, and the potential regional surface-water shortages associated with each climate projection, were calculated based on scenarios developed for the USDA Forest Service's Resources Planning Act (RPA) assessment of renewable natural resources. Nine future climate projections were explored, which include three different General Circulation Models (GCMs) applied to each of three of the emissions scenarios in the Intergovernmental Panel on Climate Change Special Report on Emission Scenarios (SRES). We entered changes in climate parameters into a crop-growth simulator to estimate their effect on crop yields and per-acre irrigation demand under alternative climate scenarios. We combine projected surface-water shortages and groundwater withdrawal reductions to derive regional constraints on irrigation water supply for each climate projection. ERS' Regional Environment and Agriculture Programming (REAP) model was used to project shifts in regional agricultural production and irrigation patterns, crop prices, regional farm income, and producer and consumer welfare, given climate-induced changes in crop yields and crop water demand, regional estimates of reductions in irrigation water availability, and market price effects.

Introduction

Agricultural production has always been closely linked with, and vulnerable to, variability and trends in weather. Farmers have learned to respond to regional weather patterns and variability through adjustments in cropping systems and production enterprises. However, the range of local weather conditions that has shaped the current structure of U.S. agriculture is itself changing in accord with national and global shifts in climate. Climate conditions changed 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 rapid increases in average temperature that are likely to greatly alter local patterns of temperature and precipitation.

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). Adaptation to changing production conditions is nothing new for farmers. Farmers have had to adapt to changes in crop demand and market prices, technological developments, evolving farm policy and regulatory environments, and shifts in development pressures on land and water supplies.

Variability in weather is one of the most significant, and uncertain, factors affecting farm returns, and farmers have developed strategies for adapting to weather as it unfolds. Corn farmers in the Corn Belt, for example, may push back planting dates in response to a wet spring and possibly switch production to soybeans or other short-season crops if persistent wetness delays corn planting excessively. During extremely dry periods, farmers in the Plains States increase their use of moisture-conserving tillage practices (Ding et al., 2009). In the arid West, irrigators may adjust preseason planting decisions or draw upon available groundwater supplies in water-deficit years. Local strategies for weather adaptation are based on local production conditions, years of collective experience, and region-specific research.

The accelerating pace of climate change, however, presents new challenges as farmers face unfamiliar climatic conditions and greater incidence of extreme weather. Producer adaptation strategies include changes in cropland area, crop mix, and planting/harvest dates; reliance on irrigation and other applied inputs; and adoption of improved production management technologies and drought-tolerant crop varieties. U.S. agriculture's vulnerability and capacity to adapt is likely to vary regionally, given differences in resource endowments and projected changes in temperature and precipitation patterns. Potential shifts in the distribution of irrigated and dryland acreage will depend on each cropping system's viability and relative profitability, regional adjustments in crop-water demand and supply, and increased competition for water from nonagricultural sectors.

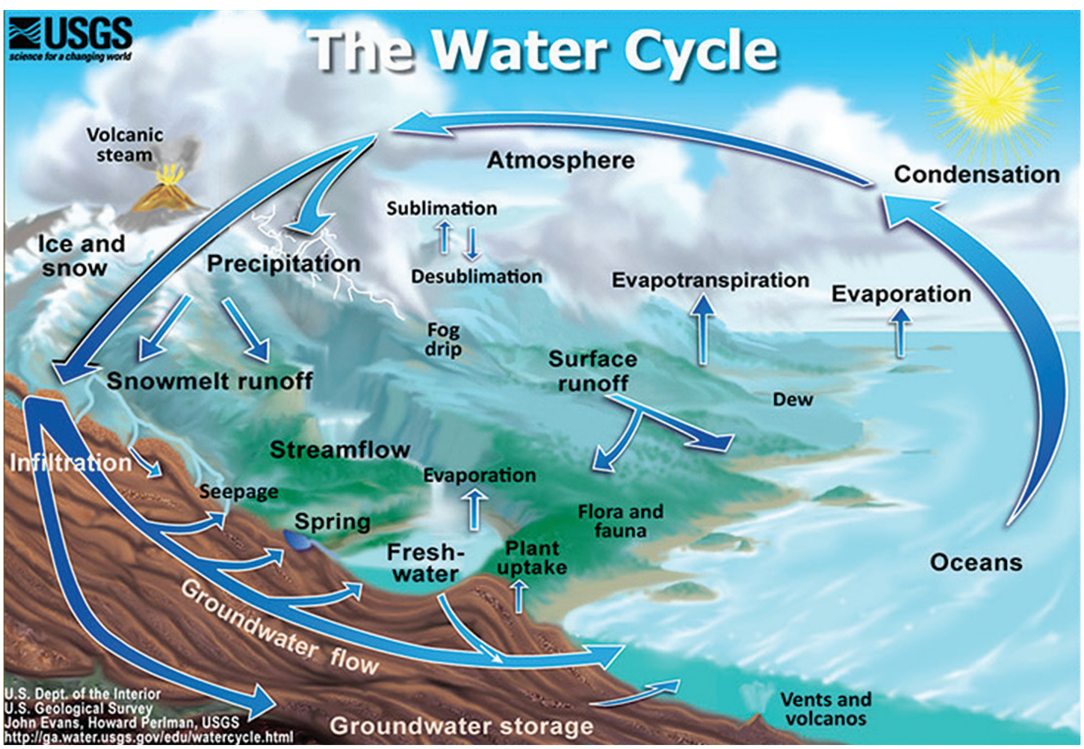
Regional impacts of a warming climate will not be uniform; while some regions may see crop growth potential wither, others may see improvements. Climate changes that alter the relative profitability of regional crop production may drive production across regions, with significant implications for local producers. Projected climate change will also likely have important regional water resource impacts. Rising temperatures and shifting precipitation patterns will have differing effects on surface water flows, as well as seasonal crop-soil moisture and growing-season precipitation. Increasing demands for water by other sectors—including expanding municipal and energy-sector water use—may combine with a changing climate to exacerbate water shortages and potentially limit the availability of irrigation water in some regions.

This report explores the yield, cost, and production impacts associated with projected increases in average monthly temperatures, regional changes in average precipitation, and increasing carbon dioxide concentration in the atmosphere, as well as the price and welfare impacts that arise from shifting patterns of production. We focus on the extent to which more expansive irrigation may be used by U.S. fieldcrop producers, exploring at a regional scale the crop-yield response to climate change, adjustments in the relative profitability of dryland versus irrigated production, and the significance of constraints on irrigation water in influencing producer decisionmaking. We first summarize climate change impacts at the national level, and then examine the relative regional importance of factors driving adjustments in irrigated and dryland production under changing climate regimes.

Climate change and agricultural water resources

The availability of freshwater supplies for agriculture and other sectors is affected by complicated water-cycle interactions across land, water, and atmosphere (fig. 1). Changes in climate can affect hydrologic processes all along the cycle, with implications for the magnitude, timing, and form of water transfers. Higher temperatures and shifting precipitation patterns alter seasonal soil-moisture reserves as well as surface-water and groundwater supplies for irrigated production. A warming climate will affect agricultural water demand through shifts in crop productivity, crop-water requirements, and costs of water access. Resulting changes in the relative competitiveness of cropping regimes, in turn, will drive shifts in crop allocations, production systems, and input use. Regional production impacts will depend on climate-induced changes to hydrologic systems and the sensitivity of current cropping regimes to shifts in water requirements and water availability.

Figure 1
Water cycle interactions across land, water, and atmosphere



Source: http://water.usgs.gov/edu/watercycle.html

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). While general circulation models are fairly consistent in predicting temperature increases under greenhouse gas (GHG) emission assumptions, future precipitation patterns and their effect on hydrologic systems are more uncertain. Nonetheless, some general trends in precipitation patterns have emerged from the climate-modeling literature. Annual precipitation is projected to increase across the higher latitudes of the Eastern, Central and Western United States, with the potential for less precipitation in other regions (IPCC, 2007; TNC, 2009). Seasonal precipitation patterns may also shift in some regions, with a greater share of annual precipitation projected to fall in the winter and early spring. Rising temperatures would interact with shifting precipitation regimes, resulting in increasingly dry conditions during the summer growing season across much of the United States. 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. Dryland production is particularly sensitive to climate, 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 under rising temperatures are offset or exacerbated by changes in precipitation. Changes in the seasonality of precipitation may also affect crops differently, reflecting the seasonal timing and duration of crop-growing seasons. Projected increases in the variability of precipitation are particularly worrisome for dryland systems. Heightened storm intensity increases fieldwater runoff, reducing the share of precipitation that infiltrates the crop root zone (SWCS, 2003).[1] In areas subject to warmer and drier conditions, projected increases in drought frequency and severity may heighten annual variability of dryland yields. The capacity of local soils, tillage systems, and crop rotations to retain available moisture during drought will determine the continued viability of dryland production.

Under irrigated production, deficits in natural soil moisture may be replenished during the growing season through applied irrigation water. In the arid West, irrigation is the primary source of crop water in most years. In more humid regions, irrigation supplements soil moisture reserves, particularly when rainfall is below normal. While irrigation reduces the risk of uncertain seasonal rainfall, irrigators too may be subject to variability in the availability and cost of purchased water supplies.

Sources of irrigation water may fare differently under climate change as well. Surface-water sources account for roughly 57 percent of water withdrawals for irrigated crop production nationally, with the remaining 43 percent supplied by groundwater (Maupin et al., 2014). Climate change is likely to have an especially important impact on surface-water resources, given the importance of regional precipitation projections on basin-water yield and surface-water flows. Surface-water flows may increase in the Northern United States where annual precipitation is projected to increase. Potential precipitation shifts with warming temperatures in the Southwest may result in reduced annual flows, with a shift in seasonal flow volumes to the wetter winter months (USDI BoR, 2011). The effect of precipitation changes on water flows may be offset or compounded by temperature-induced shifts in evapotranspiration. Higher temperatures would increase evaporative losses from land and water

[1]This report does not examine potential increases in flood risk due to climate change. However, increased crop losses and yield declines due to excessive water are significant concerns in low-lying areas subject to periodic flooding (USDI BoR, 2011).

surfaces and increase transpiration losses from noncropland cover, potentially lessening annual runoff and instream flow for a given level of precipitation.[2]

Snowpack is an important determinant of the magnitude and timing of seasonal runoff and stored water reserves. Changes in the accumulations and timing of snow and ice meltoff can have profound impacts on surface-water resources, particularly in the West where much of the surface-water runoff is derived from mountain snowmelt. Stored water reserves are projected to decline in many river basins, especially in the critical summer growing season when crop-water demands are greatest (USDI BoR, 2011). In basins with significant reservoir storage capacity, variability in annual and seasonal runoff may be mitigated through carryover storage. Where storage capacity is limited or water is diverted directly from streams, changes in the quantity and timing of spring/summer runoff may significantly impact water supplies.

Research on climate-related groundwater effects is more scarce. Groundwater is a primary water source for irrigation in the Plains States and an important source for the Eastern States, as well as areas of the Mountain and Pacific West. For many producers, groundwater is a backup irrigation supply when drought limits access to surface water. While groundwater aquifers are generally less influenced in the short term by weather patterns, changing climate patterns can affect groundwater systems over time (Dettinger and Earman, 2007). Shifts in annual precipitation and streamflow volumes may alter the recharge of nonconfined aquifers depending on soil and hydrologic conditions. Other climate-related factors—including changes in soil evaporative loss, surface runoff, and noncrop vegetative cover—may also affect groundwater recharge.

While this study focuses on the potential effects of climate change on the availability of water for agriculture, changing climate regimes may exacerbate water ***quality*** concerns related to agriculture as well. Increased precipitation and storm intensity would likely increase soil and nutrient runoff to water bodies (SWCS, 2003). Changes in crop allocation, cultural practices, and chemical input use may affect water quality in aquifers and surface-water bodies that supply drinking water and provide wildlife habitat. Changes in water-flow volumes due to precipitation runoff may further concentrate or dilute contaminants in water bodies. Irrigation drainage flows may also shift, depending on changes in irrigated area and irrigated cropping patterns.

Adaptation to climate change may be limited by irrigation availability

Recent research on agricultural adaptation suggests that yield impacts under changing temperature and precipitation will likely lead to substantial reallocation of acreage among crops and crop rotations, both within and between regions (Malcolm et al., 2012; Attavanich et al., 2013). This study builds on that research by more closely examining climate impacts on water resources and broadening the adaptation options to include potential responses to changing water-resource regimes. In particular, we consider potential adjustments in U.S. irrigated fieldcrop production and constraints to irrigation-related adaptation that may arise due to changes in the availability of irrigation water.

Agriculture's capacity to adapt to shifting crop-water regimes under climate change will be determined, in part, by factors influencing the extent and regional distribution of U.S. irrigated production. In water-limited areas of the arid West, climate change effects on regional

[2]Other factors—including precipitation, radiation, cloud cover, humidity, wind velocity, and atmospheric carbon—likely affect rates of evapotranspiration, although how such factors interact under a changing climate has not been thoroughly studied.

water supplies are likely to affect irrigated acreage. With warming, agriculture is projected to become increasingly water constrained across much of the central and southern portions of the Pacific, Mountain, and Plains regions, with potential declines in stored water reserves during the summer growing season (USDA FS, 2012; USDI BoR, 2011). Increasing competition for water from nonagricultural uses, coupled with farmland conversion in expanding urban areas, is likely to intensify pressure on the irrigated land base. In other regions where annual precipitation and runoff are projected to increase, or where reservoir capacity is adequate to capture and store seasonal shifts in peak runoff, pressure on agricultural water supplies may be lessened. Groundwater substitution may be an important adaptation, although groundwater reserves are generally in decline in major irrigated areas.

Climate change will affect the relative profitability of irrigated production

Changing climate patterns will reset the relative competitiveness of dryland versus irrigated production, with implications for land allocation and management decisions. Irrigated returns generally exceed returns to dryland production across more arid portions of the West. In the more humid eastern and northern regions, dryland production is more competitive under prevailing climate conditions. The premium received by irrigated production may be sensitive, however, to small differences in climatic factors, and land transfer between the two uses can occur (and the two types of production often coexist) even as irrigated production, when averaged regionally, remains more profitable than dryland. The coexistence of irrigated and dryland cropping systems reflects considerable intraregional variation in local production systems, soils, and water supplies, as well as differences in capital assets and management across farms. Water availability also varies temporally, and the premium received by irrigation may vary significantly across years depending on weather and price conditions. Under drought conditions that widen the difference between dryland and irrigated yields, relative returns to irrigation are likely to increase.

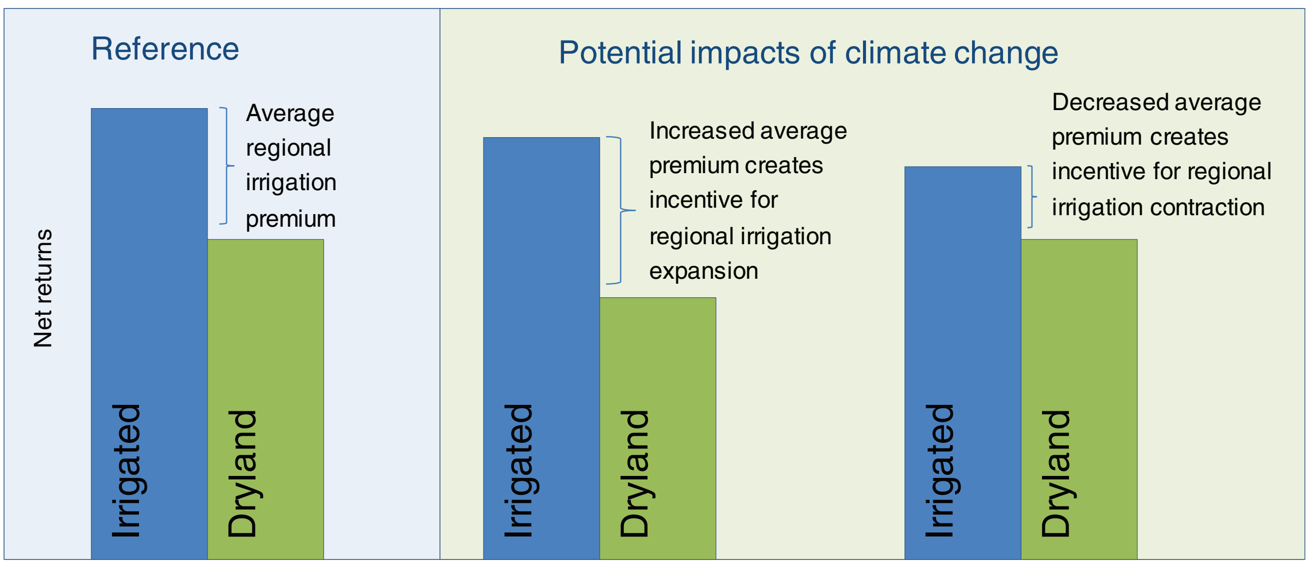
In this analysis, changes in the relative profitability of crops or management practices are the primary driver of changes in acreage allocation. The average regional premium received from irrigation under reference climate conditions forms a baseline against which premiums received under alternative climate scenarios are measured; increases in the average regional irrigation premium relative to the reference create incentives for expansion in irrigated acreage, while decreases in the premium signal the opposite (fig. 2). Climate impacts may affect the relative profitability of dryland and irrigated cropping systems through changes in crop yield and input costs (see box "Disentangling the Complex Climate Effects on Profitability of Irrigated and Dryland Production").

This analysis uses a biophysical crop-growth simulation model to explore in detail the impacts of climate change on regional growing conditions, yields, and crop-water demand in both dryland and irrigated production of major field crops in the United States. The implications of those changes in growing conditions for the relative profitability of crops, crop rotations, and production methods (including dryland versus irrigated) then drives adjustments in land allocation within and among regions in response to changing patterns of comparative advantage. This report includes a review of the aggregate impacts of climate change—both biophysical impacts and the adaptation response—on production, prices, and regional returns to producers under alternative projections of climate conditions throughout the 21st century. The report then explores that adaptation dynamic both with and without projected water availability constraints to isolate the impact of changes in relative profitability from those of future water-scarcity projections to assess the regional importance of irrigation scarcity under climate change.

Consideration of several important aspects of climate change and producer decisionmaking are beyond the scope of this report. Changes in climate conditions will have substantial impacts on the incidence and impacts of pests and disease (Malcolm et al., 2012; Walthall et al. 2012), for instance, but information limitations preclude us from including yield and management cost implications of such biotic impacts in this analysis. Furthermore, irrigated production systems and other field practices are adopted in part as risk-management strategies to protect crops and farmers against extreme weather conditions; risk-averse farmers may choose to put irrigation systems in place, even when yield premiums are low relative to dryland systems, in order to avoid the negative impacts of periodic droughts. The role of risk aversion as a factor in farmer decisionmaking is not explored in this report.

Figure 2

Incentives for acreage change in this analysis are driven by changes in relative profitability across crops, rotations, and production methods, such as irrigated versus dryland production



Source: USDA, Economic Research Service.

Disentangling the Complex Climate Effects on Profitability of Irrigated and Dryland Production

In regions with significant concentrations of irrigated production, irrigated cropping systems are often fundamentally different than local dryland cropping systems. Irrigated production is generally more productive and input intensive, with higher yields achieved through applied water as well as higher levels of applied nutrients and pesticides, field equipment use, and management. Differences in crop productivity may also reflect heterogeneity in soils, topography, and climate conditions typical of local irrigated and dryland production. In many regions, irrigated crops may differ from those grown under dryland conditions. Consequently, climate interacts differently with irrigated and dryland production, and a changing climate may affect the relative competitiveness of irrigated and dryland cropping systems in many ways.

Crop yields. Relative returns to irrigated and dryland production may be directly impacted through differential impacts on crop yields. Changes in crop yield will depend on the relative sensitivity of crops to shifting climatic factors and the coincidence of regional climatic shifts with geographic patterns of irrigated and dryland production. Yield response may differ under irrigated and dryland growing conditions reflecting various biophysical factors (e.g., humidity effects on canopy temperature, interaction of temperature with crop-water evapotranspiration and crop-level differences in photosynthesis and plant water-use efficiency due to carbon fertilization). The effect of climate change on yield will also vary with annual weather; irrigated-dryland yield differentials are most significant during drought years when natural precipitation is insufficient for full crop development. Yield trends may also change over time with the development and diffusion of new crop cultivars, which may be oriented toward drought tolerance in dryland cropping systems. As agriculture adapts to global climate change, plant breeding and genetic enhancement may offer critical assistance in producers' long-term response to the expected challenges of climate change.

Water costs. In general, irrigated production costs are typically higher than costs of dryland production, reflecting in part the costs of water access and distribution and more intensive use of production inputs. The largest cost differentials occur in more arid regions of the United States where applied water per acre is greatest and irrigation accounts for a higher proportion of crop water demand. Shifts in the physical availability of surface and groundwater supplies may alter water costs for agricultural uses, although costs of purchased surface water and pumped groundwater may not necessarily reflect the scarcity value of water. Increasing competition for water, due in part to climate effects, is likely to increase pressures on both the availability and cost of irrigation water supplies.

Energy costs. Energy use is generally greater under irrigated cropping systems, reflecting the cost of irrigation pumping and more intensive field operations and input use. Climate change may indirectly affect energy costs in agricultural production via changes in aggregate energy demand, hydropower generation costs, and climate mitigation efforts. Energy cost adjustments would have a relatively large impact on irrigation returns, with regional effects varying depending on the predominant energy source used. Shifts in the cost of petroleum-based nitrogen fertilizer may also have a disproportionately large effect on irrigated returns due to greater use of chemical fertilizers in irrigated production.

continued—

Commodity prices. Commodity market dynamics may have differential impacts on irrigated and dryland production. Changing climate conditions affect commodity production through producer land and input allocation decisions, which in turn, influence changes in crop prices. As higher irrigated revenues are required to cover the higher costs of production, irrigation returns may be particularly sensitive to commodity price fluctuations, depending on relative profit margins of local irrigated and dryland production. To the extent that commodity market dynamics affect returns to irrigation, market factors may be an important determinant of irrigated acreage response.

Prior research on climate impacts in agriculture

A comprehensive analysis of climate impacts on agriculture requires integration of frontier knowledge from multiple disciplines and areas of expertise (Beach et al., 2010; Hertel and Rosch 2010; Tubiello et al., 2007). Despite a significant foundation of research on the impacts of climate on agriculture, the scope and methods associated with that research continue to evolve. Ongoing interdisciplinary efforts are intended to address issues related to lack of consistent data, poor communication across disciplines, and the resource challenges associated with developing new data sets and analysis tools (Antle et al., 2015).

Several regional and national studies have predicted that U.S. farmers will be fairly resilient to climate change in the short term, expanding irrigated acreage, shifting cropping patterns toward higher value crops, and adjusting inputs and outputs to compensate for changing yields (Adams et al., 1990; Mendelsohn et al., 1994). Capacity for adaptation is a critical determinant of the net economic impacts of climate change and of the regional distribution of those impacts. Adaptive behavior can significantly mitigate the potential impacts of climate change on food production, farm income, and food security by moving agricultural production out of regions with newly reduced comparative advantage and into areas with improved relative productivity (Darwin et al., 1995; Rosenzweig and Parry, 1994; Mendelsohn and Dinar, 1999; Beach et al., 2010; Malcolm et al., 2012). Reilly and colleagues (2007) find that with adaptation, the production effects of climate change are reduced to less than 20 percent of the initial biophysical impact on yield.

Conclusions about likely yield impacts are highly sensitive to which climate change projection is used, the timeframe of the analysis, and assumptions about the impacts of uncertain processes such as carbon fertilization. Reilly and colleagues (2003) analyzed climate impacts on U.S. agriculture and projected (based on results from four climate models) that, on average, climate change would increase yields both in 2030 and 2090. Yield increases were regionally variable, however, with yields in the South more severely impacted than in the North. Short-term projections suggesting that climate change in temperate regions will increase yields in agriculturally important regions such as the Corn Belt are consistent with IPCC findings; the IPCC (2007) judged that "moderate climate change will likely increase yields of North American rainfed agriculture" and that crop productivity will increase slightly at mid to high latitudes under increases in local mean temperature of 1 to 3°C.

This projected increase in yields resulted in net positive estimates of welfare change in the United States, with stakeholders faring differently (Reilly et al., 2003). Agricultural producers, for instance, are affected both by the initial yield effect and then by subsequent price effects. Reilly and colleagues (2003) estimated an increase in U.S. consumer welfare from climate change, with productivity increases resulting in declining prices paid by consumers. However, net producer welfare declines because the drop in prices offsets producer benefits accruing from yield increases. As with yields, producer returns are more negatively affected in Southern production regions.

Other studies also suggest that moderate levels of climate change will increase U.S. fieldcrop production, driving down prices and net producer returns while increasing the benefits accruing to consumers and foreign trade partners (Adams et al., 1998; Adams et al., 2003). Alig and colleagues (2002) found a similar dynamic applied when the analysis included climate impacts on forest productivity; a projected increase in forest productivity leads to greater forest inventory and harvests, lower prices, and lower returns to timberland owners. The net economic impact on producers, however, depends on the magnitude of the price impact in response to yield improvements for timber. Sands and Edmonds (2005) found that the observed price effect did not always fully erode the bump in producer returns arising from increased yields. Under two of three climate scenarios evaluated, both consumer and producer welfare increased in response to climate change.

Yield and economic impact assessment results are, however, sensitive to the timeframe chosen for analysis and to the rate of change assumed by different climate projections. The IPCC (2007) analysis projected that crop productivity would begin to decline, even in temperate regions, when temperature increases exceed 1-3° C. Burke and colleagues (2011) project that both corn yields and farm profits would decline under a large range of climate projections into the mid- and late 21st century. Sands and Edmonds (2005) find that climate change impacts vary substantially across climate projections, with most leading to aggregate increases in U.S. crop productivity but at least one leading to declines across several agriculturally important crops. There is, however, no scientific consensus on projected yield changes under climate change. Projections of increased yields, even for the short term, run contrary to recent findings that climate change has already had adverse effects on U.S. corn and soybean production in agriculturally important regions (Ainsworth and Ort, 2010; Kucharik and Serbin, 2008; Lobell and Asner, 2003; Schlenker and Roberts, 2009).

Several authors have cited the sensitivity of economic impact results to the treatment of yield-enhancing effects of atmospheric CO_2. However, few studies have assessed the yield impacts of CO_2 fertilization under actual growing conditions, and its effects, when interacting with changing nutrient and water constraints, are considered highly uncertain (Adams et al., 1995; Gornall et al., 2010; Long et al., 2005; Tubiello et al., 2007; Walthall et al., 2012). Sands and Edmonds (2005) found that when uncertain carbon fertilization effects were excluded from the calculation of crop yield impacts, crop yields declined under the three climate scenarios examined, as did indicators of both U.S. consumer and producer welfare.

In exploring the impacts of climate change on agriculture, several studies have explicitly addressed the potential role of irrigation, and/or water-supply shortages, in adaptation. Expanding irrigation has been suggested as an important strategy for mitigating the adverse effects of climate change on crop production (Döll, 2002; Howell, 2009). However, water supplies may be increasingly scarce due to expanding demand from other sectors as well as changing patterns and/or timing of precipitation under climate change (Leung et al., 2004; Barnett et al., 2005; USDA FS, 2012; Elliot et al., 2014). Prior research on the implications of climate change for irrigation water supply and demand is mixed regarding potential expansion of U.S. irrigation. Some studies project increased demand for irrigation, or expansion of irrigated acreage, as a result of warming conditions (Smith and Tirpak, 1989; Adams et al., 1990), while others project a decline in water demand and irrigated acreage due to the different impacts of climate change on irrigated versus dryland systems, increased productivity of inputs, or increased precipitation (Reilly et al., 2003; Izaurralde et al., 2003; Thomson et al., 2005). Differences across studies regarding the mechanisms driving regional irrigation and irrigated acreage change arise from differences in projections of yield impacts, scope of mechanisms for adaptation, and methodologies for estimating water availability under climate change.

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 and colleagues (2003) reported a net decrease in U.S. demand for irrigation water of approximately 5-12 percent by 2030 and 34-38 percent by 2090, with irrigated acreage declines of 3-10 percent and 40-50 percent. In general, cropland contracts with temperature stress across the Southern States, with irrigation declines concentrated in the West (Reilly et al., 2003). In a study of elevated CO_2 effects on water regimes and implications for U.S. grain production, Thomson and colleagues (2005) report declines in U.S. 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 differing effects of climate on irrigated and dryland crop productivity. In a third study of constraints and potentials for global irrigated agriculture, Elliott and colleagues (2014) project significant declines in irrigated area in the West due to increasing water scarcity and that potential for irrigation expansion in the Eastern States may be limited by costs of water access. The Elliott study highlights the sensitivity of irrigation-demand projections to estimated CO_2 effects on crop production.

Study design

In this analysis, we use regionally differentiated estimates of climate change impacts on crop production (2014) to explore agricultural production under several climate scenarios. This framework allows us to more thoroughly examine the effect of climate change on irrigation incentives and the extent to which irrigation, through changes in area irrigated or water applied, may be used as an adaptation strategy. We also use regional projections of future water supply and demand (2012) to assess how, and where, shortages in irrigation water could curtail that adaptation.

Climate change impacts are measured against a set of “reference” agricultural production conditions developed for the years 2020, 2040, 2060, and 2080. Reference conditions were developed based on expert advice, literature, and a modified extrapolation of the USDA’s 10-year baseline forecast, and reflect a continuation of historic trends (population, diet, demographics, and other socioeconomic factors), but without climate change. The Results section presents the national impacts of climate change projections on fieldcrop production, relative to future reference conditions, and explores the implications for resource use, price, and consumer/producer welfare. Results assume that farmers are free to adapt to changing patterns of comparative advantage across crops and regions, but constrained by projected changes in irrigation water supply from ground- and surface-water sources.

To explore the sensitivity of the regional production and adaptation response, including irrigation extent and intensity, to shifting climate parameters and other factors projected to change with time, we conduct supporting analyses that are designed to illustrate the relative importance of various production drivers (table 1). The supporting analyses include:

- ***Biophysical Impacts:*** This analysis focuses on the biophysical crop-yield response to climate change by fixing production acreage at reference acreage allocations and assessing the impact of the new weather scenarios on aggregate measures of crop yield, production, and irrigation-water demand. This analysis is a naïve representation of potential futures under climate change, as it allows for no adaptive response or reallocation of acreage, but it isolates and clarifies the biophysical impacts of climate change that emerge from our analysis. As crop- and field-level impacts are the fundamental drivers of adaptation and resulting market dynamics, it is useful to understand the pattern and magnitude of biophysical response across crops, regions, and climate projections.

- ***Relative Profitability:*** This analysis examines producers' adaptive response to biophysical impacts of climate change through reallocation of acreage both spatially and across production enterprises (crop/rotation, tillage type, irrigation/dryland). The analysis explores the effects of climate-induced changes in the relative profitability of production enterprises on patterns and methods of production. The land allocation analysis does not incorporate constraints based on projections of future water supply associated with changing climate, as the analysis is intended to isolate adaptive responses attributable to changes in relative crop returns.

- ***Irrigation Constraints:*** This analysis explores the relative impacts of groundwater and surface-water supply constraints on production, prices, regional irrigated acreage, and regional producer returns under projected climate scenarios. The impact of regional water scarcity on producers' adaptive response is compared to the relative contribution of field-level biophysical effects and shifts in relative crop returns.

In evaluating climate effects on the irrigated field crop sector, we explore the extent to which climate impacts on regional irrigation demand are driven by changes in crop yield and crop water use (as identified in the Biophysical Impacts analysis), adjustments in the relative competitiveness of irrigated and dryland production enterprises (as addressed in the Relative Profitability analysis), and absolute availability (or shortages) of irrigation water supply (as examined in the Irrigation Constraints analysis). Understanding the importance of each of these factors across U.S. regions and field crops over time can help in the crafting of resilience strategies and programs under uncertain climate conditions.

Table 1

Assumptions defining the analyses included in this report

	Results	**Supporting Analyses**		
	Integrated economic analysis	Biophysical Impacts analysis	Relative Profitability analysis	Irrigation Constraints analysis
Biophysical yield impacts of climate change	yes	yes	yes	yes
Flexible production acreage (producer adaptation)	yes		yes	yes
Constraints on available irrigation water	yes			Disaggregates constraints into groundwater and surface-water constraints to compare results

Source: USDA, Economic Research Service

Integrating Climate Change, Water Resources, and Adaptation

This analysis uses a suite of models and supporting databases to explore interactions between climate change, water resources, and producer adaptation. We examine several projections of climate change to estimate the regional impacts of changing climate conditions on yields and crop irrigation requirements. These regional impacts are then used as inputs into an economic model of the U.S. agricultural sector to assess the producer response to those impacts, and resulting national and regional production, prices, farm returns, and other measures of producer and consumer welfare (see Appendix A for a more detailed explanation of our research methodology).

As future emissions trajectories are highly uncertain, we explore climate outcomes associated with three carbon emissions scenarios: a middle emissions scenario (A1B, or _Mid in this report), a lower emissions scenario (B2, _Low), and a higher emissions scenario (A2, _High). Because climate values (temperature change, precipitation change, etc.) vary widely across general circulation models (GCMs) for a single emissions scenario, we use the results of three separate GCMs for each emissions scenario. Nine climate projections thus illustrate a range of possible climate sensitivities associated with a range of emissions scenarios (table 2).[3]

We conducted climate impact and adaptation analyses for 2020, 2040, 2060, and 2080. Climate conditions for the 2020 timeframe 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 conditions averaged over 2001-2008.

Table 2
Climate projections used in this analysis[1]

Emissions scenario	Climate models used for climate outcome estimation	Name of scenario in this analysis
Lower emissions scenario (SRES B2)	CGCM2 MR CSIROMK2 filtered HADCM3	CGCM_Low CSIRO_Low HADN_Low
Middle emissions scenario (SRES A1B)	CGCM31 MR CSIROMK3 MIROC32 MR	CGCM_Mid CSIRO_Mid MIROC_Mid
Higher emissions scenario (SRES A2)	CGCM31 MR CSIROMK3 MIROC32 MR	CGCM_High CSIRO_High MIROC_High

[1]See Appendix A for additional discussion of the climate models.
Source: USDA, Economic Research Service

[3]These climate projections were developed for the USDA Forest Service's Resources Planning Act (RPA) assessment of renewable natural resources (USDA FS, 2012); see Joyce et al. (2014) for a discussion of why these models were selected and for more details on development of the regional climate projections.

Yield impacts of climate change are estimated regionally

Changing climate can affect crop yields (and resulting uptake of water and nutrients) via multiple pathways, including:

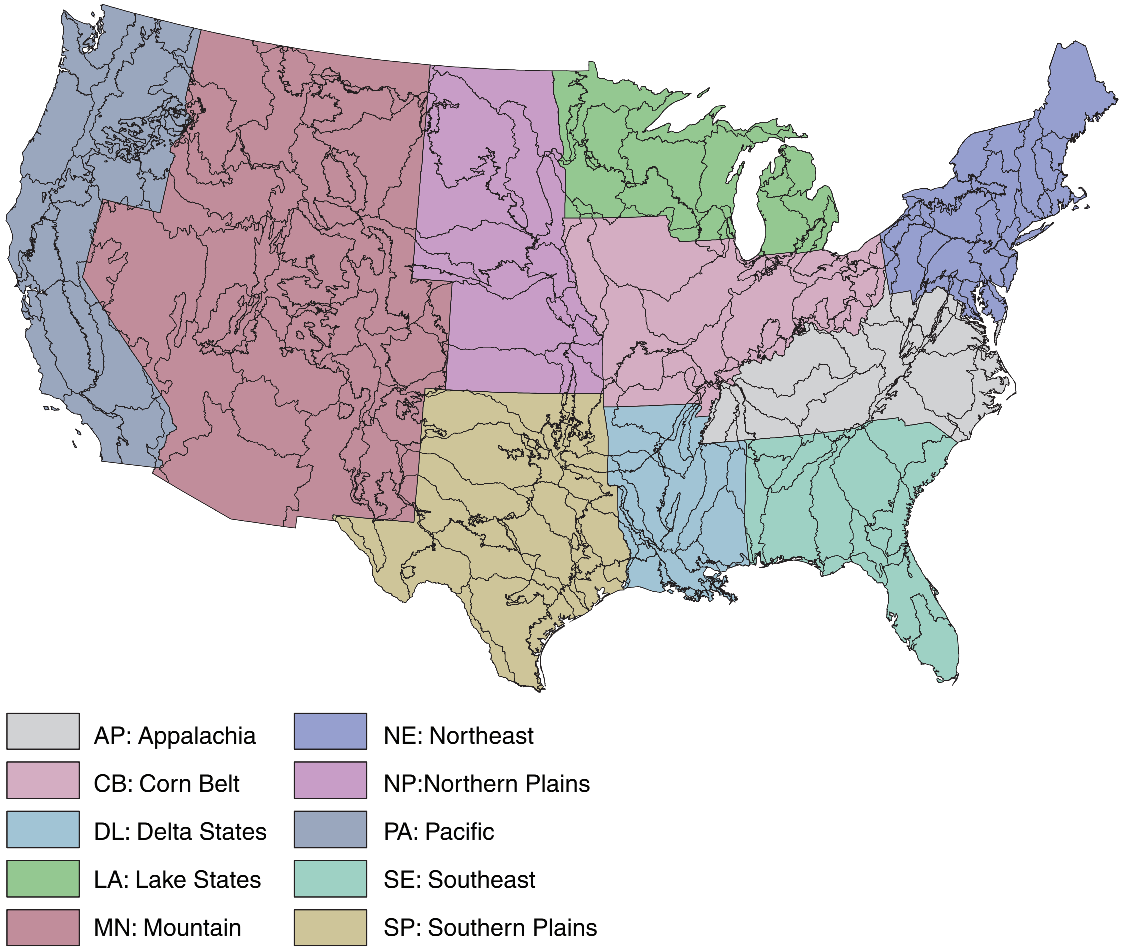
- increases in average temperature,
- local changes in rainfall amount and intensity,
- rising concentrations of CO_2 in the atmosphere,
- changes in soil fertility and erosion rates,
- changes in climatic variability and the incidence of extreme events,
- changes in the incidence of pests and disease, and
- rising concentrations of ozone and other pollutants in the atmosphere.

We account for the impacts associated with the first four of these in our crop modeling. The fifth factor—changes in the incidence of extreme events—is partially represented in our simulated growing conditions under the climate change scenarios. Walthall and colleagues (2012) argue that much of agricultural productivity is determined by environmental conditions during critical threshold growth periods. The predicted increase in extreme weather events will therefore be an increasingly significant determinant of agricultural productivity. Unfortunately, our climate impact data do not allow us to estimate changes in variability around the mean of daily temperature and precipitation, or changes in the timing of extreme temperature or precipitation events, under the future projections. When daily weather conditions are generated from a distribution with a mean that has shifted, however, even with the variance unchanged, the incidence of daily weather events that exceed current thresholds for "extreme" changes as well. Increases in average temperatures, for instance, result in an increased probability of exceeding temperature thresholds described as "extreme" by current climate standards. Decreasing average precipitation, similarly, results in an increased probability of precipitation dropping below "extreme" dry thresholds.

The remaining dynamics are beyond the scope of the present study. Prior research has suggested that climate change may exacerbate crop pressures associated with pests and disease, leading to increases in pesticide use, production costs, and externalities associated with pesticide pollution (Reilly et al., 2003; Koleva et al., 2011; Malcolm et al., 2012). Other climate factors expected to change over time—such as ground-level ozone concentrations and solar radiation—may also have an important effect on agricultural production. Both of these factors are likely to significantly increase the cost and production impacts associated with climate change (or, in the case of ozone, projected increases in air pollution) but were beyond the scope of our biophysical impact modeling.

We simulate crop production in response to changing climate conditions using the biophysical simulation model EPIC (Environmental Policy Integrated Climate model). Our analysis divides U.S. crop production into 267 regions, here called "REAP (Regional Environment and Agriculture Programming) regions," each with its own set of soil and weather conditions (fig. 3). For each region, we estimate crop yield and irrigation demand for field crop rotations identified for that region under each set of climate conditions.

Figure 3
Regional Environment and Agriculture Programming (REAP) production regions



Note: Black lines delineate the 267 analytical regions used in the Environmental Policy Integrated Climate (EPIC) calculations
Source: USDA, Economic Research Service.

Because farmers adapt to changing yield and profitability patterns, changes in climate conditions and regional yields will induce a cascading set of impacts on the agricultural sector—affecting production practices and rotations, input use and irrigation demand, production patterns and returns, commodity prices, export availability and trade, and, ultimately, producer and consumer welfare. Potential dynamics of such impacts are explored using ERS' Regional Environment and Agriculture Programming (REAP) model.

Modeling producer and market response to climate change

We use a mathematical optimization model of the U.S. agricultural sector to estimate how producers respond to climate change and how markets respond to those producer decisions. REAP allocates agricultural land use and distributes the results of production into distinct markets (domestic consumption, export, and feed use) to maximize the economic surplus that arises from agricultural production. REAP models markets for 10 major commodity crops (corn, sorghum, oats, barley, wheat, rice, cotton, soybeans, hay, and silage); a number of livestock products (dairy, swine, poultry, and beef cattle); and other retail products derived from agricultural raw materials. When REAP solves for agricultural production patterns under changed climate, technology, or policy conditions, acreage in each region is distributed among available production enterprises (crop rotations and methods of production) based on relative profitability. To capture different production conditions within each REAP region, allocation decisions are partially constrained within the model by acreage distribution parameters that reflect historically observed patterns of production (see box, "The REAP Model").

The REAP Model

The Regional Environment and Agriculture Programming Model (REAP) is a static, partial-equilibrium optimization model of the agricultural sector that quantifies agricultural production and its associated environmental outcomes for 267 regions in the United States. REAP employs detailed data (derived from the USDA Agricultural Resource and Management Survey (ARMS), the Natural Resources Inventory (NRI), and the Environmental Policy and Integrated Climate (EPIC) model) at the regional level on crop rotations, crop yields, input requirements, costs and returns, and environmental parameters to estimate longrun equilibrium outcomes. Regional production levels are determined for 10 crops and 13 livestock categories, and national production levels are determined for 20 processed products. For each REAP region, land use, crop mix, multiyear crop rotations, and tillage practices are all endogenously determined by REAP's constrained optimization process. Cropland allocations, aggregate input use, and national prices are determined endogenously. The model has been widely applied to address agri-environmental issues such as soil conservation and environmental policy design, environmental credit trading, climate change mitigation policy, and regional effects of trade agreements.

REAP is implemented as a nonlinear mathematical program using the General Algebraic Modeling System (GAMS) programming environment. The goal of the model is to find a welfare-maximizing set of crop, livestock, and processed product production levels subject to land constraints and processing/production balance requirements. Production activities for crops within a region (defined by crop rotation and tillage) are distributed according to a constant elasticity of transformation (CET) relationship; the parameters defining the CET relationship are derived by calibrating them to historically observed acreage distributions.

Shocks based on policy, technical, or environmental scenarios can be introduced as additions of or changes to constraints, modifications of baseline data assumptions, addition of terms to the objective function or a combination of approaches. Changes in policy, demand, or production/processing technology can therefore be imposed upon the model and the results examined to determine their effects on the following:

- Regional supply of crops and livestock,
- Commodity prices,
- Crop management behavior and use of production inputs,
- Farm income, and
- Environmental indicators such as nutrient and pesticide runoff, soil loss, GHG emissions, soil carbon fluxes, and energy use.

For more technical information on REAP as well as additional information on its applications, see http://www.ers.usda.gov/publications/tb-technical-bulletin/tb1916.aspx.

Climate change impacts in future periods are measured against a "reference" scenario for each period that reflects an agricultural context in which patterns of production continue to change in accord with historically observed dynamics (involving changing population, diet, demographics, and other socioeconomic factors), but without climate change (i.e., assuming "reference climate" conditions). We developed "reference scenario" conditions for 2020, 2040, 2060, and 2080 based on a combination of expert input, literature, and an extrapolation of USDA's 10-year baseline agricultural forecast; 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 (for more information on the reference scenario, see Appendix E.)

The optimal allocation of acreage in REAP is sensitive to the effect of climate on agricultural productivity and yield, which varies regionally.[4] The impacts of climate change on agricultural production are then assessed by substituting into REAP the regional yield, crop-water requirements, and cost estimates for production enterprises that were derived using the climate change projections. The REAP modeling framework reallocates production acreage under each of the climate scenarios to optimize the sum of producer and consumer surplus given the changes in regional yield and crop water use, subject to land and water resource constraints. Farmers' allocation decisions depend on changes in yields, irrigation costs (through changes in water use), and commodity price, which are also endogenous within REAP. As prices vary, consumer and producer impacts are also endogenous and can be explored separately across the climate change scenarios.

While our modeling system simulates crop production and acreage allocation decisions at the REAP region level, model results are often aggregated to "farm production region" (FPR) for simplicity in presentation (see figure 3).

Yield and water use are fixed for each crop rotation in each region under any given climate scenario, but endogenous changes in aggregate regional production, acreage, and irrigation demand emerge as cropland is reallocated across rotations and production methods. This reallocation may be constrained by the regional availability of productive land and irrigation water. Our analysis therefore incorporates constraints on regional acreage available for production and on regional availability of irrigation water under climate change.

Irrigation water use and availability

We account for the changing availability of water resources under climate change by estimating reductions in regional irrigation water for each analysis year and climate projection (see box, "Regional Survey of Agricultural Water-Supply Projections"). Such reductions arise due to changes in precipitation and temperature, as well as changes in demand from agriculture and other water-consuming sectors. Our analysis is focused on surface-water supplies, but we also consider constraints on groundwater pumping over time. Agricultural water supplies are adjusted to reflect the portion allocated to modeled field crops; while specialty crops—vegetables, fruits, and nuts—are an important source of irrigation demand, our study focuses on dynamics in the U.S. fieldcrop sector.

[4]To be more precise, yields and acreage allocation are impacted by a set of weather conditions that are randomly generated to satisfy the longer term climate condition projections.

Regional Survey of Agricultural Water-Supply Projections

Much of the policy attention regarding climate effects on irrigation water supplies has focused on the Mountain and Pacific States, reflecting both the importance of the irrigated sector in these regions and the potentially significant climate impacts on surface-water supplies (USDI BoR, 2011; Foti et al., 2012). Irrigated production accounts for 44 percent of harvested cropland acreage in the Mountain States and 66 percent in the Pacific region, including most of the regions' high-value specialty crop production (USDA NASS, 2014). In more arid areas, crop production is often entirely dependent on irrigation. The regional reliance on surface water—representing 64 percent of irrigation withdrawals in the Pacific region and 80 percent in the Mountain (Maupin et al., 2014) —is due in large part to federally financed water-supply development for agriculture and other uses.

Under a warming climate, agriculture is likely to become increasingly water-constrained across much of the central and southern portions of the Mountain West and Pacific regions. Higher temperatures with reduced annual rainfall are projected to increase soil aridity, particularly during the summer growing season. At the same time, reduced mountain snowmelt in the Southwest and central Rockies is likely to draw down surface-water reserves, potentially limiting the scale of irrigated production within the Sacramento-San Joaquin, (Upper) Rio Grande, and (Middle/Lower) Colorado River Basins, as well as the Arkansas, Republican, and Platte River systems to the east. While groundwater pumping has helped to mitigate the effect of surface-water shortfalls in dry years, declining aquifer withdrawals and increased pumping costs may limit the substitutability of groundwater for surface water. Projected increases in precipitation in the northern Rockies and Pacific Northwest, on the other hand, could result in expanded soil moisture reserves and irrigation water supplies within the Columbia and Upper Missouri River Basins (USDI BoR, 2011).

In the Plains States the irrigated crop sector is heavily reliant on groundwater, which accounts for 78 percent of irrigation withdrawals (Maupin et al., 2014)—primarily from the Ogallala Aquifer. This has helped to shield the Plain States' irrigated sector from declines in water availability. However, groundwater pumping in excess of natural recharge has caused significant water-table declines across the central and southern portions of the High Plains, and groundwater withdrawals are likely to be further constrained over the long term. In contrast, irrigation withdrawals have held relatively steady in the Northern Plains where rates of groundwater recharge are higher and groundwater reserves are more abundant. Regional river systems originating in the central Rocky Mountains are projected to face increasing reductions in dry-year flows, with implications for both surface-water supplies and groundwater recharge (USDI BoR, 2011; Foti et al., 2012). Shifting precipitation patterns may increase surface-water supplies in the Lower Missouri River Basin of the Central and Northern Plains (USDI BoR, 2011; Ojima et al., 2007).

Dryland production accounts for 85 percent of harvested acreage in the Northern Plains and 81 percent in the Southern Plains (USDA NASS, 2014). As a transitional zone between the more humid East and arid West, dryland production systems in the Plains States may be particularly susceptible to small shifts in soil moisture availability. While precipitation levels are expected

continued—

to increase in more northerly latitudes, model projections vary considerably. The net effect on soil-moisture reserves for dryland production will depend on local changes in both seasonal precipitation and soil-moisture loss under warming temperatures.

Across the relatively humid Southeast and Delta regions, irrigated production accounts for 28 percent and 50 percent of harvested cropland, respectively (USDA NASS, 2014). Groundwater is the predominant water source, representing 59 percent of irrigation withdrawals in the Southeast and 85 percent in the Delta (Maupin et al., 2014). Both regions have seen a significant expansion in irrigated production since 1980. However, groundwater tables have declined in many areas while reservoir storage is limited, restricting the capacity to manage regional surface-water shortfalls. Meanwhile, climate projections suggest drier summer conditions (Appendix B), potentially exacerbating soil-moisture deficits during drought.

In the more northern Corn Belt, Lake States, Northeast, and Appalachian regions, water availability is generally adequate for dryland crop production in normal-rainfall years. Irrigated acreage accounts for roughly 3 percent of harvested acreage across the regions (USDA NASS, 2014). However, the irrigated land base has expanded steadily in recent decades as irrigation is used increasingly to maintain yields during below-normal rainfall years. Groundwater accounts for nearly 75 percent of irrigation withdrawals across the regions, including 93 percent of withdrawals in the Corn Belt (Maupin et al., 2014). With low-cost groundwater reserves and projected increases in precipitation across the northern producing areas, water-supply reserves are likely adequate to accommodate a limited expansion in irrigated acreage.

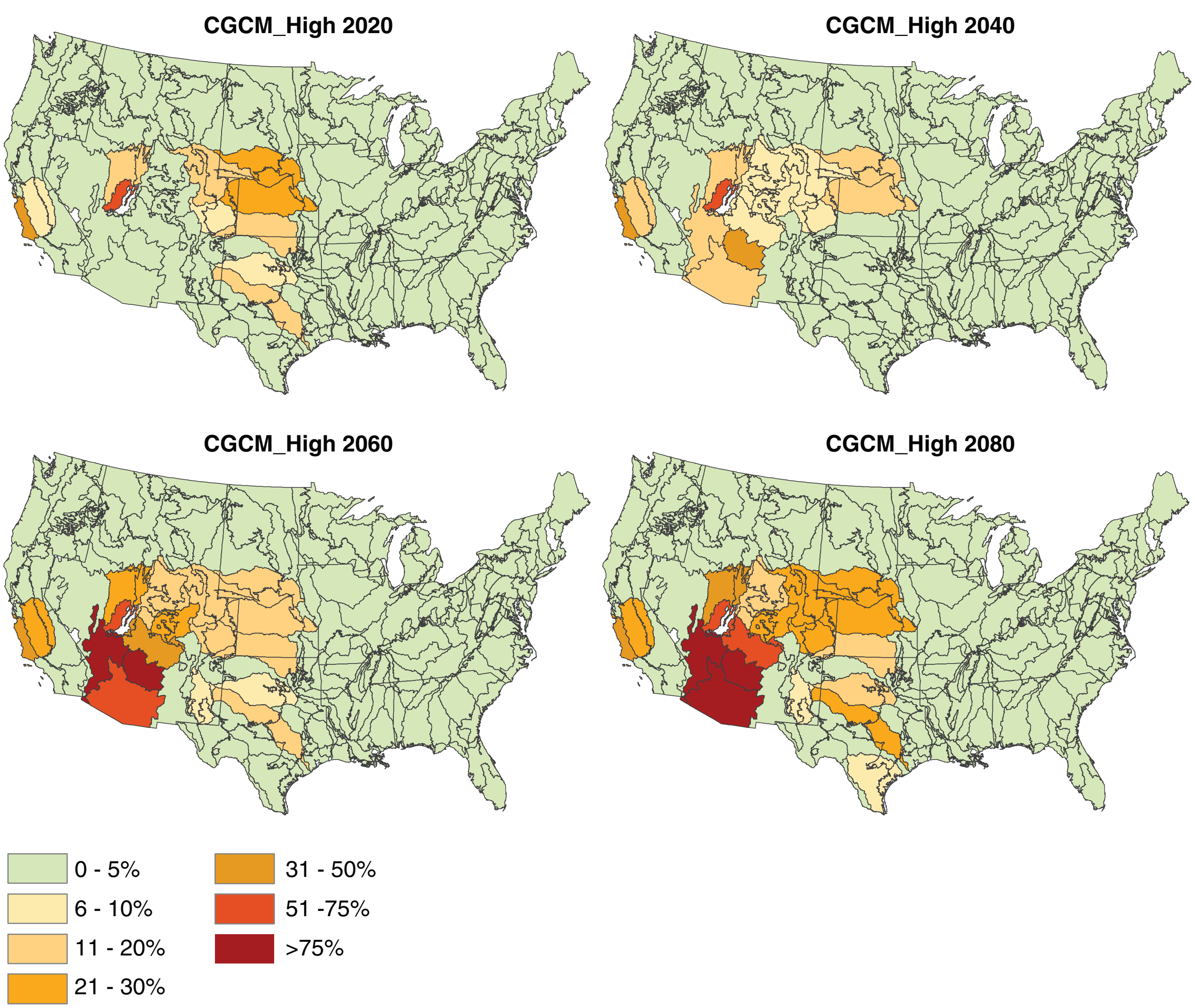
Reductions in surface-water irrigation supply under the nine climate projections are calculated from regional water-demand and water-supply estimates developed by Foti et al. (2012). Figure 4 illustrates the surface-water reductions associated with the climate projection CGCM_High (maps for the remaining projections are in Appendix F). Surface-water supply reductions (relative to current agricultural surface-water use) range from 20 percent to more than 75 percent across areas of the Mountain, Pacific, and Plains regions in 2080. The 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, surface-water supply impacts for irrigated agriculture under climate change are increasingly severe over time, with the most significant impacts occurring after 2050. These reductions are calculated based on climate conditions averaged over a 20-year window; they do not reflect the magnitude of supply reduction that could occur under multiyear drought conditions.

Changing climate may affect groundwater supplies through changes in both aquifer recharge and groundwater withdrawals. While aquifer dynamics under climate change have received increasing research attention, we do not project changes in groundwater withdrawals under alternative climate futures. Groundwater recharge is highly site-specific, based on local soils and hydrologic systems, and climate effects on groundwater are uncertain (Taylor et al., 2013). For this analysis, fixed declines in irrigation groundwater withdrawals are projected for selected regions (fig. 5), based on recent trends in irrigation withdrawals and water-table depth (USGS, 2013; Konikow, 2013), as well as estimates from the published literature. (Appendix A details how we derive estimates of reductions in groundwater and surface-water availability.)

This analysis does not consider additional water-supply development that could offset shortages in some regions. Moreover, because we do not account for the capital costs of increased irrigation infrastructure, expansion of irrigation in areas *not* projected as irrigation constrained is limited to an increase of 10 percent over reference-case volumes to avoid unreasonable levels of costless irrigation expansion. Furthermore, changing climate conditions may affect the price of surface water through shifts in market-supply conditions and water-supply development costs, as well as the cost of groundwater through changes in aquifer recharge and pumping depths. Such detailed hydrologic and institutional projections are beyond the scope of this analysis. While the amount of applied water per acre varies, as does the resulting per-acre cost of irrigation, the cost per unit of water is assumed to be constant. In this analysis, availability of irrigation water is a physical constraint to adaptation, but the increased marginal cost of water is not modeled.

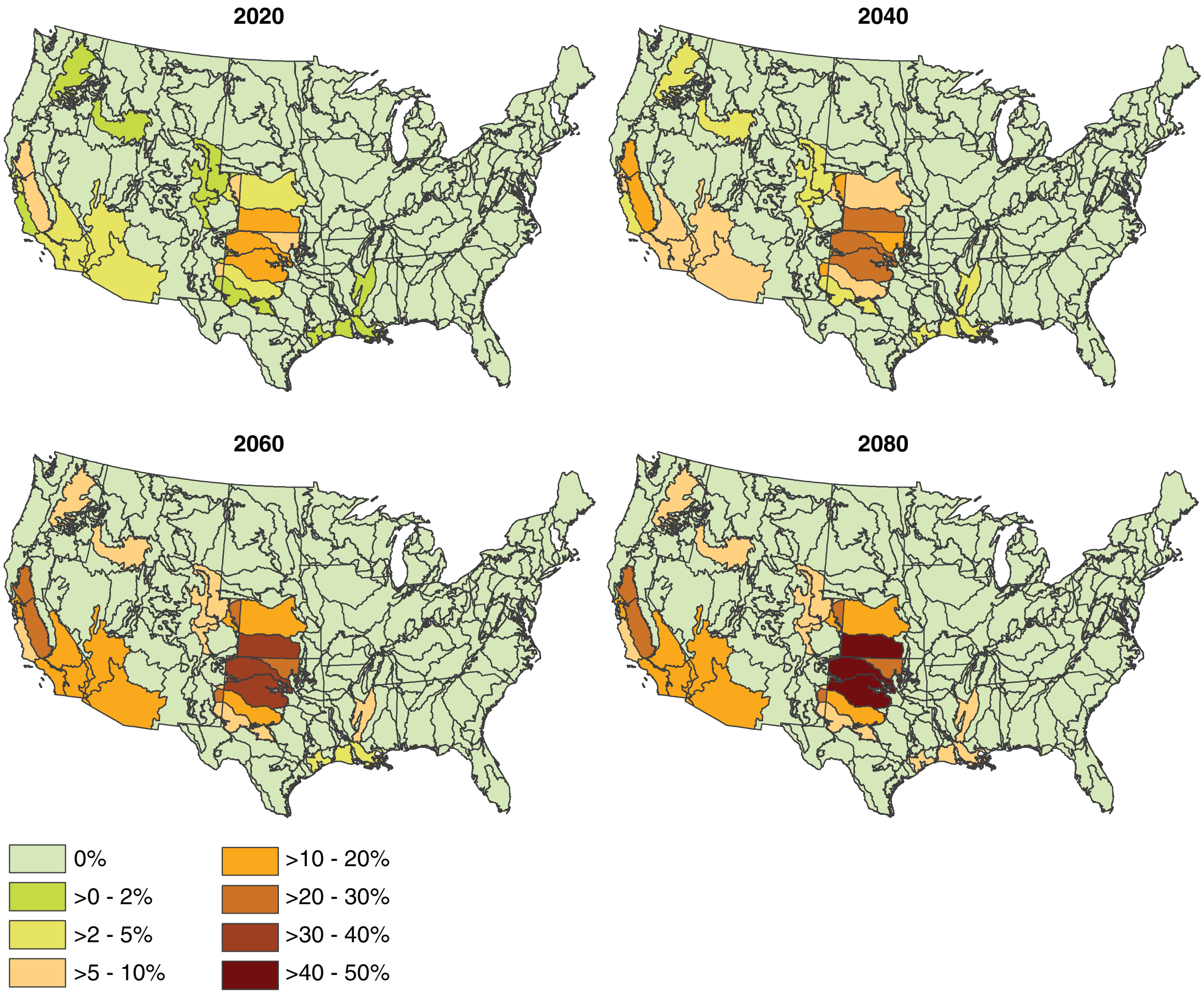
Figure 4

Reductions in surface-water supply availability for the CGCM_High projection, 2020-2080



Note: CGCM = Coupled Global Climate Model
Source: USDA, Economic Research Service.

Figure 5
Reductions in groundwater withdrawals for irrigation, 2020-2080



Source: USDA, Economic Research Service.

Results: Economic Impacts of Climate Change on U.S. Field Crops

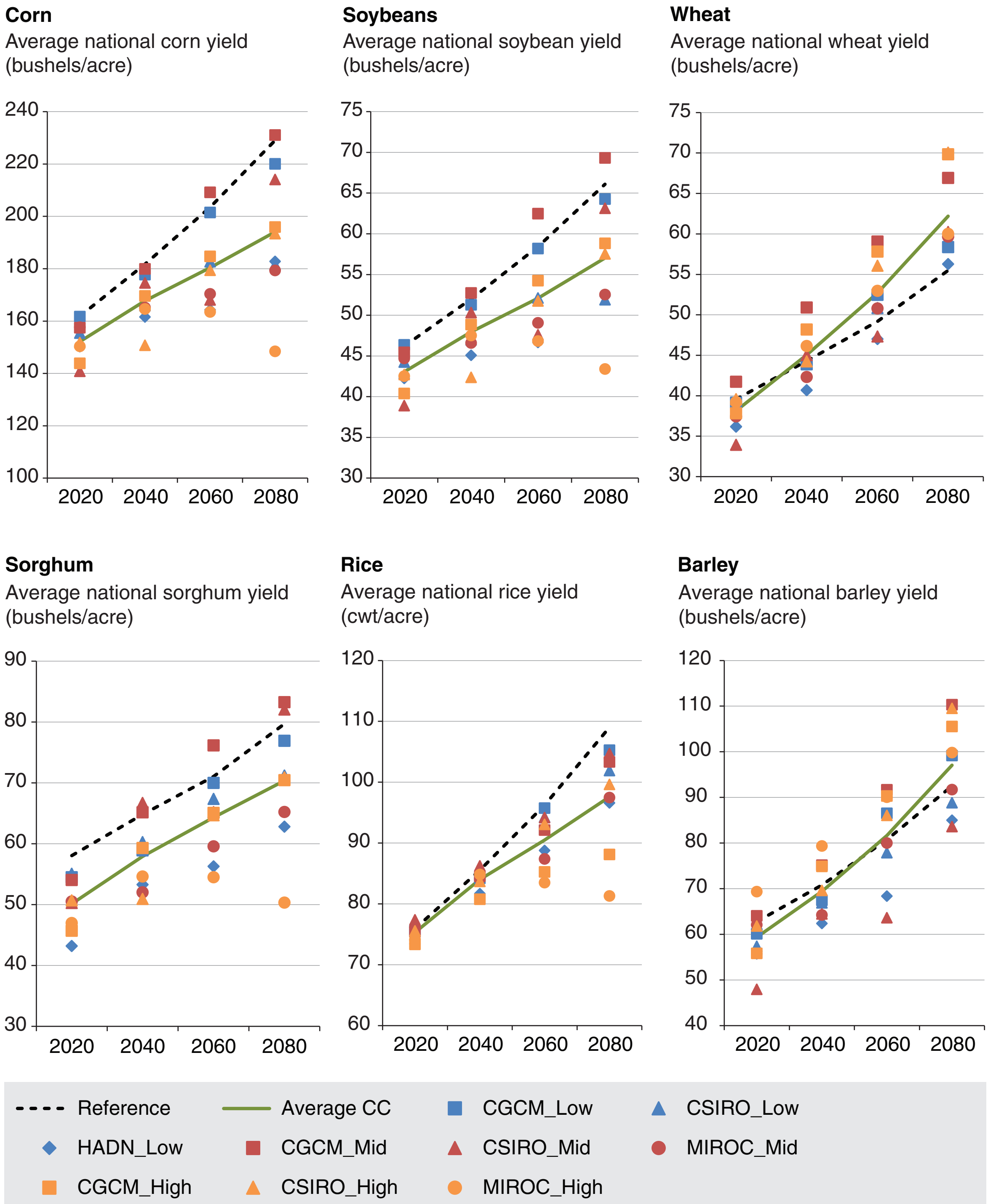
Our analysis suggests that a changing climate will affect the scale and regional composition of U.S. fieldcrop production over the coming decades. The impacts occur through multiple pathways, including biophysical changes in yield and in the availability of irrigation water from surface-water sources, as well as shifting economic returns to cropping systems. All climate change impacts are deviations from a reference scenario that projects aggregate agricultural production and market conditions in the absence of climate change. The reference scenario reflects historical trends in crop productivity, prices, and exports and accounts for projected changes in population and income growth (see Appendix E).

Crop yields generally decline as a result of climate change

Climate-impacted yields are compared against a reference case that assumes no climate change but in which crop yields increase over the century to reflect projected increases in crop productivity. Each climate change scenario and analysis year is characterized by unique regional combinations of temperature (daily maximum and minimum) and precipitation, as well as a national atmospheric CO_2 level that varies across emissions levels (Low, Mid, and High). In figure 6, the dashed black lines represent the reference trajectory of yield growth without climate change and the green lines represent yields averaged over the climate change projections. When scenario/emission level markers lie below the dotted black line, they illustrate yield declines due to climate change; above the line they represent yield increases.

Relative to their reference levels, yields of several major field crops decline under climate change. In 2040, only two crops—wheat and hay—experience yield increases (1.7 percent and 0.1 percent) over reference yields. By 2080, average barley yields are also boosted by climate change, with average wheat, hay, and barley yields increasing 12.1 percent, 2.4 percent, and 4.9 percent over reference yields. The largest yield declines, on the other hand, are observed for oats, corn, soybeans, and silage, with average declines across climate change scenarios of 13.8 percent, 7.7 percent, 7.8 percent, and 6.3 percent, respectively, by 2040; and 20.8 percent, 15.3 percent, 13.7 percent, and 13.4 percent, respectively, by 2080, relative to their reference yields in those years.

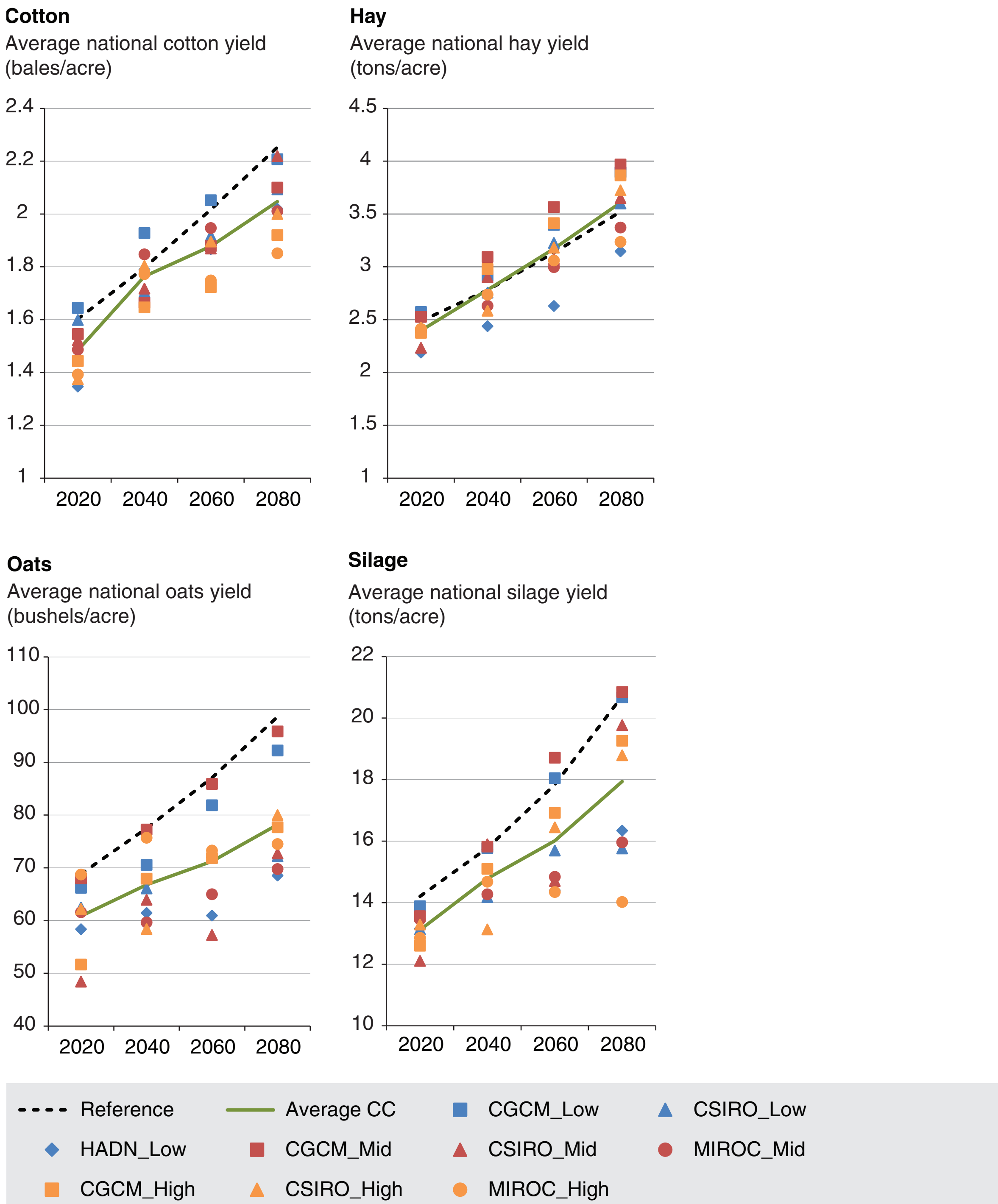
Figure 6
Average national yields for several major REAP crops under future climate projections for analysis years 2020-2080



Note: REAP = Regional Environment and Agriculture Programming model.
See Appendix A for explanation of climate models.
Source: USDA, Economic Research Service.

continued—

Figure 6 (continued)
Average national yields for several major REAP crops under future climate projections for analysis years 2020-2080



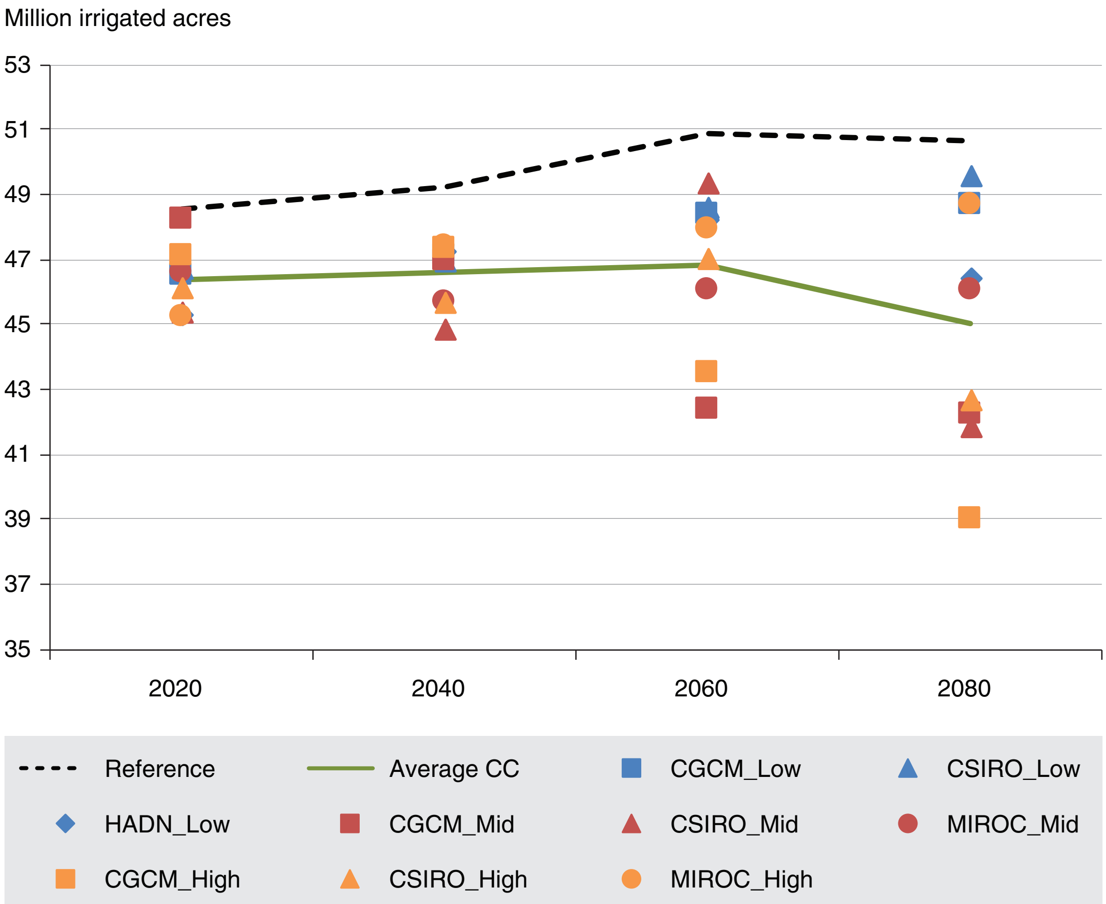
Note: REAP = Regional Environment and Agriculture Programming model.
See Appendix A for explanation of climate models.
Source: USDA, Economic Research Service.

Irrigated acreage generally declines under climate change projections

Consistent with other studies (Reilly et al., 2003; Thomson et al., 2005), U.S. irrigated acreage declines under projected shifts in climate patterns. While reductions in irrigated production under drier conditions may seem counterintuitive, the finding is robust across climate projections. Regional impacts, however, vary depending on shifting yields and crop-water requirements, the shift in relative profitability of irrigated production, and the availability of water supplies for irrigated production.

Irrigated fieldcrop acreage under reference climate conditions is projected to increase from 48.6 million acres in 2020 to 50.7 million acres in 2080. Projected reductions in groundwater withdrawals are not specific to climate projections and are therefore applied to the reference scenario as well as the climate scenarios; those reductions in groundwater withdrawals limit projected expansion in irrigated acreage. Relative to the reference case, changing climate conditions result in declines in U.S. irrigated fieldcrop acreage under all climate scenarios (fig. 7). The variability in estimates increases over time, reflecting the widening spread in temperature estimates across emissions scenarios and increased variability in precipitation projections across climate models as projections move into the late century.

Figure 7
Extent of irrigated acreage under reference weather and under climate change projections



Note: See Appendix A for explanation of climate models.
Source: USDA, Economic Research Service.

The projected decline in U.S. irrigated fieldcrop acreage under climate change is partially driven by reduced water-supply availability, as surface-water supplies become more constraining across much of the arid West. However, even when potential reductions in irrigation supply are not considered, national irrigated acreage declines in 2080 under more than half of the climate projections despite warming temperatures. Changes in the relative profitability of cropping systems are a primary driver of acreage changes in REAP. The decline in irrigated acreage under climate change in some regions is therefore partly due to the decline in relative profitability of irrigated cropping systems, which derives from changes in temperature, precipitation, and CO_2 concentrations (see "Supporting Results: Relative Profitability Analysis").

Figure 8 illustrates how changes in national acreage, averaged over climate projections, are distributed across the major field crops. After midcentury, declines in irrigated acreage are generally greatest for corn and hay. Cotton and soybeans also lose significant acreage under some climate projections. Acreage in irrigated hay—with generally lower returns to irrigation and high water-consumptive requirements—is particularly sensitive to increasing constraints on water supply; irrigated hay generally declines across the Mountain region, for instance, despite increased yields in that region under several climate projections.

Declines in irrigated production acreage are offset for many crops by increases in dryland production. Past midcentury, declines in irrigated acreage in cotton, hay, oats, barley, soybeans, and wheat are accompanied by an increase in dryland production under several climate projections. On average, rice, hay, and cotton are grown on more acreage after midcentury, while corn, soybeans, sorghum, wheat, and silage are grown on less (fig. 8).

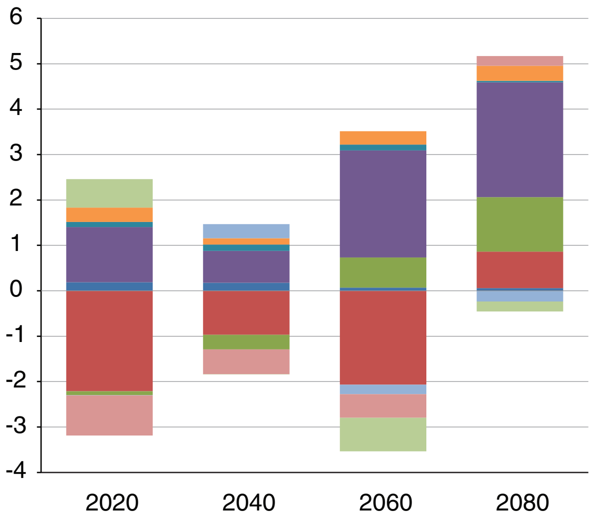
Significant conversion of irrigated to dryland acreage occurs for most climate projections in the Mountain and Pacific regions (fig. 9). The response reflects both the effect of irrigation-supply contractions in the southern and central reaches, and expansion in dryland hay and small-grain production in the northern latitudes. While irrigated acreage in the Southern Plains contracts under almost all climate scenarios, dryland acreage experiences mixed impacts across the projections. Acreage impacts in the Northern Plains are mixed for both dryland and irrigated production, with some scenarios showing significant increases and others showing significant decreases. The Delta region generally experiences a contraction in both irrigated and dryland acreage, suggesting a loss of comparative advantage under climate change. The Corn Belt, with little area to expand production, also generally loses both irrigated and dryland acreage. A heavy reliance on corn and soybean production, both of which suffer yield declines under climate change, may erode comparative advantage in the Corn Belt as well. On average across climate scenarios, total production acreage contracts in the Delta, Corn Belt, and Northern Plains regions and expands in the Mountain States and Pacific region.

Figure 8

Change in national acreage across crops under future climate projections

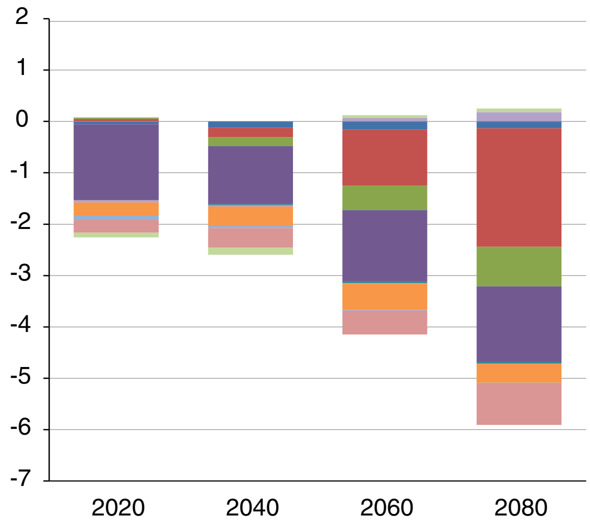
Dryland acreage

Average change in dryland acreage relative to reference (million acres)



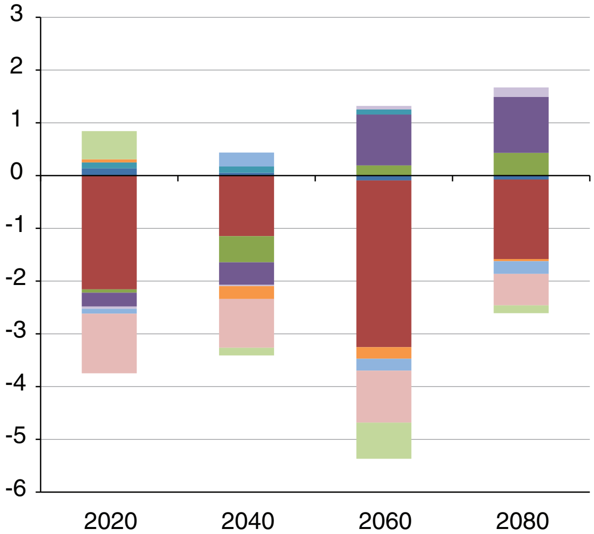
Irrigated acreage

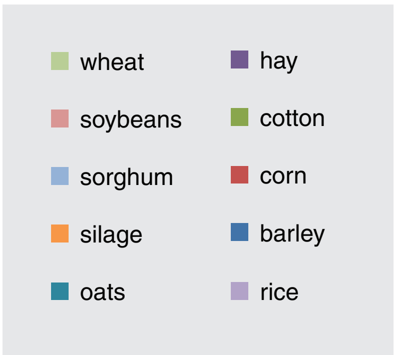
Average change in irrigated acreage relative to reference (million acres)



Total acreage

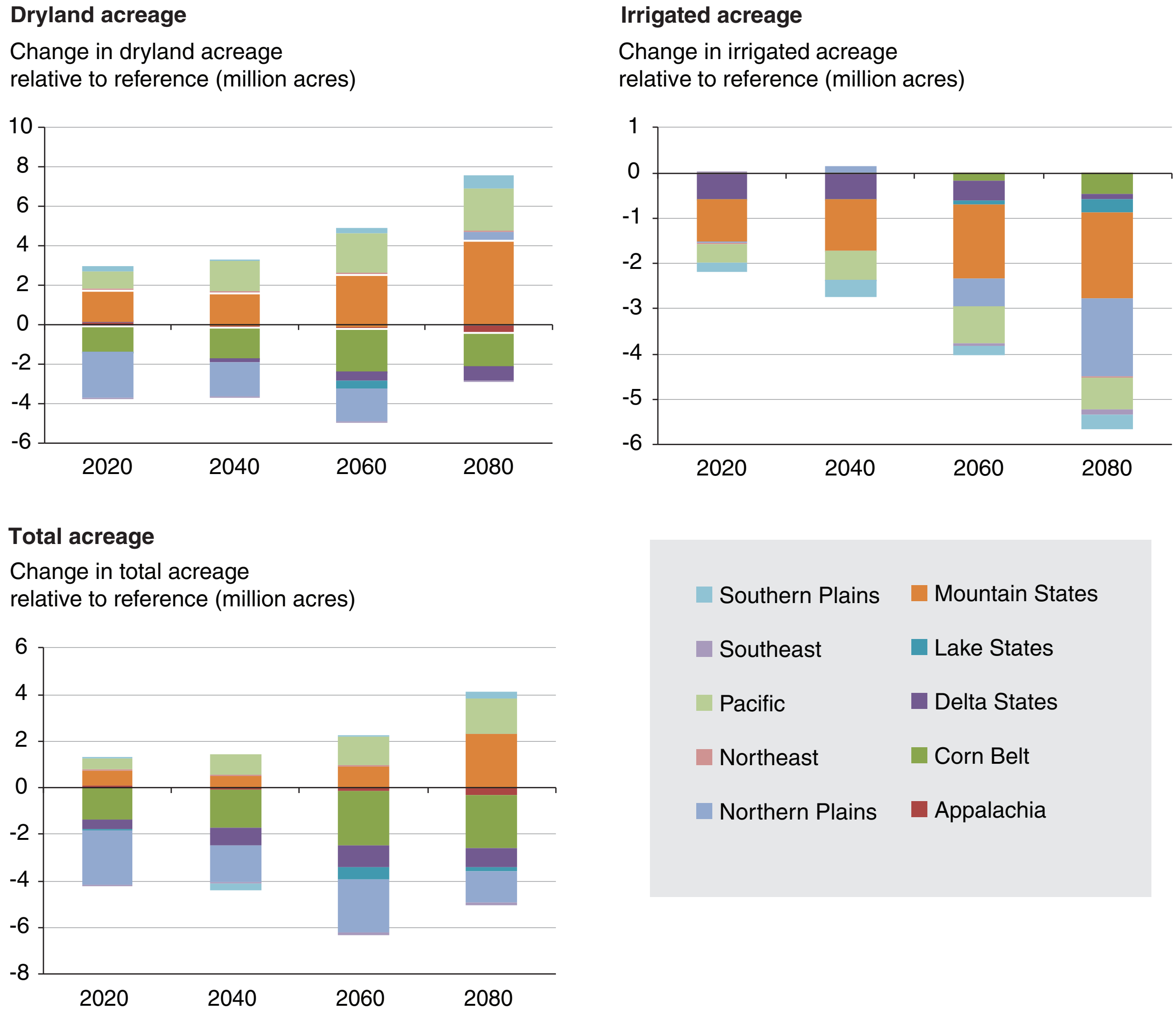
Average change in total acreage relative to reference (million acres)





Source: USDA, Economic Research Service.

Figure 9
Change in dryland and irrigated acreage across regions averaged over future climate projections



Source: USDA, Economic Research Service.

Climate change reduces total production of most field crops

As a result of changed yields under climate change, together with shifting patterns of production from the adaptive response, U.S. production of corn, soybeans, oats, rice, silage, and sorghum generally declines relative to reference production levels in each analysis period. For corn and soybeans, production declines average less than 10 percent prior to 2040 and more than 10 percent in 2060 and beyond. In contrast, wheat production generally increases (beyond 2040), while the production impact on barley and hay is mixed (table 3). Production declines reflect both the drag on yields and a climate-induced shift in irrigated and dryland production, with declining acreage in higher yielding irrigated production only partially offset by an increase in dryland production.

Table 3
Percent change in national production relative to reference production levels averaged over all climate futures for each analysis period

	Average % change in production			
	2020	**2040**	**2060**	**2080**
Barley (bushels)	-1.9	-0.6	-3.5	1.0
Corn (bushels)	-8.1	-8.7	-13.8	-16.2
Cotton (bales)	-7.9	-6.1	-5.6	-5.9
Hay (dry tons)	-4.0	-0.6	2.7	4.2
Oats (bushels)	-8.7	-10.7	-16.1	-20.8
Rice (cwt)	-2.2	-2.5	-4.2	-6.1
Silage (dry tons)	-6.9	-9.5	-13.1	-14.4
Sorghum (bushels)	-15.1	-5.4	-14.0	-17.0
Soybeans (bushels)	-8.1	-8.8	-11.9	-14.3
Wheat (bushels)	-2.8	1.3	5.6	11.6

Source: USDA, Economic Research Service.

Prices generally increase and returns decline under climate change

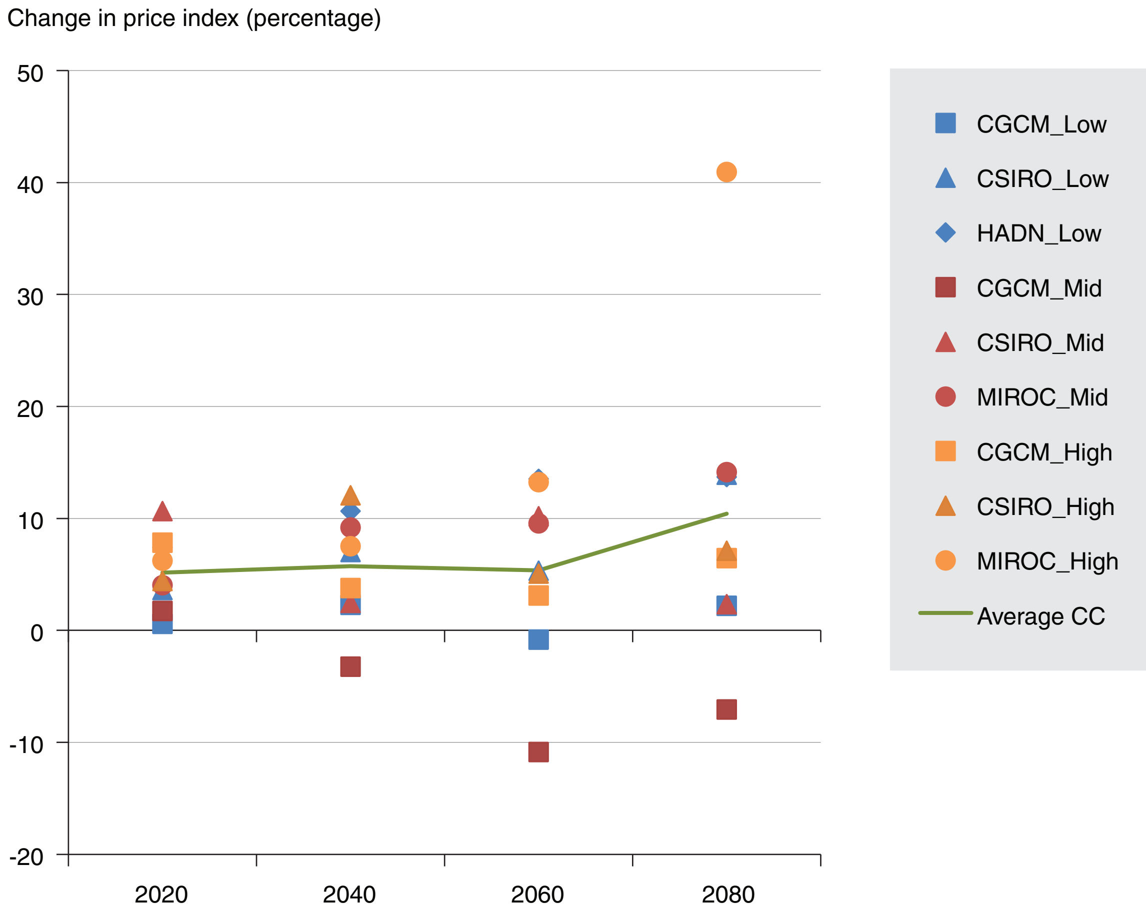
Climate change generally increases a production-weighted price index calculated across the 10 commodity crops (fig. 10).[5] In 2040, estimated price impacts range from -3 percent for the CGCM_Mid scenario, indicating a decline in aggregate price levels under those climate conditions, to +12 percent for the CSIRO_High scenario, with an average increase across scenarios of 5.74 percent. In 2080, the average price increase jumps to 10.4 percent, reflecting a projected price increase of over 40 percent under the exceptionally dry and hot MIROC_High scenario. The impacts of price changes on consumer welfare are unambiguous; consumers are worse off when prices increase. The range of potential price impacts widens over time; such uncertainty is an important source of variability in estimates of consumer and producer welfare under different levels of climate change.

Prices of corn and sorghum generally increase relative to the reference price, along with the price of soybeans, cotton, rice, oats, and silage (fig. 11). National prices increase largely because both national average yields and total production of these crops generally drop under the climate change projections. Corn and sorghum have a different photosynthetic pathway than other crops in this analysis and receive less of a photosynthetic efficiency boost from increased atmospheric carbon dioxide; that efficiency boost helps mitigate temperature- and precipitation-related yield losses in the other crops.[6] The prices of wheat, barley, and hay, on the other hand, fall relative to their reference levels due to increased yields and production in the later analysis periods.

[5]The middle emissions scenario run through the CGCM model (CGCM_Mid) is an exception across all analysis periods. The CGCM_Mid projection is characterized by the smallest national average temperature increases across all climate projections in 2040 and beyond, and, as shown in the precipitation maps in Appendix B, is a relatively wet projection, with increases in average growing-season precipitation from 2040 through 2080.

[6]Corn and sorghum are the only two C_4 crops in this analysis; see "Supporting Results: Biophysical Impacts of Climate Change" for an explanation of C_4 versus C_3 crops.

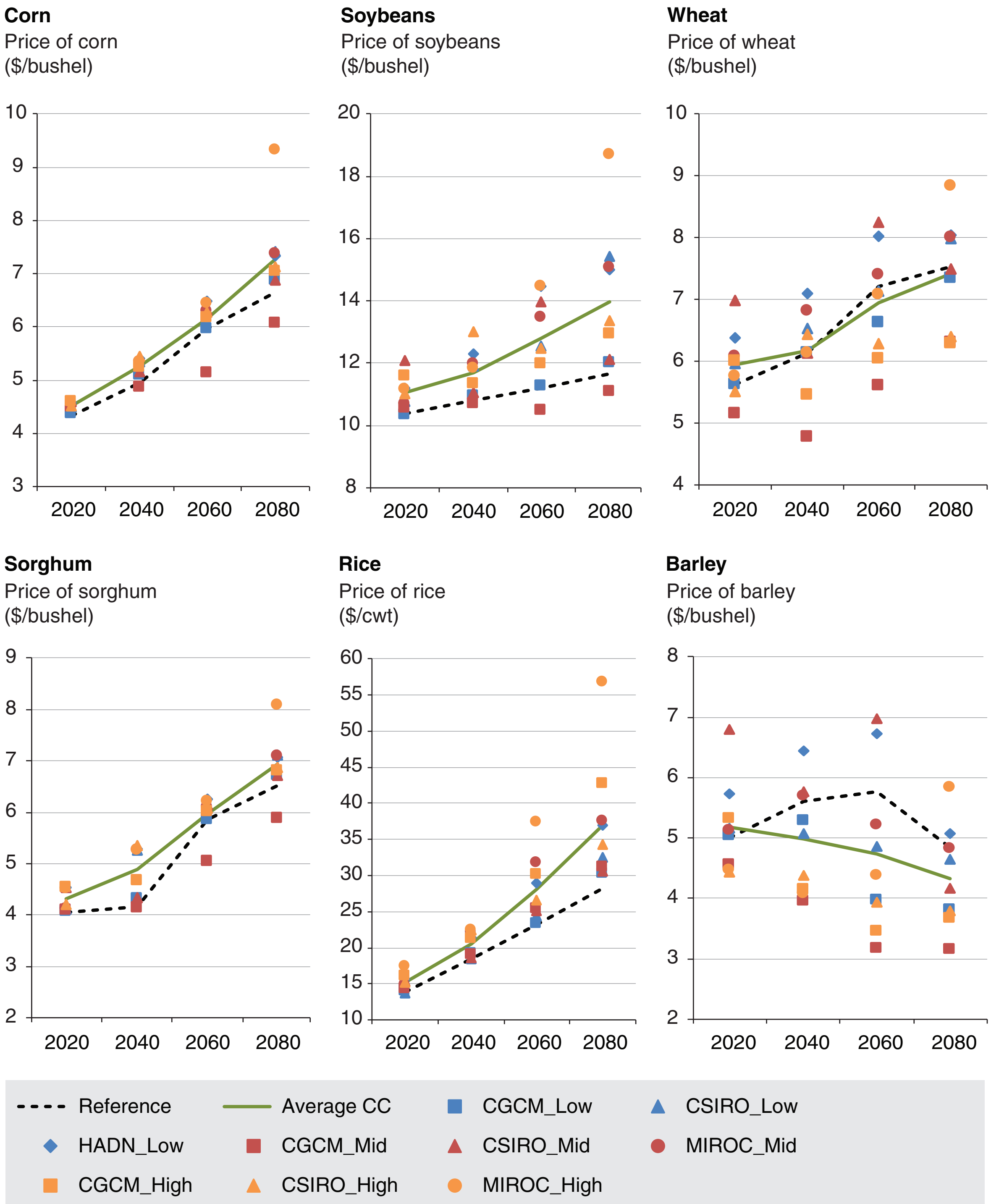
Figure 10
Percent change in aggregate price index for each analysis year



Note: See Appendix A for explanation of climate models.
Source: USDA, Economic Research Service.

Producer welfare in this analysis is represented by net returns to production, defined as the returns to fixed factors of production (i.e., land and management) and calculated as the difference between gross value of production and variable costs of production. Net returns are sensitive to a wide range of variables—changes in crop yield, production costs, and crop prices—all of which vary by crop, region, climate projection, and time period. As a result of climate change, average returns decline relative to the reference level, with declines ranging from -2.2 percent in 2040 to -7.1 percent in 2060 (fig. 12). The magnitude of the decline relative to the reference scenario increases sharply for all climate scenarios between 2040 and 2060, but producer returns are boosted by higher prices in 2080 as a result of increasingly severe yield and production declines for many crops. There is considerable variability across climate scenarios, however. In 2040, estimated annual changes in net returns across the modeled crops in REAP range from an increase of 2.4 percent associated with the CSIRO_Mid projection to a loss of 9.9 percent associated with the CSIRO_High projection; in 2080, potential changes range from an increase of 1.25 percent (CGCM_Low projection) to a loss of 9.7 percent (HADN_Low).

Figure 11
Average national prices for several major REAP crops under future climate projections for years 2020-2080

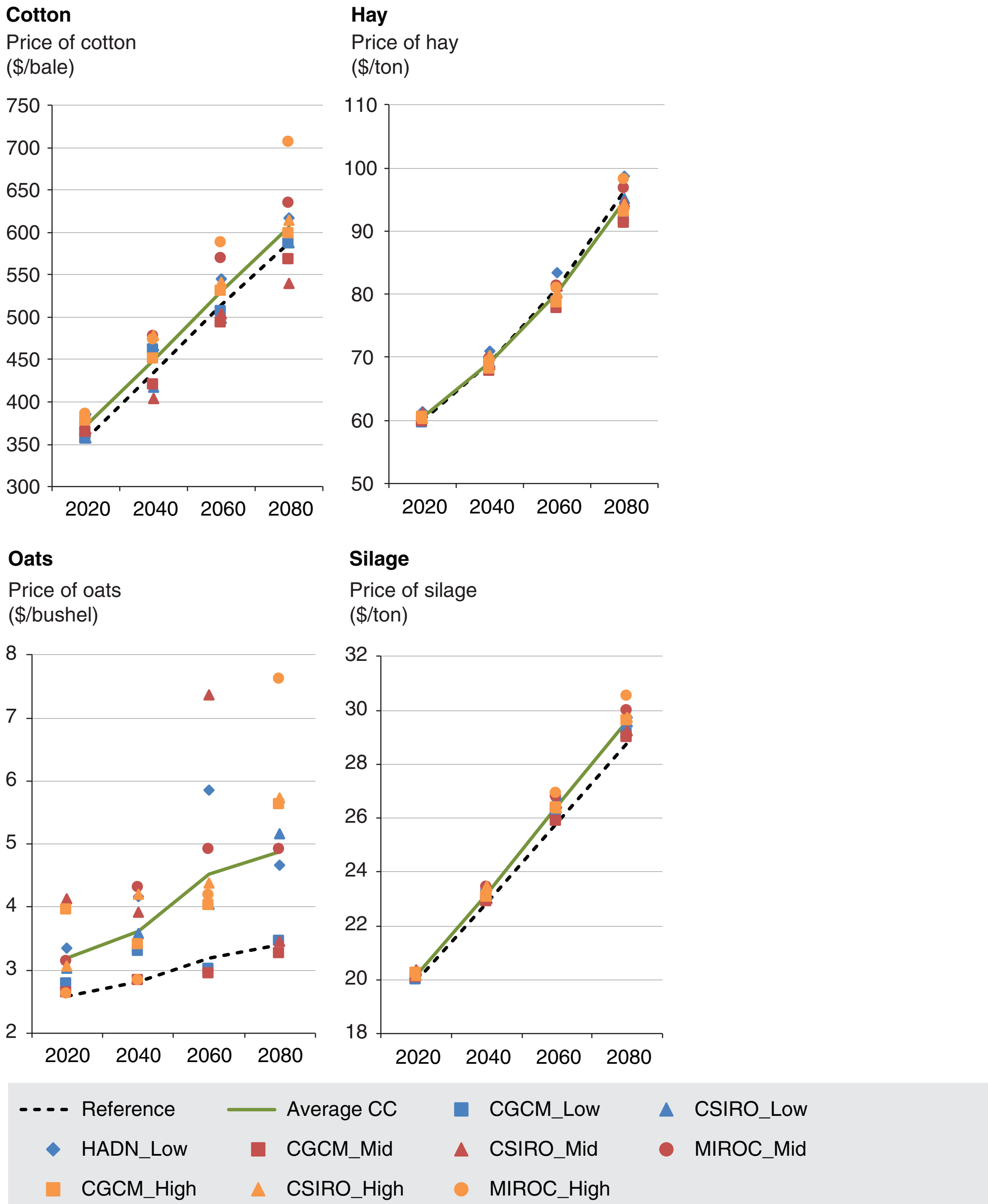


Note: REAP = Regional Environment and Agriculture Programming model.
See Appendix A for explanation of climate models.
Source: USDA, Economic Research Service.

continued—

Figure 11 (continued)

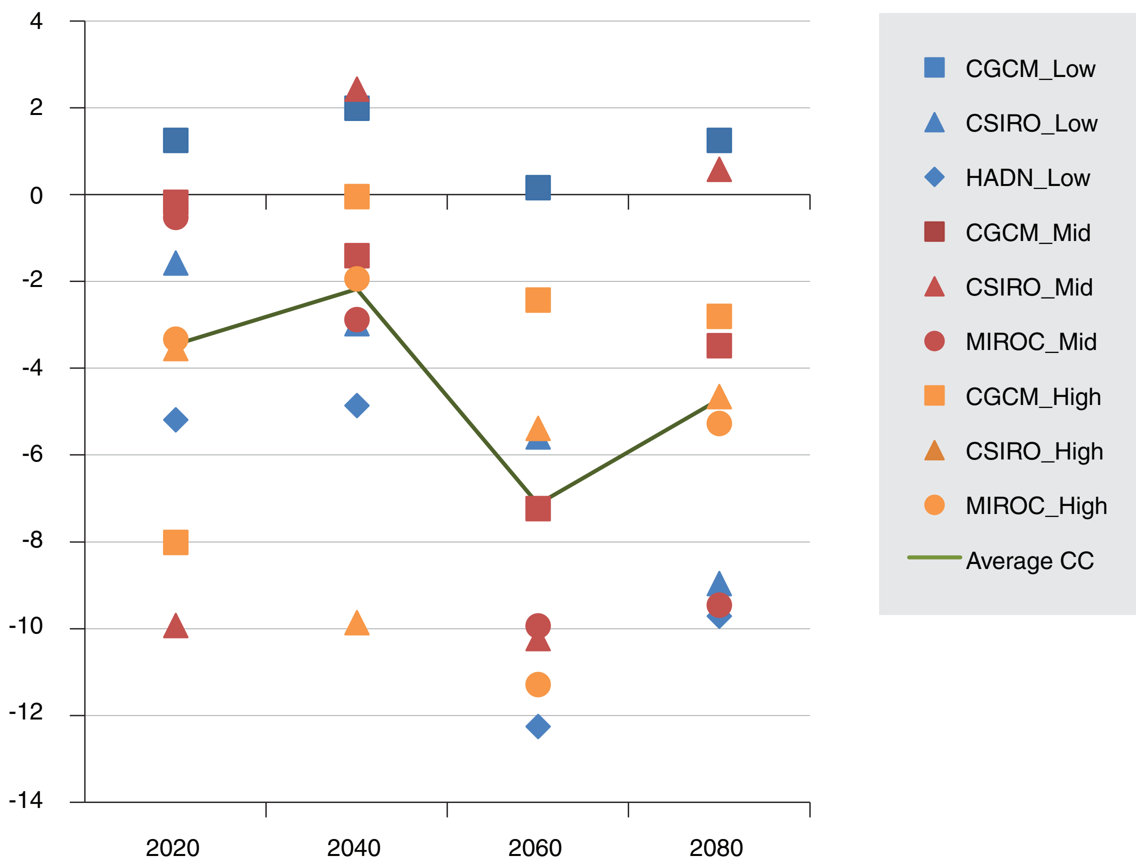
Average national prices for several major REAP crops under future climate projections for years 2020-2080



Note: REAP = Regional Environment and Agriculture Programming model.
See Appendix A for explanation of climate models.
Source: USDA, Economic Research Service.

Figure 12
Domestic net returns under future climate projections

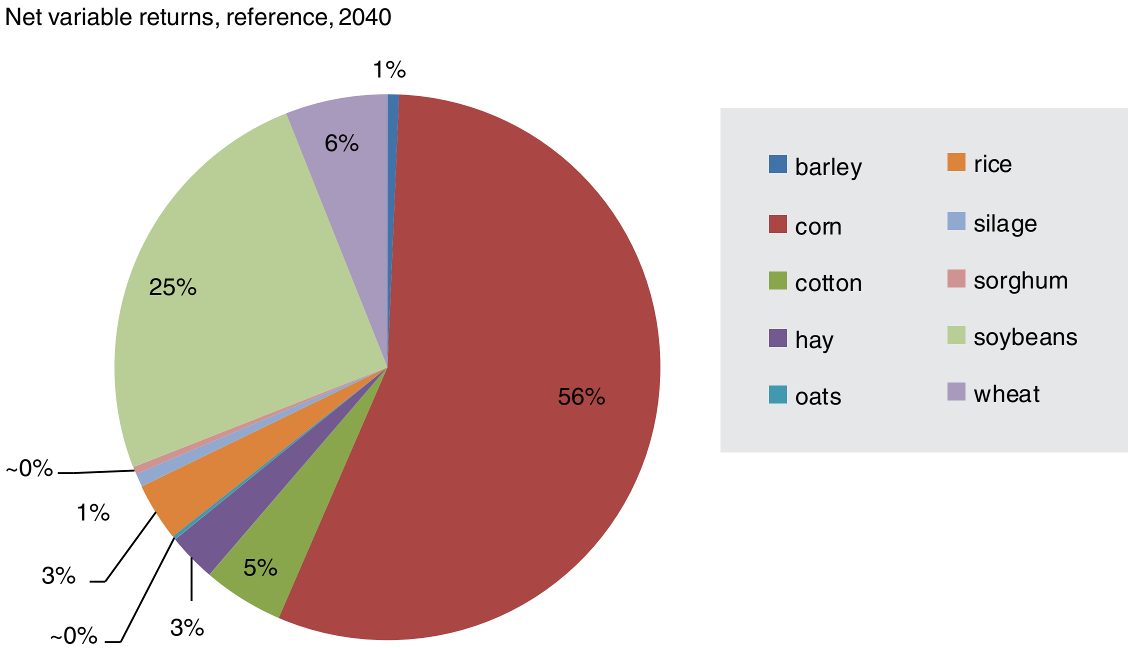
Change in net variable returns relative to reference (percentage)



Note: See Appendix A for explanation of climate models.
Source: USDA, Economic Research Service.

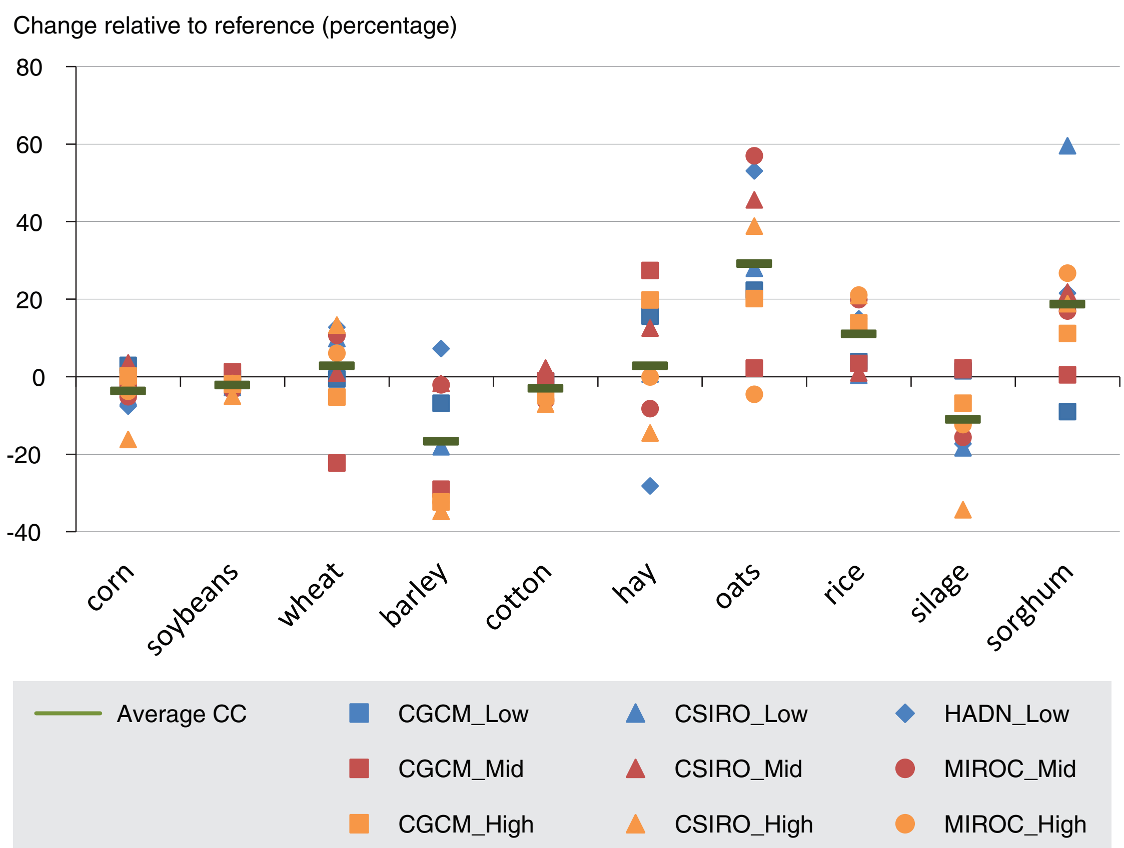
Corn producers capture the largest share of net returns among field crops in 2040, followed by soybeans and wheat (fig. 13). In a breakdown of climate impacts by crop, there is general consistency (occurring across six or more climate change projections) in the direction of impact under climate change, though the magnitude of impact may vary across climate projections. Net returns for corn, soybeans, barley, cotton, and silage generally decrease under climate projections in 2040, while net returns for sorghum, oats, rice, and wheat generally increase (fig. 14). There is variability across climate projections, however. In the CGCM_Mid scenario, for instance, wheat producers suffer losses in returns despite a 14-percent increase in average wheat yields in 2040; market forces drive the price of wheat down to 78 percent of its reference level and erode the revenue benefits of increased wheat yields. (This is an extreme case, however, and on average across climate scenarios, the price of wheat changes only slightly relative to the reference scenario.) By 2080, climate change impacts on net returns have become more positive for rice and wheat, while net returns in the soybean sector edge into the positive range and those in the sorghum sector average -15 percent (fig. 15).

Figure 13
Relative producer returns by REAP crop sectors under reference climate conditions, 2040



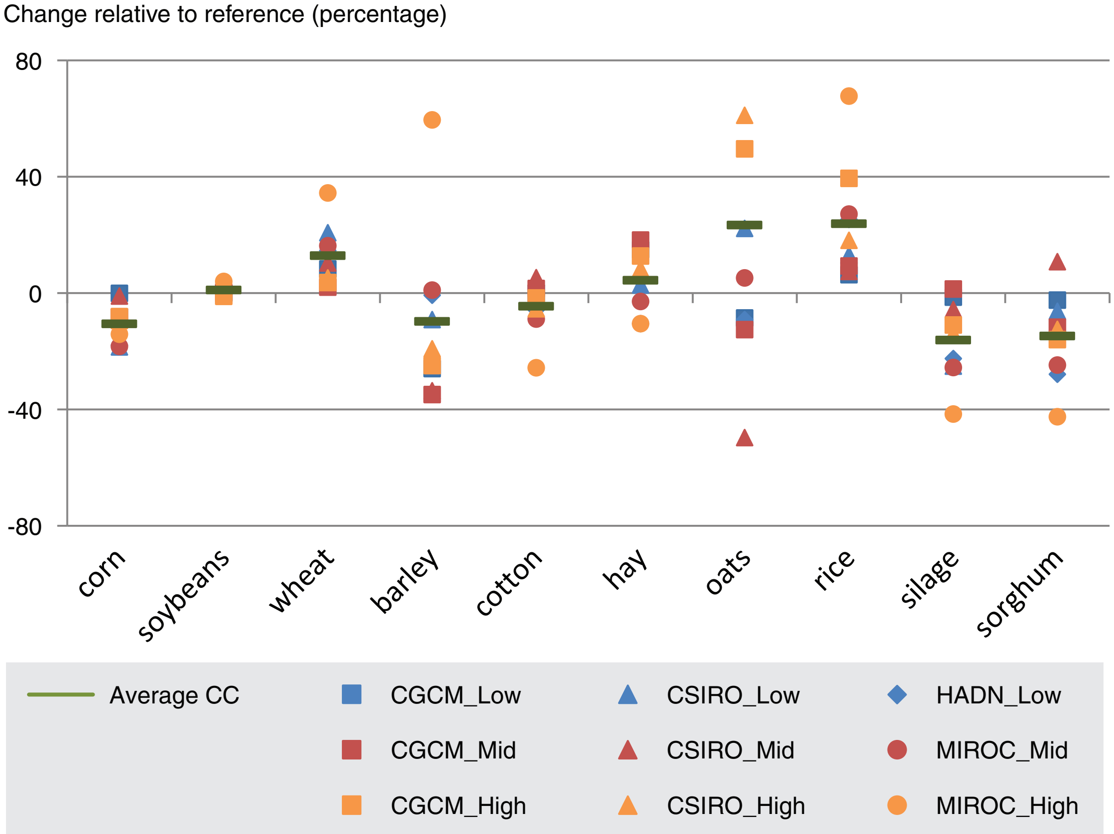
Note: REAP = Regional Environment and Agriculture Programming model
Source: USDA, Economic Research Service.

Figure 14
Change in net returns by crop sector under climate change scenarios, 2040



Source: USDA, Economic Research Service.

Figure 15
Change in net returns by crop sector under climate change scenarios, 2080



Note: (MIROC_High result for oats (an outlier of +152%) was omitted for presentation purposes).
See Appendix A for explanation of climate models.
Source: USDA, Economic Research Service.

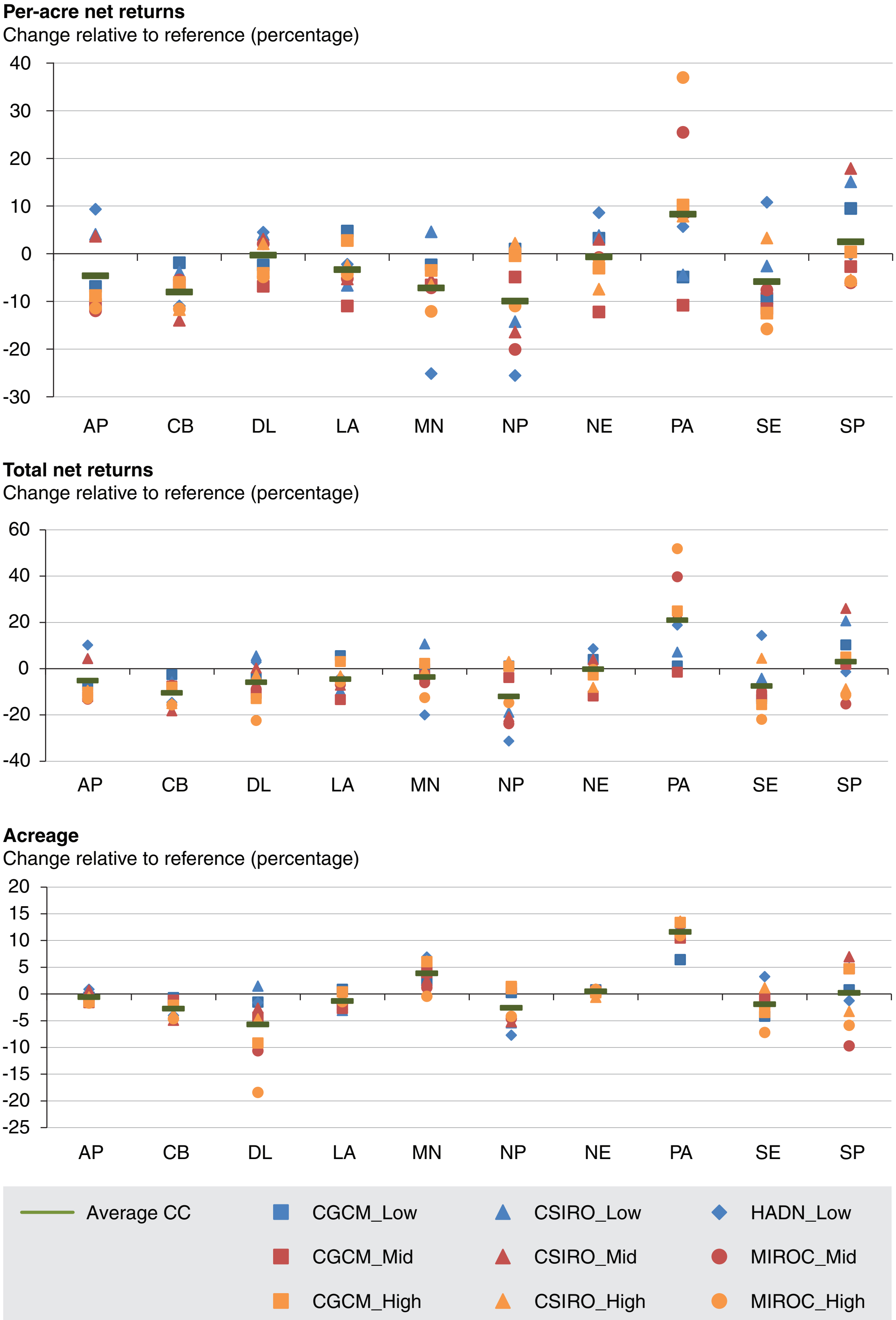
Impacts of climate change on producer returns vary across regions

National measures of producer welfare mask significant variation across regions. Figure 16 illustrates the change in per-acre net returns observed under each climate scenario, relative to returns observed under the reference scenario, by farm production region, for the year 2060.[7] Per-acre net returns (averaged across crops) decline across all climate projections for the Corn Belt, with declines in at least seven climate projections for the Northern Plains, Mountain, Southeast, and Lake States. In contrast, the Delta, Northeast, Southern Plains, and Pacific regions experience increases in per-acre net returns under four or more climate change projections. When results are averaged across climate projections, however, only the Pacific and Southern Plains regions experience projected increases in per-acre net returns in 2060.

Total net returns by region reflect both changes in per-acre field crop returns and change in area under production. The Pacific region, for instance, increases total net returns under a couple of climate projections by increasing acreage in production, despite drops in per-acre net returns (fig. 16). In contrast, production acreage in the Corn Belt declines across all future climate projections, exacerbating losses in total net returns.

[7]While intraregional variations in production returns are observed, returns are shown by USDA Farm Production Region for simplicity of presentation.

Figure 16
Net returns and acreage by farm production region and climate future 2060



Note: AP = Appalachia, CB = Corn Belt, DL = Delta States, LA = Lake States, MN = Mountain States, NE = Northeast, NP = Northern Plains, PA = PacificS, SE = Southeast, and SP = Southern Plains.
See Appendix A for explanation of climate models.
Source: USDA, Economic Research Service.

Supporting Results: Drivers of Adaptation

To clarify the relative impacts of the biophysical and economic dynamics underlying our modeling results, we present results from a series of analyses that isolate particular dynamics within the modeling system (see table 1). The first—the ***Biophysical Impacts*** analysis—fixes acreage at the reference level (no changes to acreage allocated to crops, rotations, or production methods are permitted), but yield and applied irrigation water are allowed to vary according to the new climate conditions.[8] Because the analysis does not allow for farmer adaptation to crop-level changes, however, potential climate impacts on the agricultural sector are incomplete. The analysis does illustrate how comparative advantage in crop production shifts with changing yields and irrigation costs.

The biophysical impacts of climate change drive the adaptation response through shifts in relative profitability across regions, crops, and production methods. To explore the acreage and production dynamics arising from changes in relative profitability of dryland versus irrigated production, the ***Relative Profitability*** analysis considers a world in which farmers experience the biophysical impacts on yields and costs, but face no additional limitations on irrigation due to climate change. Without constraints on their adaptation response, producers engage in the changes observed in this analysis—including shifts in crops, crop rotations, and movements between dryland and irrigated production—driven solely by the shifts in relative profitability, together with the market price response.[9] This analysis illustrates how economic incentives associated with land allocation respond to the yield and crop-water demand implications of climate change, and how those adjusted incentives vary regionally according to regional biophysical impacts, national price impacts, and prevailing patterns of production within a region.

Increasing water scarcity may limit the flexibility of farmers to adapt to climate change through irrigation expansion. In the final analysis, we explore ***irrigation-water supply limitations*** and assess how impacts vary regionally. We differentiate reductions in surface-water supplies due to climate change from projected reductions in groundwater withdrawals. We explore the impact and relative magnitude of those reductions in water availability regionally, as well as the limitations that irrigation shortages impose on the production of specific crops.

[8]Variation in yield and irrigation requirements under each set of new climate conditions is captured in the EPIC estimates.

[9]While there are also no explicit constraints on irrigated acreage in the Relative Profitability analysis, there are implicit constraints that operate through the acreage distribution parameters associated with REAP's land-allocation constraints. These parameters are calibrated to historical acreage distributions and therefore reflect resistance to additional irrigated acreage expansion in those areas that have historically been irrigation constrained.

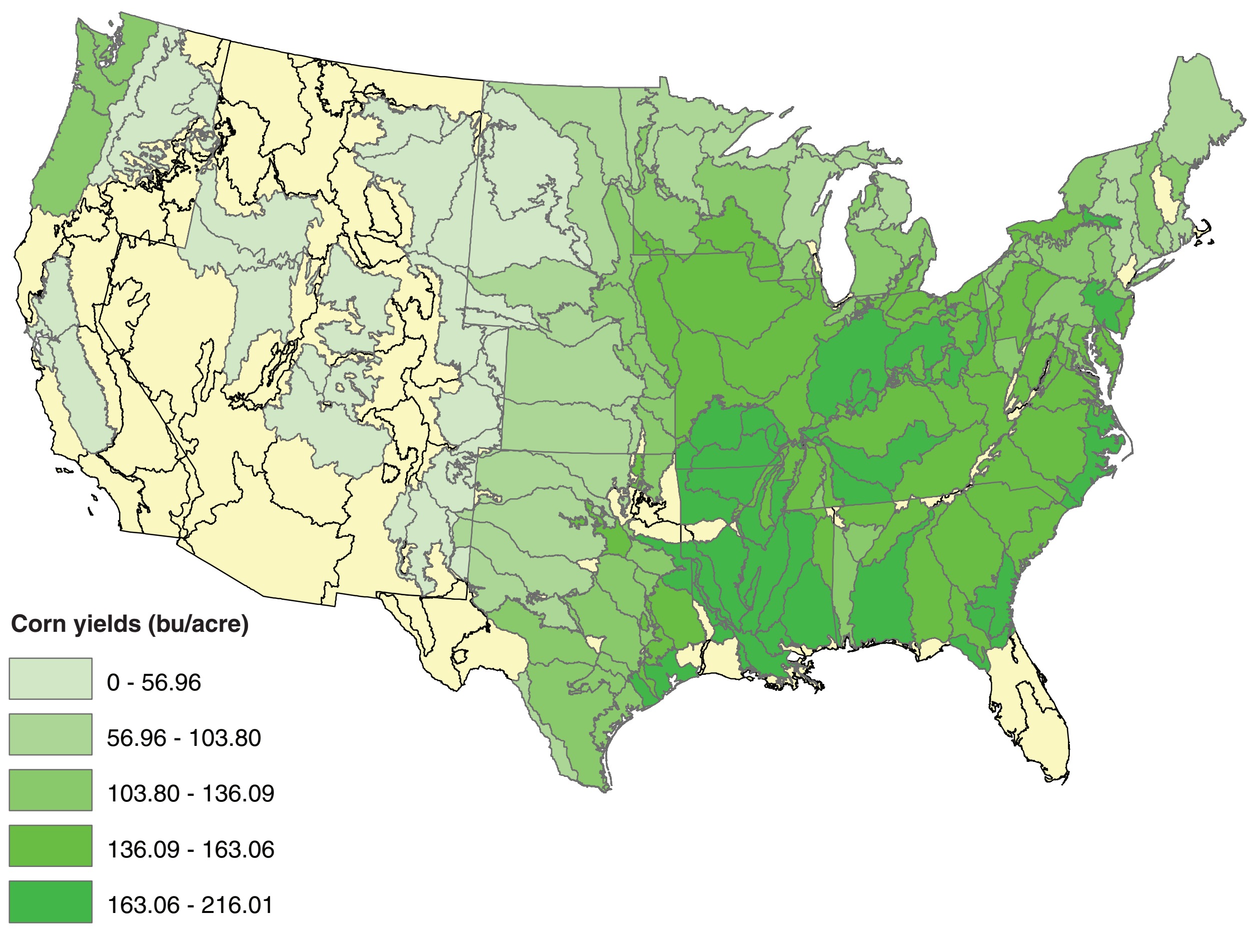
Biophysical Impacts of Climate Change

This analysis illustrates the aggregate biophysical impacts of climate change by holding production acreage fixed across regions, crops, and cropping systems, and calculating how field-level impacts on yields and crop-water use manifest at the regional level, assuming fixed production patterns. Applying biophysical impacts to current production patterns is naïve as it precludes any attempt by farmers to mitigate worsening conditions or capitalize on improved growing conditions in some cases. The analysis also disregards potential changes in water supply associated with climate shifts; water supply is assumed adequate to meet adjustments in irrigation due to changed growing conditions. These biophysical impacts, however, drive the adaptation response of both farmers and market forces.

Crop yields

Due to differences in soils, weather, and production practices, crop yields vary widely across regions. The biophysical modeling in this analysis captures this spatial and behavioral heterogeneity, and allows yields to respond differently in accord with regional changes in growing conditions under the climate projections. The underlying variability of the biophysical modeling is reflected in a map of average dryland corn yields for reference weather conditions in the year 2020, weighted across acreage in corn rotations (fig. 17)

Figure 17
Average corn yields in bushels/acre under reference weather conditions in 2020



Note: Regions in yellow do not have dryland corn acreage in this analysis
Source: USDA, Economic Research Service.

For simplicity of presentation, crop yields and other model results are averaged up to the Farm Production Region (FPR) level for comparison across climate projections. While such averages obscure intraregional variation, significant variability remains across the FPRs (table 4).

Table 4
Average yields for dryland and irrigated production at the regional level for reference weather conditions in 2020

Region	Irrigation	Corn (bu/ac)	Soybeans (bu/ac)	Wheat (bu/ac)	Hay (Dt/ac)
AP	D	120.3	38.3	55	2.2
AP	I	150	43.6	68.7	na
CB	D	164.5	50.5	53.1	2.3
CB	I	203.4	58.9	53.9	na
DL	D	164.6	40.3	51	2.1
DL	I	185.3	48.5	50.1	na
LA	D	180.4	47.5	53.4	2.7
LA	I	224.6	56.5	61	3.2
MN	D	77.4	35.1	31.9	1.2
MN	I	223.1	na	82.5	4
NP	D	114.4	35.5	35.4	1.9
NP	I	227.7	67.5	59.2	3.6
NT	D	143.8	45.9	55.5	2.2
NT	I	195.4	63.7	67	na
PA	D	65	na	46.9	3.9
PA	I	238.1	na	129.2	5
SE	D	128.3	33.1	48.7	2.5
SE	I	183	45.8	49.2	2.9
SP	D	117.5	23.4	25.8	1.7
SP	I	174.4	34.7	43.3	1.6

Note: Dt/ac = dry ton/acre; bu/ac = bushels/acre; D = dryland; I = irrigated. “na” refers to crop/region combinations that are not included in our analysis due to insufficient acreage.
AP = Appalachia, CB = Corn Belt, DL = Delta States, LA = Lake States, MN = Mountain States, NE = Northeast, NP = Northern Plains, PA = Pacific, SE = Southeast, and SP = Southern Plains.
Source: USDA, Economic Research Service.

The changed growing conditions associated with each climate projection—including adjustments in temperature (daily maximum and minimum) and precipitation, as well as atmospheric CO_2 levels that vary across emissions scenarios (low, mid, and high)—affect the dynamics of crop growth, yields, and crop-water demand through several pathways:

- Precipitation
    - Changes in precipitation affect dryland yields through impacts on soil moisture and crop moisture stress. Decreases in precipitation, for instance, can lead to increased crop stress and reduced yields in areas where soil moisture is insufficient.
    - Changes in both the timing and magnitude of rainfall affect irrigation demand. Increases in precipitation can reduce applied irrigation. Conversely, decreases in precipitation may trigger additional irrigation demands if they occur during growing periods and result in crop water stress.

- Temperature
    - Higher temperatures affect both dryland and irrigated yields. Where temperatures are below optimal growth thresholds, higher temperatures can boost plant growth. However, temperatures above optimal thresholds may stress plant development. At sufficiently high temperatures, irrigated production is not immune to the impacts of climate change because irrigation is not able to completely offset the impacts of temperature stress on crop growth. Temperature changes not only increase water demand by crops, but completely alter the phenology of crop development, including the rate of biomass accumulation and grain set (Walthall et al., 2012).
- Carbon Fertilization
    - Increased CO_2 can have a positive impact on crop yields by stimulating plant photosynthesis. The effect is strongest for C_3 crops such as wheat, barley, soybeans, and alfalfa hay; for C4 crops such as corn and sorghum, the effect is much weaker.
    - Increased CO_2 also improves the water-use efficiency of crops, which can boost crop yields (see Appendix B for details). While improved water-use efficiency generally favors dryland production, irrigated crops may also benefit since irrigated fields are often not sufficiently watered to completely eliminate stress. Irrigation water requirements may therefore decline due to CO_2-induced improvements in water-use efficiency.

Yield and applied irrigation demands for each of the climate change scenarios and analysis years are estimated using the Environmental Policy Integrated Climate (EPIC) model. EPIC-generated yield and irrigation-use estimates then become inputs into the REAP economic model, which considers the changing pattern of costs and returns under climate scenarios in re-optimizing the allocation of production acreage. However, to isolate and illustrate the biophysical impacts of climate change on crop production, in this supporting analysis we fix acreage levels and production patterns at their reference levels, effectively preventing the agricultural system from adapting to changes in growing conditions. These production and yield impacts therefore represent a hypothetical scenario in which climate change affects yields and costs, but farmers do not adapt in any way. This supporting analysis illustrates the initial, climate-driven impacts on yields, costs, applied irrigation demand, production, and prices for subsequent comparison against the impacts of adaptation and other drivers of producer/market response, including irrigation constraints.

Tables 5-7 illustrate corn, soybean, and wheat yields for the year 2060, assuming that acreage levels are fixed while climate and associated yields and applied irrigation water vary by climate projection. (Biophysical yield impacts for the remaining modeled crops are in Appendix G tables.) The first highlighted column illustrates reference crop yields for the year 2060 (which are calibrated to assumptions made in developing the reference production scenario), while the next column shows the average yield across the climate change (CC) projections.[10] The remaining columns illustrate the estimated impacts (measured as percent change) under nine climate scenarios. Because acreage is fixed across the analysis, the shifts shown are driven purely by EPIC-estimated changes in yield due to altered growing conditions.

[10]These are acreage-weighted averages of the yields associated with production enterprises within each region. Because acreage is fixed across the analysis, the acreage weighting is constant across climate scenarios; the shifts shown are driven purely by EPIC-estimated changes in yield due to altered growing conditions.

Table 5

Biophysical impacts of climate change on corn yields (bushels/acre) in 2060 by farm production region

				Percent change in corn yields, 2060								
Region	Irr/Dry System	Ref yield	Average CC yield	CGCM_ Low	CSIRO_ Low	HADN_ Low	CGCM_ Mid	CSIRO_ Mid	MIROC_ Mid	CGCM_ High	CSIRO_ High	MIROC_ High
AP	D	152.8	142.5	-3.4	-3.3	-6.5	2.4	-6	-12.8	-6.4	-8.9	-15.6
AP	I	190.5	173.7	-4.2	-3.1	-8.1	-1.2	-7.3	-13.7	-14.8	-11.3	-15.4
CB	D	208.6	184.2	-1.6	-9.9	-21.3	7.6	-21.2	-14	-8.6	-15.1	-21.3
CB	I	258.9	216.7	-5.7	-12.5	-21.8	-2.4	-20.3	-21.4	-20.4	-20.7	-21.7
DL	D	208.6	186	-1.9	1.5	-11.1	-2.3	-9.6	-20.2	-15.4	-8.5	-30.1
DL	I	235.8	234.7	1.1	3.1	-0.8	-0.1	7.6	-2.7	-5.2	1.1	-8.4
LA	D	228.5	210.7	3.9	-11.6	-14.5	3	-13.3	-12.8	-1.9	-7.9	-15.1
LA	I	286.2	264.6	-0.4	-9	-7.4	-2.4	-12.7	-10.6	-6.5	-9.7	-9.3
MN	D	95.1	84.7	2	-5.5	-31.7	19.7	-18.9	-20.7	-10.7	-5.6	-26.4
MN	I	280.6	229.9	-9.8	-6.4	-24.1	-11	-22.5	-25.9	-19.7	-16	-27.3
NP	D	141.1	125.3	1.8	-26.3	-33.9	17.9	-22.6	-21.8	3.8	0.5	-19.9
NP	I	285.1	239.6	-4.1	-10.2	-29.2	1.3	-22.1	-24.9	-16.7	-13.1	-24.8
NE	D	182.4	170.5	0.8	-4.7	-6.4	1	-8.6	-10.2	-6.5	-11.7	-12.4
NE	I	248.3	236.6	0.1	-2.5	-4.4	-4.4	-6.4	-5.9	-7	-7.4	-4.3
PA	D	84	80.1	-11.2	13.6	-35.7	-8.1	-14.7	4.7	9.7	-3.4	3.3
PA	I	301.9	260.1	-9.1	-16.5	-22.4	-16.1	-9.6	-16.5	-13.3	-7.5	-13.5
SE	D	162.9	152.5	-5.4	-4.4	-0.9	0.6	-9.7	-8.1	-6.7	-1.4	-21.7
SE	I	231.6	213.4	-3.3	-2.3	-5.7	-2.8	-8.8	-15.6	-13.5	-6.1	-12.7
SP	D	148.9	137	8.1	11	-14.4	3.2	-3	-23.7	-11.1	-13.6	-28
SP	I	220.2	204.5	-1.3	-0.7	-13.2	-2.7	-4.2	-7.3	-11.9	-7.1	-15.8

Note: AP = Appalachia, CB = Corn Belt, DL = Delta States, LA = Lake States, MN = Mountain States, NE = Northeast, NP = Northern Plains, PA = Pacific, SE = Southeast, and SP = Southern Plains.
See Appendix A for explanation of climate models.
Source: USDA, Economic Research Service.

Table 6

Biophysical impacts of climate change on soybean yields (bushels/acre) in 2060 by farm production region

				Percent change in soybean yields, 2060								
Region	Irr/Dry System	Ref yield	Average CC yield	CGCM_ Low	CSIRO_ Low	HADN_ Low	CGCM_ Mid	CSIRO_ Mid	MIROC_ Mid	CGCM_ High	CSIRO_ High	MIROC_ High
AP	D	48.6	43.9	-5.2	-3.3	-8.6	6.2	-9.1	-23.6	-9.5	-12.9	-20.8
AP	I	55	45.9	-10.9	-8.3	-16.1	-1.4	-14.6	-25.9	-24.3	-17.6	-29.4
CB	D	64	57	-1.5	-8.9	-20.2	7.5	-20.4	-11.9	-9.1	-15.5	-19
CB	I	74.3	62.7	-5.6	-11.9	-22.1	0.4	-18.1	-20.8	-19.6	-19.3	-23.4
DL	D	51.1	41.6	-6.2	-4	-22.6	-4.8	-13.1	-32.9	-28.5	-17.1	-37.8
DL	I	60.9	48.1	-7.1	-8.7	-23.5	-7	-16.7	-34	-30.2	-20.4	-41.4
LA	D	60.3	56.2	4.3	-12.4	-14.1	6.1	-13.8	-11.3	-0.3	-6.6	-13.4
LA	I	71.6	65.6	-0.9	-10.3	-8.6	-1.1	-15.1	-10.8	-7.4	-11.3	-10
MN	D	44.6	48.3	-1.6	-1.3	-6.8	31.5	-25.4	-16.1	51.6	35	8.5
NP	D	44.7	40.8	4.2	-25.8	-32.4	22.1	-23.5	-19.5	10.2	5	-18.4
NP	I	85.4	70.7	-3.8	-12.7	-31.3	1.9	-25.5	-25.4	-18.8	-14	-25.5
NE	D	58.1	53.7	0.9	-6.6	-7.1	4.1	-11.9	-12.7	-5.9	-14.2	-15.4
NE	I	81.1	77	0	-4.4	-5.7	0	-8.5	-6.3	-6	-10.2	-4.6
SE	D	42	35.9	-12.4	-6.8	-2.8	4.7	-16.3	-37.6	-10.5	-17.4	-31.4
SE	I	58.2	50	-10.2	-7.6	-10.3	-5.9	-14.7	-26.5	-17.5	-15.2	-18.3
SP	D	29.8	22.8	-3.9	-6.9	-37.7	-5.4	-14.5	-41	-28.5	-21.2	-50.8
SP	I	44.1	38.7	-2.3	-1.3	-19.6	-13.8	-10.5	-14.6	-23.8	-11.5	-14

Note: AP = Appalachia, CB = Corn Belt, DL = Delta States, LA = Lake States, MN = Mountain States, NE = Northeast, NP = Northern Plains, PA = Pacific, SE = Southeast, and SP = Southern Plains.
See Appendix A for explanation of climate models.
Source: USDA, Economic Research Service.

Table 7

Biophysical impacts of climate change on wheat yields (bushels/acre) in 2060 by farm production region

				Percent change in wheat yields, 2060								
Region	Irr/Dry System	Ref yield	Average CC yield	CGCM_ Low	CSIRO_ Low	HADN_ Low	CGCM_ Mid	CSIRO_ Mid	MIROC_ Mid	CGCM_ High	CSIRO_ High	MIROC_ High
AP	D	69.7	69.8	-8.1	3.5	3.4	-3	-4.7	5.8	0	1.2	3.7
AP	I	85.6	87.3	-7.1	7.5	1	0.7	1.9	8.2	0.1	5.7	-0.7
CB	D	67.2	67.6	-0.9	7.8	-2.5	8.1	-10.2	3.9	1	0.1	-2.2
CB	I	68.3	70	-6.2	10.9	3.3	3.7	-3.2	7.7	1.5	0.2	4.4
DL	D	65.1	68.7	-8.1	12.7	6.2	6.3	-2.8	8.9	4.7	13.1	8.9
DL	I	60.9	62.4	-4.4	14.1	0.7	5.9	-3.5	-1.7	-0.5	6.4	5.4
LA	D	67.6	66.2	3.1	0.3	-9.5	9.1	-15.7	-5.3	1	-1.8	-0.3
LA	I	77.3	76	2.6	2.8	-9.9	3.8	-5.9	0.5	-6.2	-5.9	3.5
MN	D	39.4	45.8	16.8	14.4	-12.3	37.5	-6.5	14.2	43.9	29.6	10.5
MN	I	103.9	109.1	6.5	5.5	-4.3	9.6	0	7.6	4.5	9.1	6.6
NP	D	44.5	45.1	8.3	-7.1	-12.5	22.3	-19.2	-13.1	15.7	12.8	4.7
NP	I	74.7	75.8	4.3	3.2	-6.4	6	-4.8	0.2	-1.1	5.1	5.6
NE	D	70.2	76.8	7.1	14.2	-0.9	14.4	1.5	16.3	11.7	10.1	10.4
NE	I	85.1	89.5	1	12.6	-1.2	16.3	-3.8	11.2	2.4	6.8	0.9
PA	D	59.8	82.2	18.2	28.3	16.4	36.7	27.3	59.5	58.5	53.1	39.7
PA	I	162.2	182.8	7.2	13.1	13.3	16.2	11.5	13.8	1.4	22	16.1
SE	D	61.6	65.3	7.7	7.2	3.1	2.1	10.7	8.3	2.3	5	8.2
SE	I	61.4	62.5	-13.7	15	-9.5	0.8	-1.3	1.1	-1.3	8.5	16.7
SP	D	32.7	33.7	7.6	1.3	-6.2	24.5	-1.1	-11.1	14.4	6.9	-9
SP	I	53.5	56.5	-4.6	3.1	4.9	17.4	2.9	8.3	-8.2	14.8	12.2

Note: AP = Appalachia, CB = Corn Belt, DL = Delta States, LA = Lake States, MN = Mountain States,
NE = Northeast, NP = Northern Plains, PA = Pacific, SE = Southeast, and SP = Southern Plains.
See Appendix A for explanation of climate models.
Source: USDA, Economic Research Service.

Crop yields under reference weather conditions are assumed to increase across all regions between 2020 and 2080, reflecting technological improvements, with growth fixed at 0.6 percent per year (see Appendix E for more details about development of the reference scenarios for each analysis period).

A few generalizations on climate-induced yield impact by crop emerge:

- ***Corn*** yields suffer significantly under changing climate conditions across almost all regions and climate projections. Corn, a C_4 crop, does not photosynthesize more efficiently as a result of increased atmospheric CO_2. Some corn-producing regions experience an increase in growing-season precipitation, but in general the negative impacts of temperature on yield trump potential gains from increased precipitation. Under the CGCM_Mid scenario—characterized by lower-than-average temperature changes across all analysis periods and a general increase in precipitation for the year 2060—dryland corn yields increase in all regions except the Delta and Pacific. For most regions and climate projections, irrigated corn yield is much lessened by climate change. Temperature change is a significant driver of yield reductions, and the effects of increased warmth on yield cannot be fully offset with increased irrigation.

- ***Soybean*** yields are generally reduced across climate projections and regions. The relatively cooler and wetter CGCM_Mid scenario is again an exception, with both dry and irrigated yields increasing in several regions. Declines in yield occur across all climate scenarios for both dryland and irrigated production in the southern portion of the soybean range—the Delta region and the Southern Plains.

- ***Wheat*** yields undergo decidedly mixed impacts under the climate change scenarios. Yields generally increase (i.e., increase under six or more climate projections) in the Mountain, Pacific, Northeast, and Southeast regions for both dryland and irrigated production, with wetter conditions often projected across the northern-tier wheat-producing areas. Wheat, a C_3 crop, experiences a boost in photosynthesis as a result of increased CO_2 concentrations. Wheat yields fare poorly, however, under the CSIRO_Mid scenario and the HADN_Low scenario, with declines in dryland and irrigated yield in the Northern Plains, Mountain, and Lake States regions (table 7). Under some scenarios, the regions showing higher yields are seeing more precipitation; in other cases, the yield impacts appear to be largely driven by changes in temperature and CO_2 concentrations. Shifts in the seasonality of precipitation—with a greater share of annual precipitation falling in the winter and early spring—may also boost production of dryland winter wheat in some scenarios.

- ***Cotton's*** primary production region, the Southern Plains, experiences mixed impacts across climate change projections, under both dryland and irrigated production. In the remaining regions where cotton is produced, including the Delta States, cotton yields generally decline under both irrigated and dryland production. Reduced irrigated yields under several climate projections suggest that yield impacts for cotton are largely due to warming temperatures.

- As with corn, the other C_4 crop in REAP, yields of ***sorghum*** decline across virtually all regions and climate projections. In the Delta region, however, irrigated yields are generally higher across climate projections. The CGCM_Mid climate scenario, which is cooler and wetter than the others in 2060, is again an exception; yields increase (or only slightly decline) for several regions.

- The impact of climate change on ***hay*** varies widely across regions. In humid areas—the Appalachian, Corn Belt, Delta, and Southeast regions—hay yields generally decline under climate change. In those regions, the yield boost from increased CO_2 concentrations is more than offset by the impacts of increased temperature. In the cooler areas, including higher latitudes of the East and across the Plains and Western States, yield impacts are mixed. This likely reflects a combination of temperature effects (indicating hay is further from the upper end of its optimal temperature range for growth in those regions), CO_2 fertilization, and increases in annual/winter precipitation across the northern latitudes under several climate projections. The CGCM_Mid scenario is again an exception; under this relatively cool and wet scenario, hay yields increase across almost all regions.

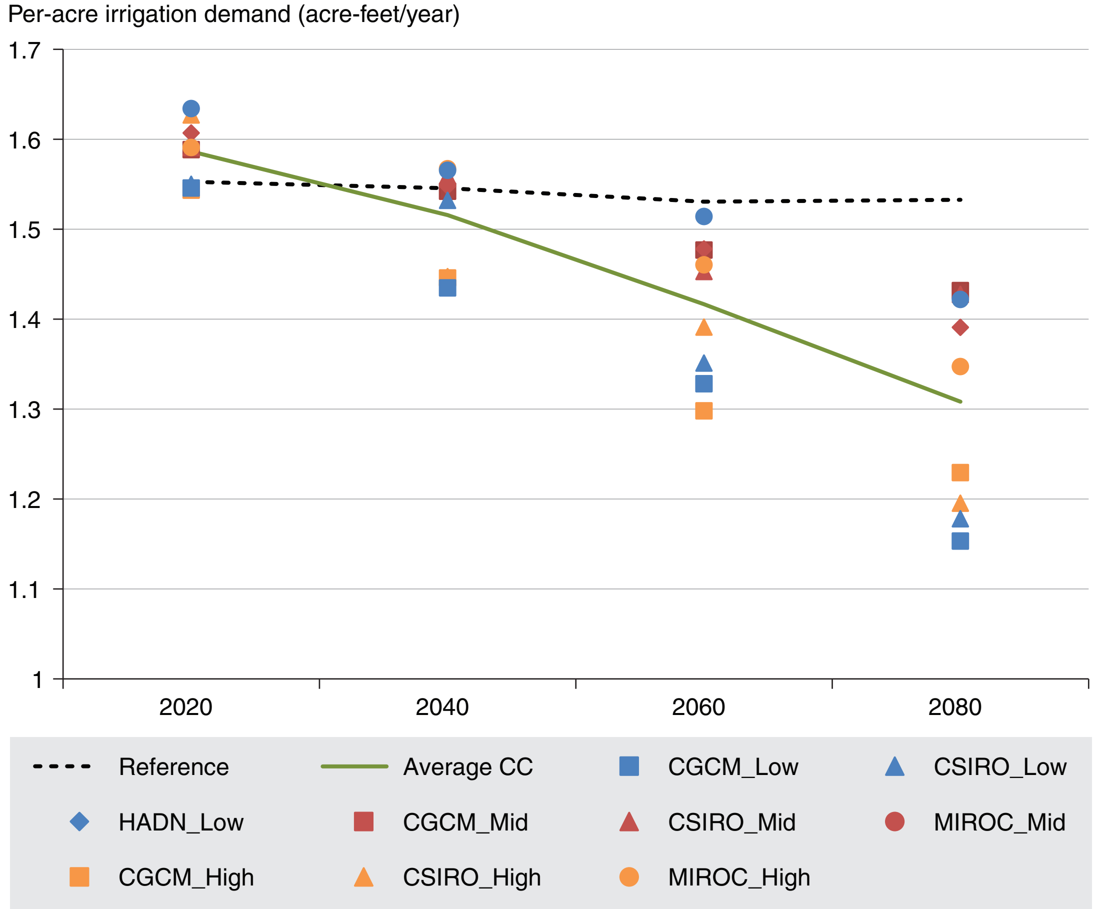
Irrigation-water demand declines as a result of changing growing conditions

Per-acre crop water use under climate change reflects the combined effect of higher evapotranspiration (ET) demand due to warmer temperatures, greater plant water-use efficiency under increased atmospheric CO_2, and potential changes in crop-water requirements due to the impacts of temperature and CO_2 on crop growth and biomass. Farmer adaptation would likely lead to additional changes in irrigation-water demand arising as irrigated acreage shifts across crops and regions, but this analysis fixes acreage within an analysis year in order to isolate the biophysical impacts of changing climate conditions on irrigation demand.

Under reference climate conditions, aggregate demand for irrigation water grows roughly 12 percent between 2020 and 2080, reflecting expansion in the extent of irrigated acreage necessary to satisfy the production and price assumptions implicit in each year's reference case. Aggregate per-acre water demand, however, remains roughly constant in the reference scenario between 2020 and 2080. Water demand per irrigated fieldcrop acre (excluding specialty crops or pasture) is shown for each climate projection in figure 18.

Figure 18

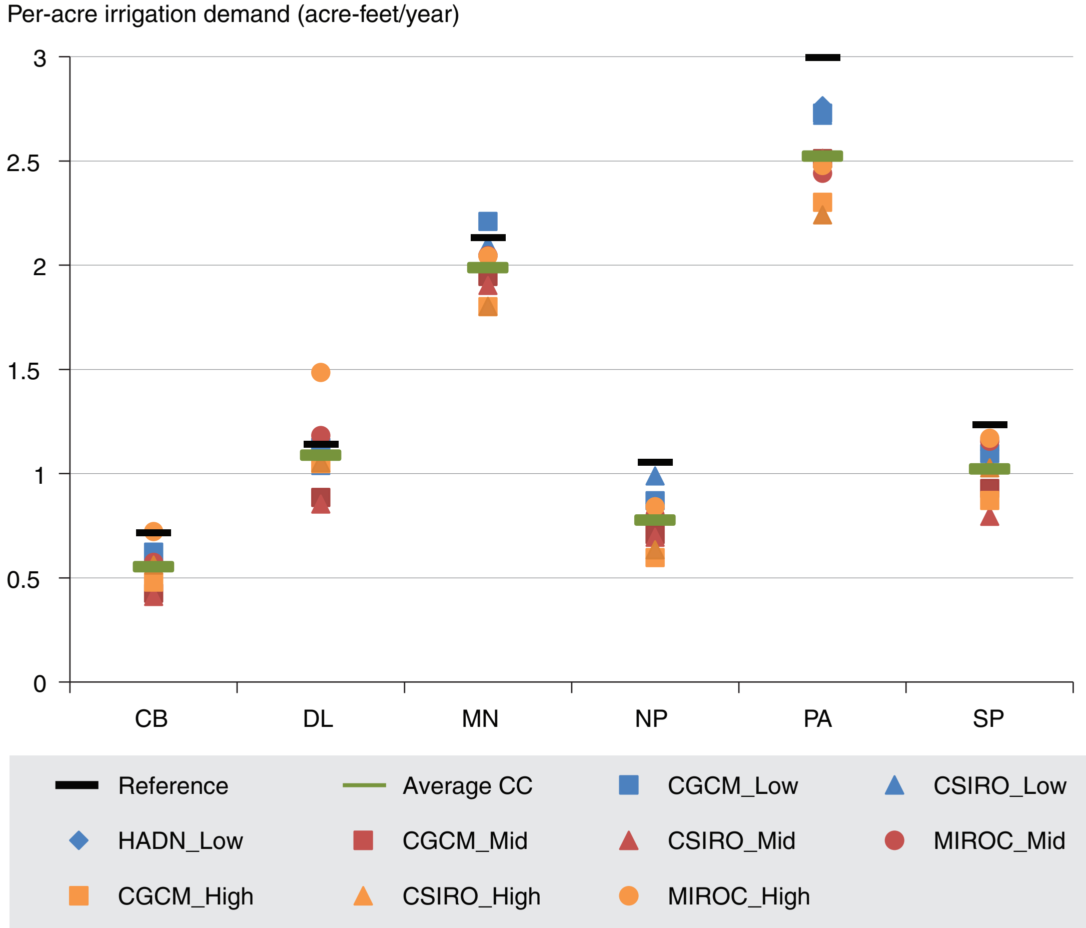
National estimates of average per-acre irrigation demand over time, all field crops, for future climate projections under the Biophysical Impact scenario, assuming fixed acreage allocations



Note: See Appendix A for explanation of climate models.
Source: USDA, Economic Research Service.

Per-acre irrigation demand declines over time for many climate scenarios, which is seemingly at odds with production conditions that are projected to be hotter and drier in heavily irrigated regions. One might expect irrigation demand to increase with rising temperatures and to change inversely with precipitation change. In fact, a regional breakdown of changes in average irrigation demand under the various climate projections (with fixed acreage relative to the reference) shows wide variation across regions and climate projections in year 2080 (fig. 19), reflecting the complexity of interactions among temperature, yield, precipitation and crop water demand in determining irrigation demand. (Total regional applied irrigation demand across analysis periods under each climate scenario is shown in Appendix H.)

Figure 19
Regional estimates of average per-acre water demand, all field crops, under future climate change scenarios in 2080



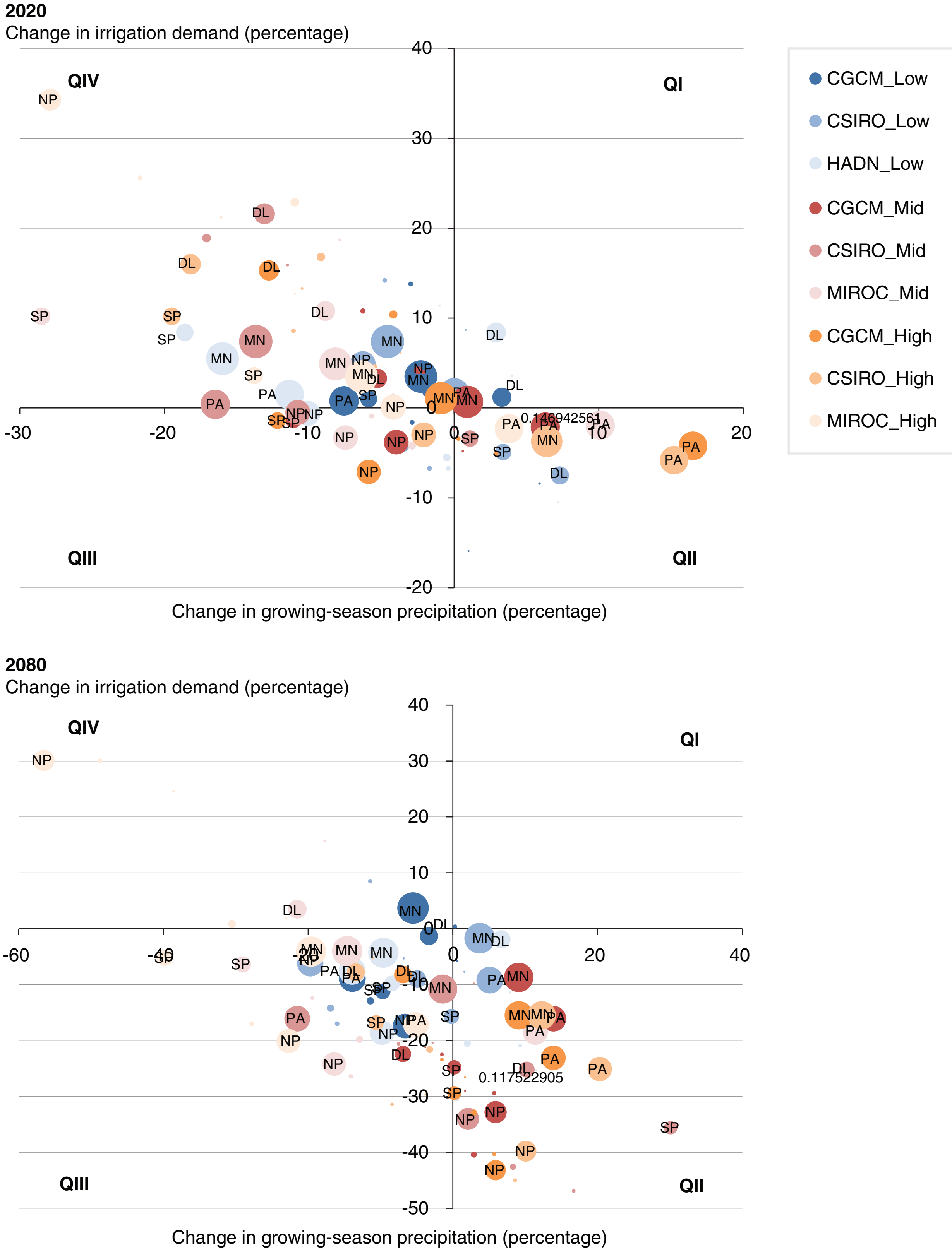
Note: CB = Corn Belt, DL = Delta States, MN = Mountain States, NP = Northern Plains, PA = Pacific, and SP = Southern Plains. See Appendix A for explanation of climate models.
Source: USDA, Economic Research Service.

Mapping shifts in regional irrigation demand against changes in growing-season precipitation in 2020 confirms a mostly inverse relationship, as shown by regions appearing in graph quadrants II and IV (QII and QIV). Still, several regions depart from that pattern under various climate projections (fig. 20). As early as 2020, several regions, including the heavily irrigated Northern Plains, appear in quadrant QIII for one or more climate projections. In QIII, regional irrigation demand declines despite regional declines in growing-season precipitation. QI reflects the equally counterintuitive—and less often observed—case where increased precipitation is met with increased irrigation demand.

There are several biophysical pathways through which such apparently anomalous results can arise. Temperature-related declines in yield, for one, lead to the appearance of regions in quadrant QIII over time. Lower yields reduce crop-water demand (due to lower crop biomass) proportionally more than the decline in precipitation, resulting in a drop in irrigation demand despite less rain. Timing of precipitation can also be an important determinant of irrigation demand. In some areas of the Northern Plains, for instance, seasonal precipitation shifts under some climate projections toward earlier rainfall, which can alter irrigation demand. This may be particularly important for winter wheat acreage, where the crop is maturing during the "early growing season" months (May and June).

Figure 20

Relationship between precipitation and irrigation demand by farm production region under climate projections for 2020 and 2080, assuming fixed acreage allocations



Note: AP = Appalachia, CB = Corn Belt, DL = Delta States, LA = Lake States, MN = Mountain States, NE = Northeast, NP = Northern Plains, PA = Pacific, SE = Southeast, and SP = Southern Plains.
See Appendix A for explanation of climate models.
Source: USDA, Economic Research Service.Note: See Appendix A for explanation of climate models.

Mapping the precipitation/irrigation relationship into 2080 reveals that, as expected, precipitation changes play a role in declining irrigation demand (fig. 20). Between 2020 and 2080, the movement of regions from left (quadrants QIII and QIV) to right (QII) suggests that under several climate scenarios in 2080, some heavily irrigated agricultural regions will see increases in growing-season precipitation relative to 2020, which reduce irrigation demand in those regions. That shift is particularly evident in the Northern Plains.

However, comparing the 2020 distribution to the 2080 distribution of regions also reveals a significant decline in irrigation demand across several regions and climate projections (as reflected in the downward shift of regional bubbles), despite precipitation declines in several of those regions. There is a marked shift of regions out of QIV, and a downward shift in the dispersion of regions in QII and QIII, reflecting the magnified decline in irrigation demand over time. Due to continuing temperature increases over the century, declining growth and biomass of crops such as corn and soybeans appear to be increasingly important in reducing irrigation demand.

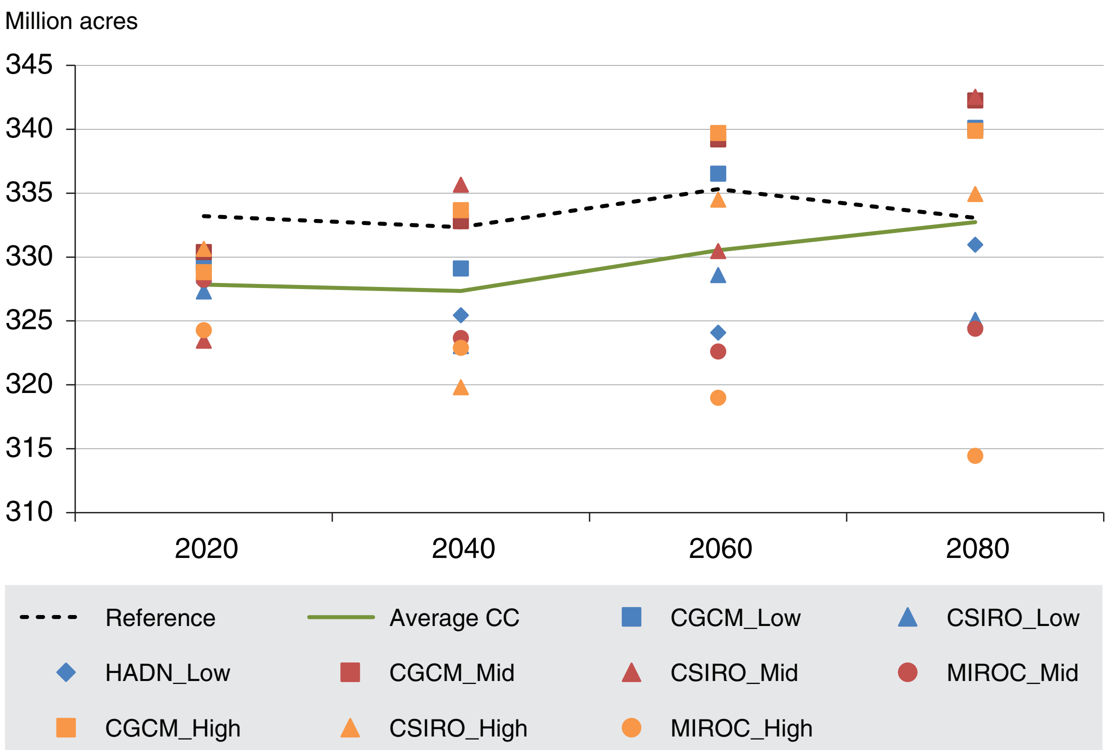
Relative Profitability Analysis

The biophysical impacts analysis intentionally excluded behavioral responses to climate change. Early studies of climate change estimated economic impacts based solely on such biophysical impacts. Subsequent research recognizes that farmers and other stakeholders regularly adapt to weather variability through changes in production and consumption patterns. Thus, production flexibility may facilitate adaptation to changing climate conditions. The Relative Profitability analysis therefore lifts the restrictions on acreage adjustment that were imposed in the Biophysical analysis to explore how farmers alter their production patterns to suit the new growing conditions and the shifting pattern of comparative advantage under different climate change scenarios. In order to isolate the underlying economic drivers of the adaptation response, the Relative Profitability analysis does not impose any additional limitations on irrigation that might constrain future economic decisions.

Acreage in production has mixed impacts under climate change

Once producers within our model are allowed to adjust their production acreage decisions in response to climate change, total amount of land in production shifts relative to the reference scenario (fig. 21). On average, acreage falls relative to the reference acreage through 2060, although impacts vary across climate change projections. By 2080, estimates of total land in production range from 314 to 343 acres, compared with 333 million acres under reference climate conditions.

Figure 21
Impact of climate change on land in agricultural production relative to a reference scenario



Note: See Appendix A for explanation of climate models.
Source: USDA, Economic Research Service.

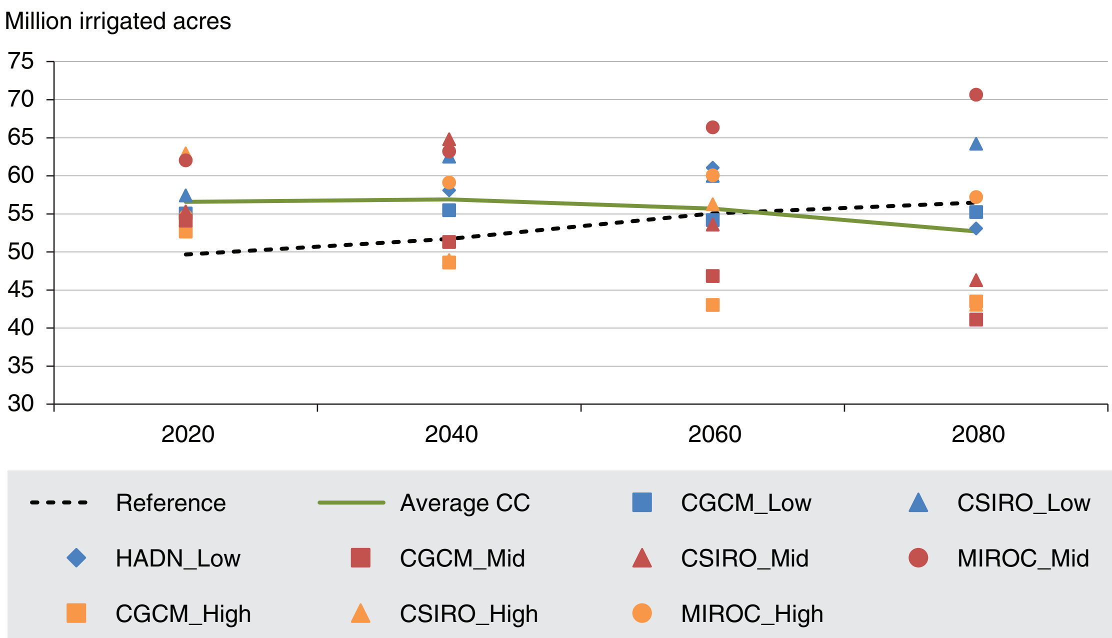
Across the climate scenarios, greater variability appears to exist across climate models than across emissions levels (low, medium, high) within a single model, which highlights the importance of understanding differences across GCM models in the effort to reduce uncertainty in future projections. The CGCM model generally produces climate projections that are cooler and that result in the largest amount of acreage in production (with increased acreage relative to the reference scenario), while the MIROC projections are for warmer temperatures that result in the smallest amount of acreage in production (lower acreage than in the reference scenario). The CSIRO climate projections produce acreage estimates with the most erratic behavior over time, but beyond 2040, its acreage results generally fall between those produced by CGCM and MIROC projections.

Without constraints on irrigation, the reference scenario for the Relative Profitability analysis is characterized by increases in both the share of fieldcrop acreage that is irrigated and in total levels of irrigated acreage, from 49.6 million acres in 2020 to 56.2 million acres in 2080. This suggests, unsurprisingly, that even in the absence of climate change (and in the absence of constraints on irrigation availability), there are economic incentives to expand irrigated production in the United States over time.

Changing climate conditions, however, produce mixed impacts on the amount of fieldcrop production acreage that is irrigated (fig. 22). In 2020, both the share of acreage irrigated and absolute level of irrigated acreage increase relative to the reference scenario, across all climate projections; regionally, the largest absolute increases in irrigated acreage occur, on average, in the Northern Plains, Delta, and Corn Belt (fig. 23).

Under the climate change scenarios, the period beyond midcentury is generally characterized by declines in both the share of acreage irrigated and the absolute level of irrigated acreage. By 2080, the share of irrigated acreage varies widely across climate projections for the Northern and Southern Plains, with the Delta, Mountain, and Pacific regions maintaining relatively constant irrigated area (fig. 23).

Figure 22
Impact of climate change on irrigated production acreage (without water-supply constraints)

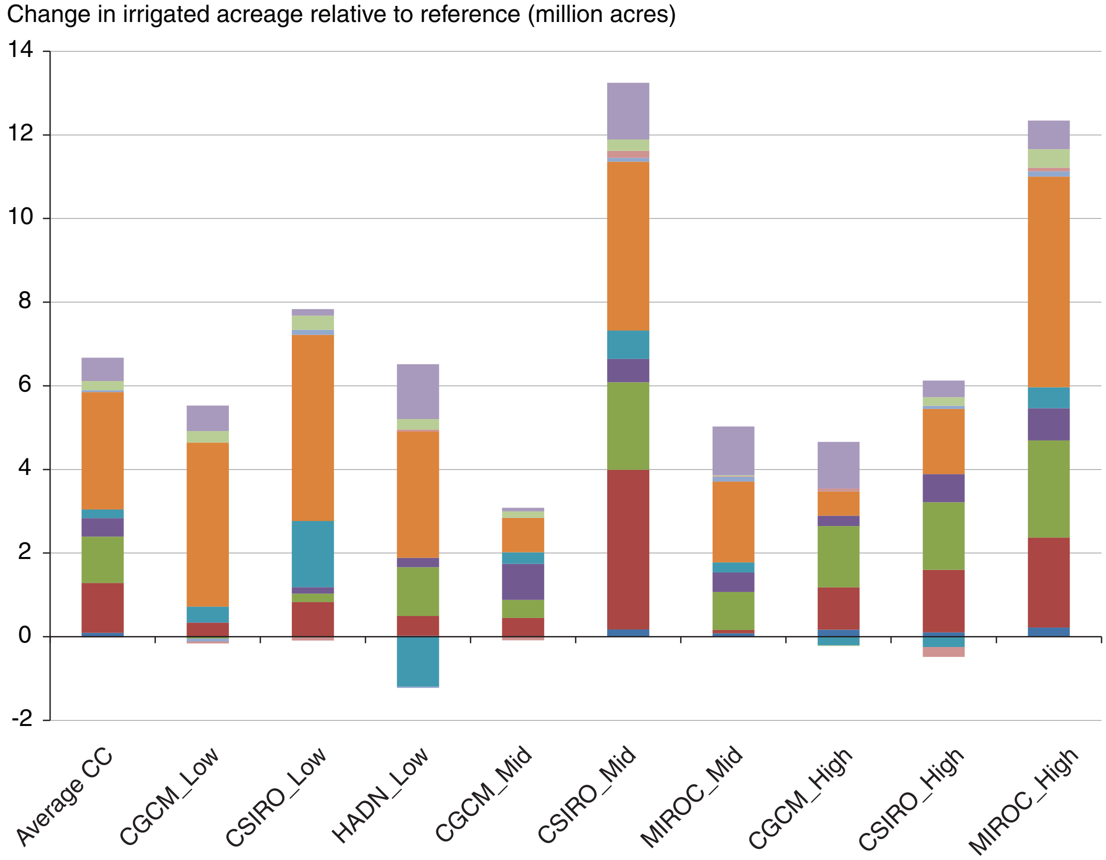


Note: See Appendix A for explanation of climate models.
Source: USDA, Economic Research Service.

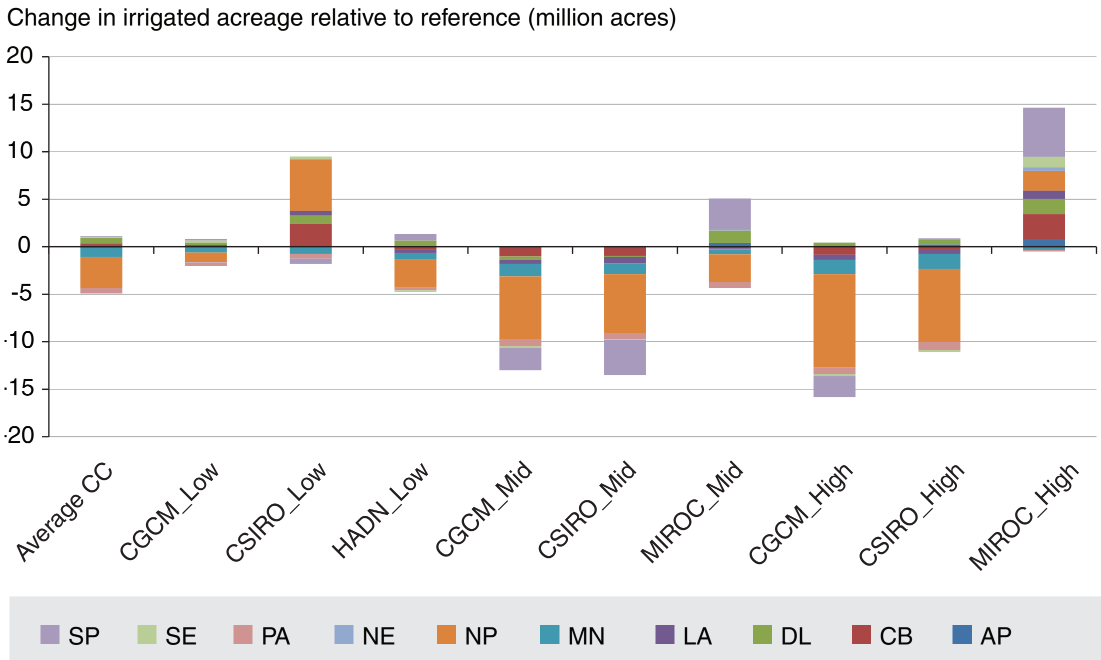
Figure 23

Impacts of climate change on regional irrigated acreage in 2020 and 2080 (without water-supply constraints)

2020



2080



Note: AP = Appalachia, CB = Corn Belt, DL = Delta States, LA = Lake States, MN = Mountain States, NE = Northeast, NP = Northern Plains, PA = Pacific, SE = Southeast, and SP = Southern Plains.
See Appendix A for explanation of climate models.
Source: USDA, Economic Research Service.

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

- ***More precipitation*** generally increases dryland yields but also reduces irrigation requirements, and therefore decreases the costs of irrigated production. The inverse holds for declining precipitation.

- As seen in the Biophysical Impacts analysis, ***higher temperatures*** affect both dryland and irrigated yields. Changes in the relative profitability of dryland versus irrigated agriculture, and resulting acreage response, will depend on the differential between reference irrigated and dryland yields, how much irrigated yields decline relative to dryland yields under changed growing conditions, and how irrigation use and cost change to compensate.

- The ***impact of CO_2*** on the water-use efficiency of crops can boost both dryland and irrigated yields. (Irrigated crops are often not sufficiently irrigated to completely eliminate water stress.) Irrigation water requirements may decline, which can reduce costs and increase the profitability of irrigated production. If dryland yields increase sufficiently through improved water-use efficiency, CO_2 changes alone can increase the profitability of dryland production relative to irrigated production.

- The impact of ***changes in relative profitability*** in determining irrigated acreage allocation applies across crops as well as across different methods of producing the same crop (i.e., dryland versus irrigated). The impact of increased CO_2 crop yields may confer a profitability advantage to C_3 crops such as wheat, barley, soybeans, and alfalfa hay. In western regions where regional dryland production alternatives are dominated by C_3 crops, such as wheat and alfalfa hay, and C_4 crops are likely to be irrigated, the carbon fertilization effect may favor dryland production systems.

In this analysis, the relative profitability of dryland versus irrigated production is influenced by complex interactions among all four factors noted above—change in seasonal precipitation, change in temperature, and the impacts of atmospheric CO_2 concentration on both photosynthesis and crop water-use efficiency.[11]

[11]Several other factors not included in this analysis, including changes in tropospheric ozone and solar radiation, may also affect irrigated and dryland production differently.

Tables 8 and table 9 present shifts in the relative profitability of irrigated agriculture (wheat and corn) by farm production region for the year 2060. The numbers represent the percentage change in the ratio of irrigated to dryland returns (per acre) for each climate projection relative to reference climate conditions; a positive number indicates an increase in the relative profitability of irrigated production, while a negative number indicates a decrease, with increasing darkness of fill representing larger declines in the irrigation premium.

Table 8

Percent change in the ratio of returns to irrigated production versus returns to dryland production for wheat in 2060

	Wheat, 2060									
Region	Average CC	CGCM_ Low	CSIRO_ Low	HADN_ Low	CGCM_ Mid	CSIRO_ Mid	MIROC_ Mid	CGCM_ High	CSIRO_ High	MIROC_ High
AP	5.3	8	3.7	-4.5	21.8	9.9	0.3	7.5	10.4	-9.4
CB	3.16	-13.3	9.3	15.2	-13.4	16	9.8	-3.7	-3.9	12.4
DL	-6.01	-9.1	13.4	-0.8	-17	7.2	-12.9	-25.6	-6.2	-3.1
LA	1.34	-0.4	3.8	-0.3	-8.6	19.4	9.5	-11.1	-6.4	6.2
MN	-8.94	-10.2	-8.6	13.1	-24.9	13.5	-6.9	-33.6	-20.7	-2.2
NP	6.13	-3.6	18.1	13.9	-16.6	35	29.3	-18.8	-7.9	5.8
NE	-6.17	-9.1	0.3	1.9	6.1	-6.9	-6.6	-14.9	-9.1	-17.2
PA	-20.32	-12.4	-14.3	-3.1	-19.1	-14	-33.2	-42.7	-23.5	-20.6
SE	-7.6	-49.1	21.8	-11.3	-24.3	-3.5	-4.8	-21.3	3.3	20.8
SP	1.82	-37	0.8	29.5	-28.1	20.9	42.8	-60.5	3	45

Note: Darker shades reflect larger declines in relative profitability of irrigated production. AP = Appalachia, CB = Corn Belt, DL = Delta States, LA = Lake States, MN = Mountain States, NE = Northeast, NP = Northern Plains, PA = Pacific, SE = Southeast, and SP = Southern Plains. See Appendix A for explanation of climate models.

Source: USDA, Economic Research Service.

Table 9

Percent change in the ratio of returns to irrigated production versus returns to dryland production for corn in 2060

	Corn, 2060									
Region	Average CC	CGCM_ Low	CSIRO_ Low	HADN_ Low	CGCM_ Mid	CSIRO_ Mid	MIROC_ Mid	CGCM_ High	CSIRO_ High	MIROC_ High
AP	-0.5	0.9	1.6	0.2	-3.2	0.4	1.2	-7.2	-0.5	1.9
CB	-5.8	-4.4	-3.1	-1	-10.1	0.8	-9.8	-14.3	-7.2	-1.3
DL	13.3	4.3	1.9	12.2	1.5	21	25.3	12.3	10.7	38.7
LA	1.1	-4.1	3.7	10.1	-5.6	1.5	3.4	-4.7	-1.6	8.2
MN	-6.4	-13	-0.4	19.8	-29.3	-1.9	-2.3	-9.1	-11.5	5
NP	-5.1	-6.4	27.8	10.1	-15.4	2.5	-3.3	-22	-15.1	-6.2
NE	3.4	-0.5	3.4	3.2	-5.3	4	6.2	0.8	6.8	11.5
PA	-13.5	10.4	-37.2	54.1	-4.8	7.5	-28.3	-29.4	-10.7	-23.8
SE	-1.8	0.8	2	-4.1	-4.8	0.4	-8.3	-9.8	-3.4	12.7
SP	2	-10.3	-12.2	2.2	-7.8	0.6	28.2	0.8	9.6	22.8

Note: Darker shades reflect larger declines in relative profitability of irrigated production. AP = Appalachia, CB = Corn Belt, DL = Delta States, LA = Lake States, MN = Mountain States, NE = Northeast, NP = Northern Plains, PA = Pacific, SE = Southeast, and SP = Southern Plains. See Appendix A for explanation of climate models.

Source: USDA, Economic Research Service.

In wheat, per-acre irrigated returns often decline relative to dryland returns; under some climate projections that decline occurs over a majority of production regions (table 8). For corn, the regional impact on the competitiveness of irrigation is mixed. In the Corn Belt and the heavily irrigated Northern Plains, however, which account for much of the Nation's corn acreage, the impact is predominantly negative, indicating a decline in the returns to irrigation relative to dryland production in 2060. For the Delta region, irrigated corn returns ***increase*** relative to dryland returns across all climate projections, suggesting an incentive to substitute irrigated for dryland corn in that region.

Precipitation change is a potentially important factor in the relative profitability of irrigated versus dryland agriculture. Increased precipitation would disproportionately benefit dryland agriculture, causing farmers to shift from irrigated production in those regions where dryland production is feasible. Figure 24 illustrates for each farm production region the percent change in irrigated acreage against the percent change in growing-season precipitation for the year 2060. The size of the bubbles reflects the region's extent of irrigated acreage under the reference scenario. The distribution of bubbles suggests that, in some cases, regional increases in growing-season precipitation are accompanied by regional declines in irrigated acreage (QII).[12] In other cases, declines in growing-season precipitation are accompanied by increases in irrigated acreage (QIV). However, there are also some cases, often in heavily irrigated regions, where the response departs from that pattern and decreases in precipitation are accompanied by decreases in irrigated acreage (QIII). In one significant case, increases in precipitation are accompanied by increases in irrigated acreage (QI). Such changes, where the extent of irrigated acreage moves in tandem with precipitation change, reflect the more complex changes in the relative profitability of dryland versus irrigated acreage illustrated in tables 8 and 9.

In the early analysis periods, the aggregate benefits of irrigated relative to dryland agriculture increase incentives for irrigated production, and farmers expand irrigated acreage. By mid to late century, however, temperature impacts on both dryland and irrigated yields have increased significantly and absolute declines in irrigated yields may be disproportionately larger than declines in dryland yields, though irrigated yields remain higher than dryland yields both before and after the change in climate. As yields of both irrigated and dryland production become increasingly affected by temperature, the relative benefits of irrigation appear to decline in many regions, resulting in a shift from irrigated production.

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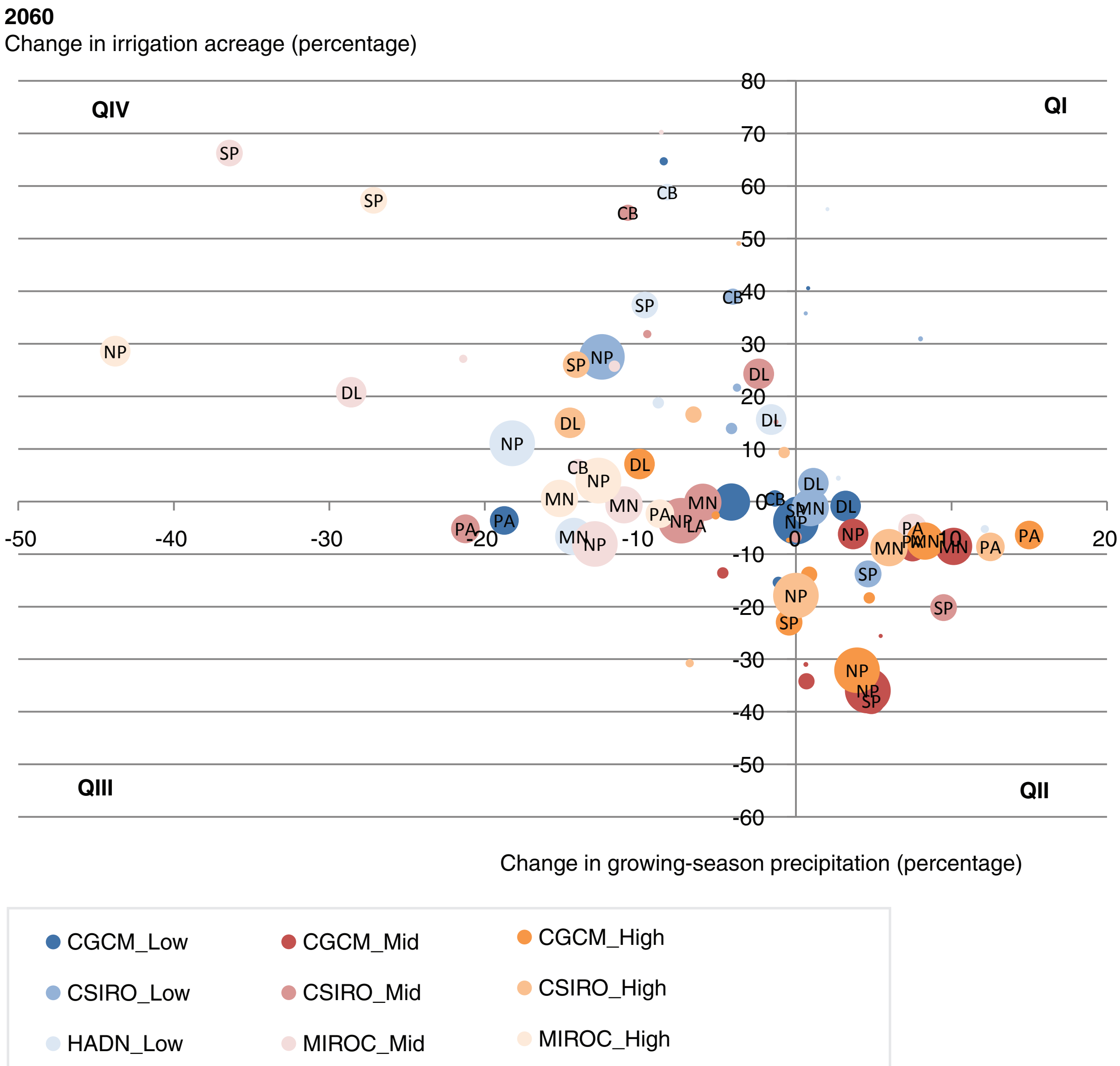
[12]Irrigated acreage changes shown in figure 23 are driven by shifts in the relative profitability of dryland versus irrigated production, while the applied irrigation changes shown in Figure 19 illustrate shifts in crop water demand under altered growing conditions but absent any acreage changes.

Figure 24

Regional relationship between change in growing-season precipitation and change in irrigated acreage under climate projections for the year 2060 (without water-supply constraints)



Note: AP = Appalachia, CB = Corn Belt, DL = Delta States, LA = Lake States, MN = Mountain States, NE = Northeast, NP = Northern Plains, PA = Pacific, SE = Southeast, and SP = Southern Plains.
See Appendix A for explanation of climate models.
Source: USDA, Economic Research Service.

Irrigation Constraints Analysis

The projected irrigation water constraints imposed in this analysis comprise three elements (discussed earlier in the report and in more detail in Appendix A). To represent the impacts on agriculture of potential reductions in ***groundwater withdrawals***, we apply estimated groundwater withdrawal reductions by region; these reductions, expressed as a percent of current withdrawals, are assumed constant across climate change projections. To represent the impact of climate-related changes in water cycling and ***surface-water availability***, we also apply surface-water availability reductions projected by region. Regional reductions in surface-water supply, arising in part from rising temperatures and shifting patterns of regional precipitation, vary by climate projection (see Appendix F for maps of surface-water supply reductions under each climate projection). Furthermore, because our analysis does not incorporate the ***costs of expanding irrigation infrastructure***, a third irrigation constraint limits the potential for costless irrigation expansion under climate change to a 10-percent increase over regional reference levels of applied irrigation water volumes. Such constraints may also serve as a constraint on irrigated acreage if there is a regional incentive for greatly expanded irrigation use.

Figure 25 illustrates the impacts on national irrigated acreage of applying these irrigation constraints in sequence to observe their incremental impact across time periods.[13]

The first set of markers in each analysis year repeats the results shown in figure 22, which reflect producer incentives to change irrigated acreage levels as a result of changing relative profitability of irrigated acreage in the absence of any additional water-supply constraints. The second set of markers illustrates the impact on irrigated acreage decisions of imposing a 10-percent expansion limit on applied irrigation volume in each region. When an expansion constraint is imposed, reference acreage stays the same, but irrigated acreage under the climate scenarios falls relative to the unconstrained case, as expected given irrigated volume limitations.

Under several climate scenarios that suggest expanded national acreage in the absence of constraints, imposing regional irrigation volume constraints results in a contraction of acreage below reference acreage levels, despite the fact that some expansion in applied irrigated volume is still permitted. Two factors contribute to this dynamic:

- The incentive for expansion is highly regional, so while national irrigation in the unconstrained case may be increasing by 10 percent, some regions are increasing by more than 25 percent and others are decreasing. Applying the irrigation constraint limits those regions that are experiencing significant expansion incentives, while only indirectly affecting regions with contraction incentives, which may result, in aggregate, in a contraction of irrigated acreage relative to the reference.

- Applied irrigation demand per acre is also changing across climate scenarios (see figure 18). When regional per-acre irrigation demand under a climate projection is above the reference level, imposing an applied volume expansion constraint of 10 percent relative to the reference will allow irrigated acreage expansion of less than 10 percent relative to the reference acreage, since each irrigated acre is already consuming more water than under the reference levels.

[13]In this analysis, which looks at the incremental impacts of the irrigation constraints and shortages included in our final climate change analysis, all acreage changes are measured relative to acreage levels in the unconstrained reference scenario. Because reductions in groundwater withdrawals are assumed to be independent of climate change, they would not be included in an exploration specific to the impacts of climate change. When assessing climate change impacts, groundwater constraints are incorporated into a revised reference case as well as into the climate projections themselves, so that change relative to the reference includes climate change-specific impacts only.

For many climate scenarios, the impact of the irrigation expansion constraint on acreage decreases over time, due to the declining incentives for irrigation expansion described in the Relative Profitability analysis section.

The third set of markers in each time period shows the impact of adding the groundwater constraint, which limits groundwater withdrawals in certain regions, while maintaining the irrigation expansion constraints. The fourth set of markers illustrates the subsequent addition of regional constraints on the availability of surface water for irrigation under climate change. Both groundwater and surface-water constraints result in further declines in irrigated acreage for each climate projection, with their relative importance varying by region and shifting over time. In the early to midcentury, irrigation water-supply reductions are clearly an important factor in limiting acreage in irrigated production; the incentives for irrigated acreage expansion illustrated in the first column are severely curtailed by the imposed irrigation constraints and shortages illustrated in the subsequent columns.

By late century, however, incentives for irrigated acreage expansion have declined with changed growing conditions across many climate projections; as illustrated in the Relative Profitability analysis, a combination of changing precipitation patterns and lower yields due to increasing temperature stress reduces the relative profitability of irrigated production. Beyond 2060, irrigated fieldcrop acreage under many climate projections contracts, even in the absence of limits on water supply (fig. 25). The effect of irrigation shortages remains significant in some regions, though later in the century the magnitude of the irrigated acreage response to water-supply limitations declines for several climate projections.

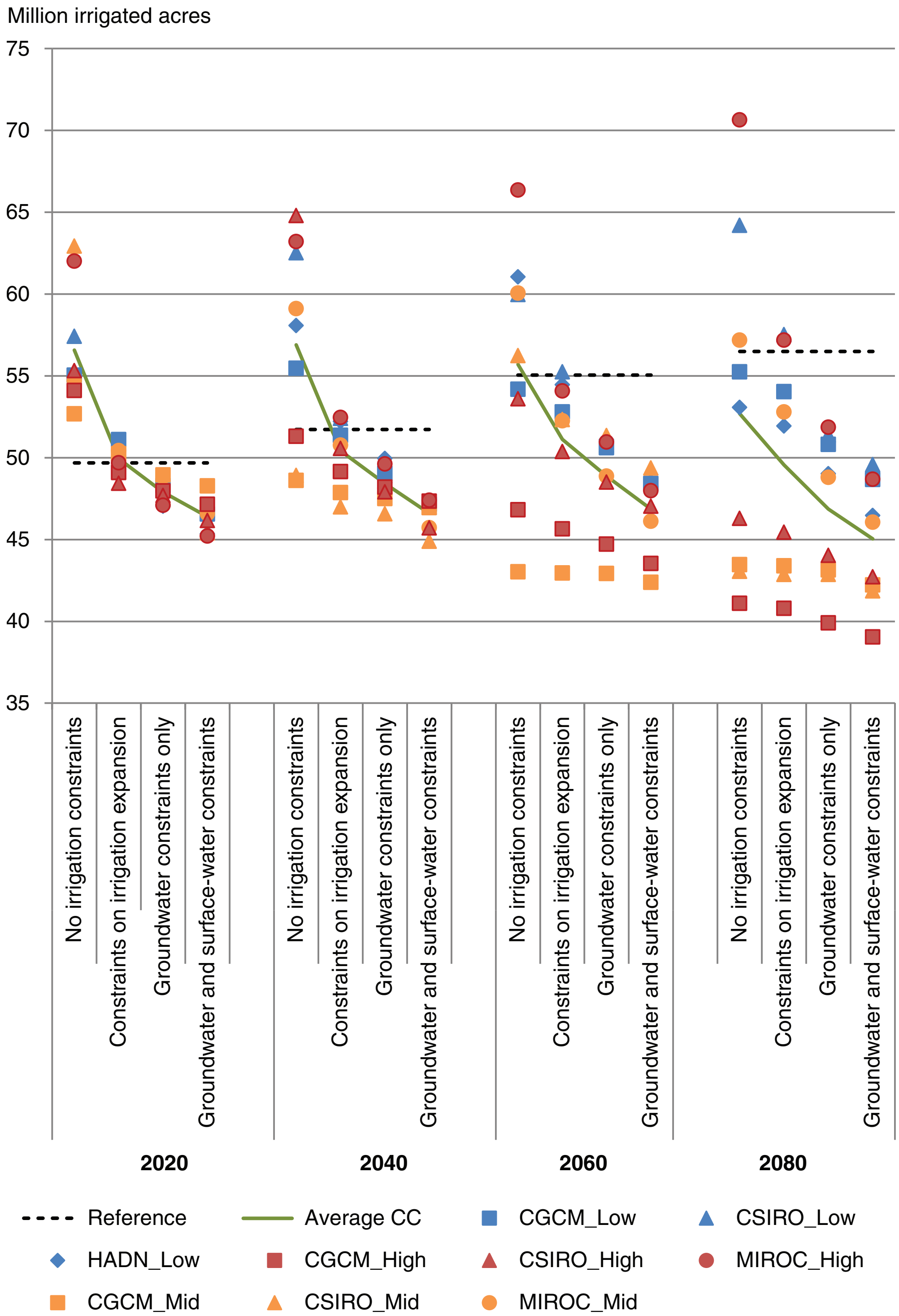
The regional impacts of groundwater and surface-water constraints on irrigated acreage, and the change in those impacts over time, can be explored regionally by averaging impacts over all climate projections (fig. 26). In early to midcentury, substantial incentives for irrigation expansion exist, with the largest expansion occurring in the Northern Plains, followed by the Corn Belt and Delta regions. Irrigation supply shortages, however, reverse the acreage response, resulting in a contraction of irrigated acreage across all farm production regions.[14] In 2020, groundwater constraints have the greatest impacts on the Northern and Southern Plains regions, with smaller impacts on the Delta and Mountain States. Climate-change-induced surface-water constraints have additional impacts on the Northern Plains, the Pacific region, and the Mountain States in 2020.

By 2060, the incentives for irrigated acreage change have reversed in the Northern Plains (and Mountain region) due to changes in the relative profitability of irrigated versus dryland production (as described in the Relative Profitability analysis), leading to a further contraction in irrigated acreage in those regions. A disincentive to expand irrigated acreage also appears in the Pacific region for 2060. Average extent of irrigated acreage under the climate change projections declines in those regions even in the absence of limitations on irrigation availability, despite warmer temperatures. Incentives for irrigated acreage expansion remain positive but decline slightly (relative to 2020) in the Corn Belt, Delta, and Southern Plains in the unconstrained adaptation scenario (fig. 26, column 1). While climate change is projected to affect surface-water supplies in the Southern Plains, the effect is small relative to the impacts of projected declines in groundwater for irrigation use. In contrast, climate-related surface-water shortages have a greater incremental impact on the acreage response in the Mountain and Pacific States.

[14]Further disaggregation of the response reveals that a few of the underlying REAP regions experience increases in irrigated acreage, but when aggregated to the FPR or national level, the net effect is negative.

Figure 25

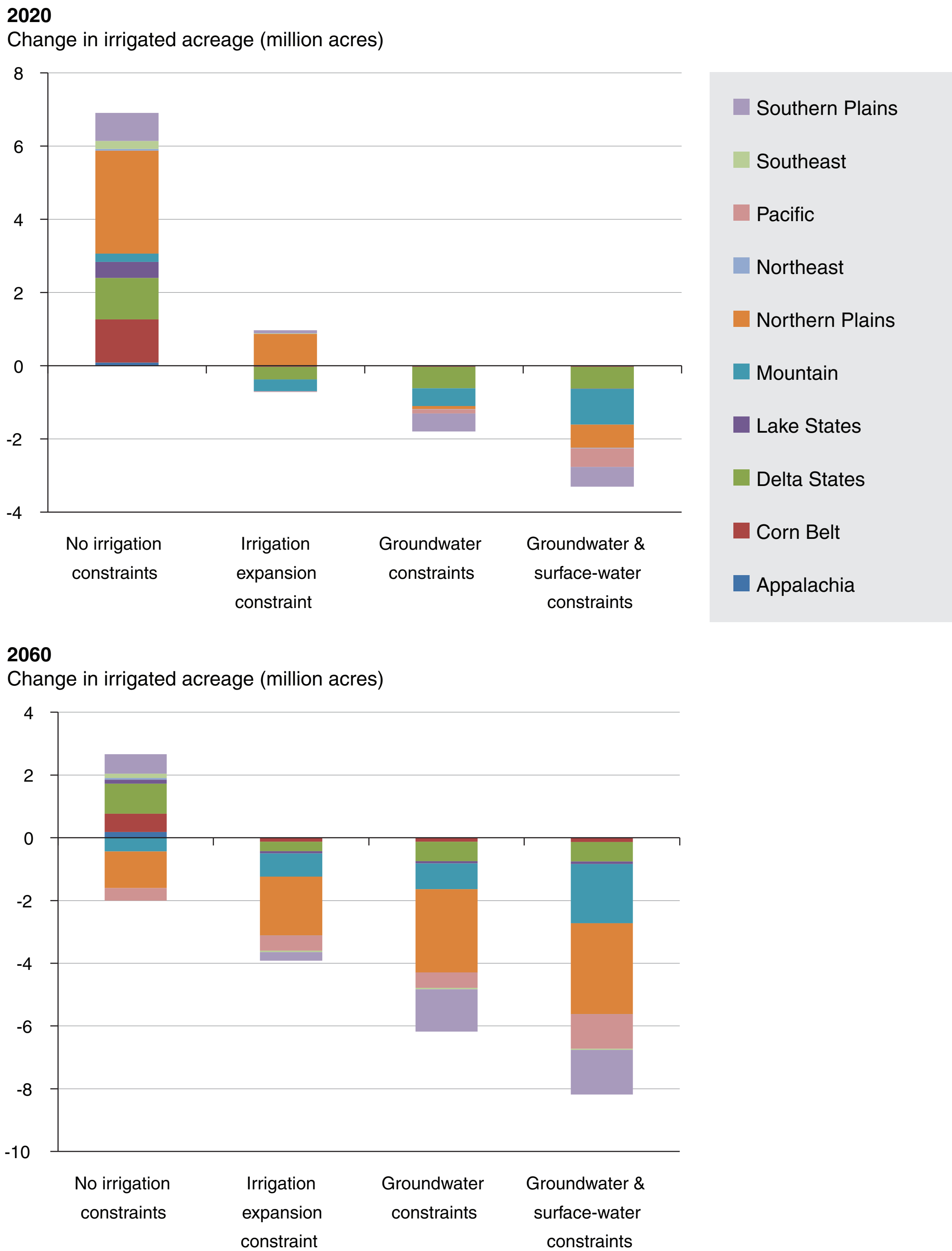
Impacts of climate change on irrigated acreage under irrigation constraints



Note: See Appendix A for explanation of climate models.
Source: USDA, Economic Research Service.

Figure 26

Implications for regional irrigated production acreage, averaged over the climate change scenarios, of irrigation constraints imposed in sequence



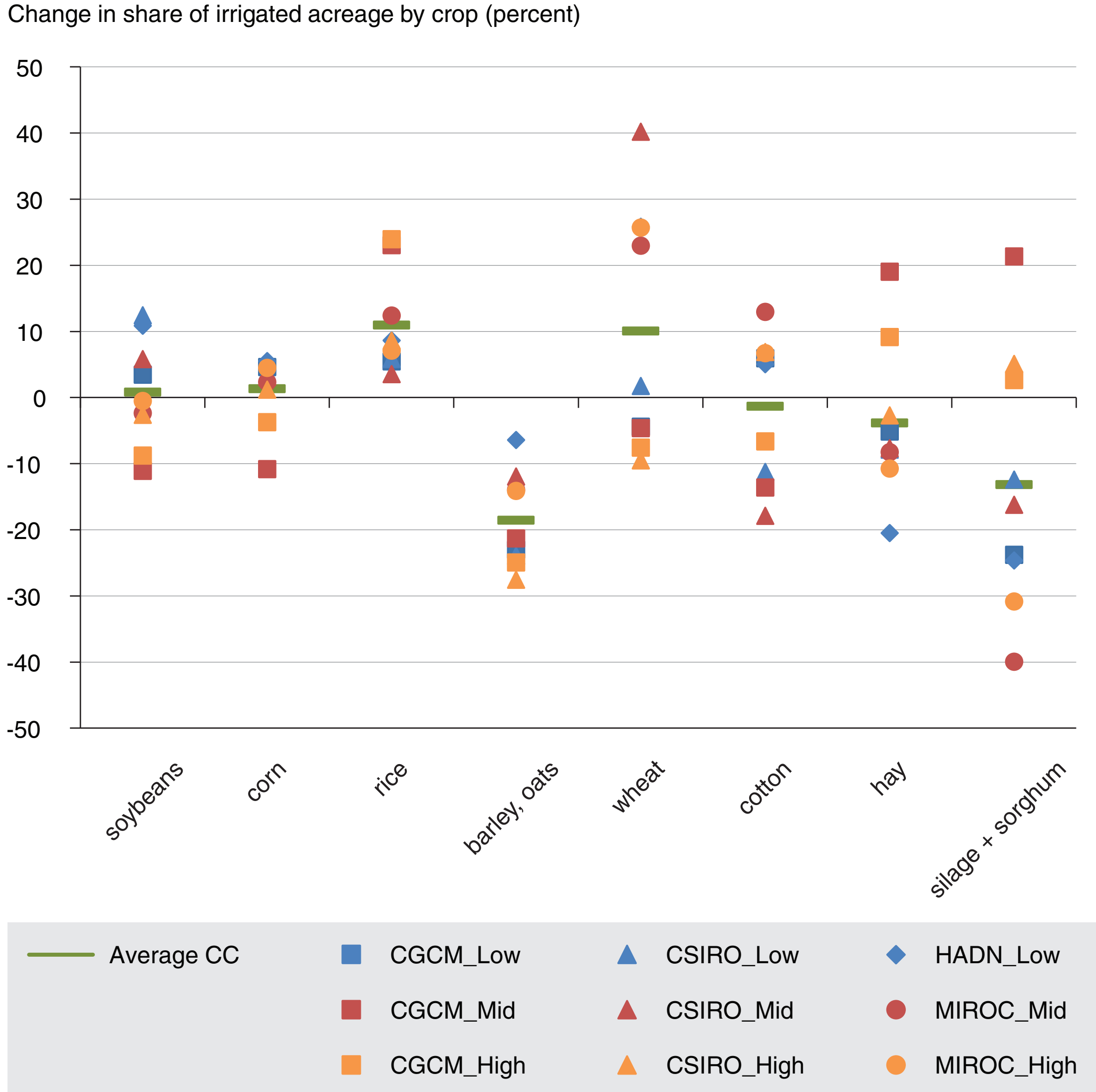
Source: USDA, Economic Research Service.

Irrigation constraints influence irrigated crop mix

Increasing scarcity of irrigation water affects the extent and distribution of irrigated acreage in areas facing water-supply shortfalls. Irrigation constraints also induce a shift in acreage toward higher value irrigated field crops, reflecting the increased marginal value of scarce water supplies. In 2060, for instance, irrigated acreage impacts are highly variable across climate scenarios, but less irrigated acreage on average is allocated to lower value hay, silage, sorghum, barley, and oats under increasing irrigation shortages. At the same time, a higher share of irrigated acreage is allocated to higher value field crops such as corn, soybeans, and rice, although corn and rice use water intensively (fig. 27). Wheat, with average yields increasing under climate change by 2060, also attracts a greater allocation of irrigated acreage.

Irrigated acreage in cotton experiences mixed impacts across the climate scenarios, but declines slightly, on average, under climate change, despite being a high-value crop. Across climate scenarios and regions, the profitability of dryland cotton production generally increases in this analysis while that of irrigated cotton production declines. As a result, cotton experiences a contraction in irrigated acreage nationwide and an expansion in dryland acreage.

Figure 27
Change in share of irrigated acreage allocated to each crop under climate projections relative to scenarios without irrigation constraints, 2060



Note: See Appendix A for explanation of climate models.
Source: USDA, Economic Research Service.

Conclusions

The U.S. agricultural sector is expected to face significant changes in crop productivity, resource availability, and market conditions under climate projections through the 21st century. Rising temperatures and shifting precipitation regimes are expected to slow or reverse yield growth trends for major field crops across much of the Nation. Farmers can adapt to changing growing conditions—and resulting changes in relative profitability across production enterprises—by altering crops, rotations, input levels, production methods, and amount of land cultivated. The nature and magnitude of climate change impacts, and the resulting incentives for reallocating production and constraints to producer adaptation, will vary significantly across crops and regions.

The net impacts associated with changes in seasonal precipitation, minimum and maximum temperatures, and atmospheric CO_2 concentrations in this analysis suggest that climate change will generally reduce yields of major field crops—except for wheat, hay, and barley—relative to a scenario with reference climate conditions. Our projections of reduced agricultural productivity differ from those of some other studies, which suggest that climate change will be productivity enhancing in the United States, even toward the end of the century (Reilly, 2003). However, they are consistent with the projections of the 2014 National Climate Assessment, wherein climate disruptions will have increasingly negative impacts beyond midcentury on most crops and livestock in the United States (Melillo et al., 2014).

Irrigated acreage—an important focus of our analysis—is projected to decline over the latter half of the century despite the warming climate. Declines are expected in part due to precipitation and temperature effects on crop-water demand and water-supply availability, and in part due to climate-induced yield effects and resulting shifts in the relative profitability of irrigated and dryland cropping systems. When changes in growing conditions reduce the yield premium achieved through irrigation, the relative profitability of irrigated and dryland cropping systems may shift. Dryland cropping systems can become relatively more profitable in cases where precipitation is sufficient to support dryland production, and yield/revenue declines are large in higher cost irrigated systems, causing land to move out of irrigated and into dryland production.

Agricultural production is projected to decline relative to reference production levels for major U.S. field crops throughout the century, reflecting (1) a decline in crop productivity (yields/acre) in response to changing growing conditions, (2) regional declines in surface-water irrigation supplies, and (3) the contraction of higher yielding irrigated acreage after midcentury due to declining premiums to irrigation under several climate scenarios. In general, prices are expected to increase for most crop commodities, resulting in declines in national consumer welfare. Producer returns are also generally projected to decline with climate change, as higher prices are offset by declines in production. However, declines in production returns are highly variable across climate scenarios.

Drivers of adaptation response vary by region

National projections of acreage and production response to climate change mask considerable variation at the crop level and regional scale. Here we summarize the primary factors driving three key outcome measures: irrigated acreage response, crop production, and crop prices.

Drivers of irrigated acreage response across regions

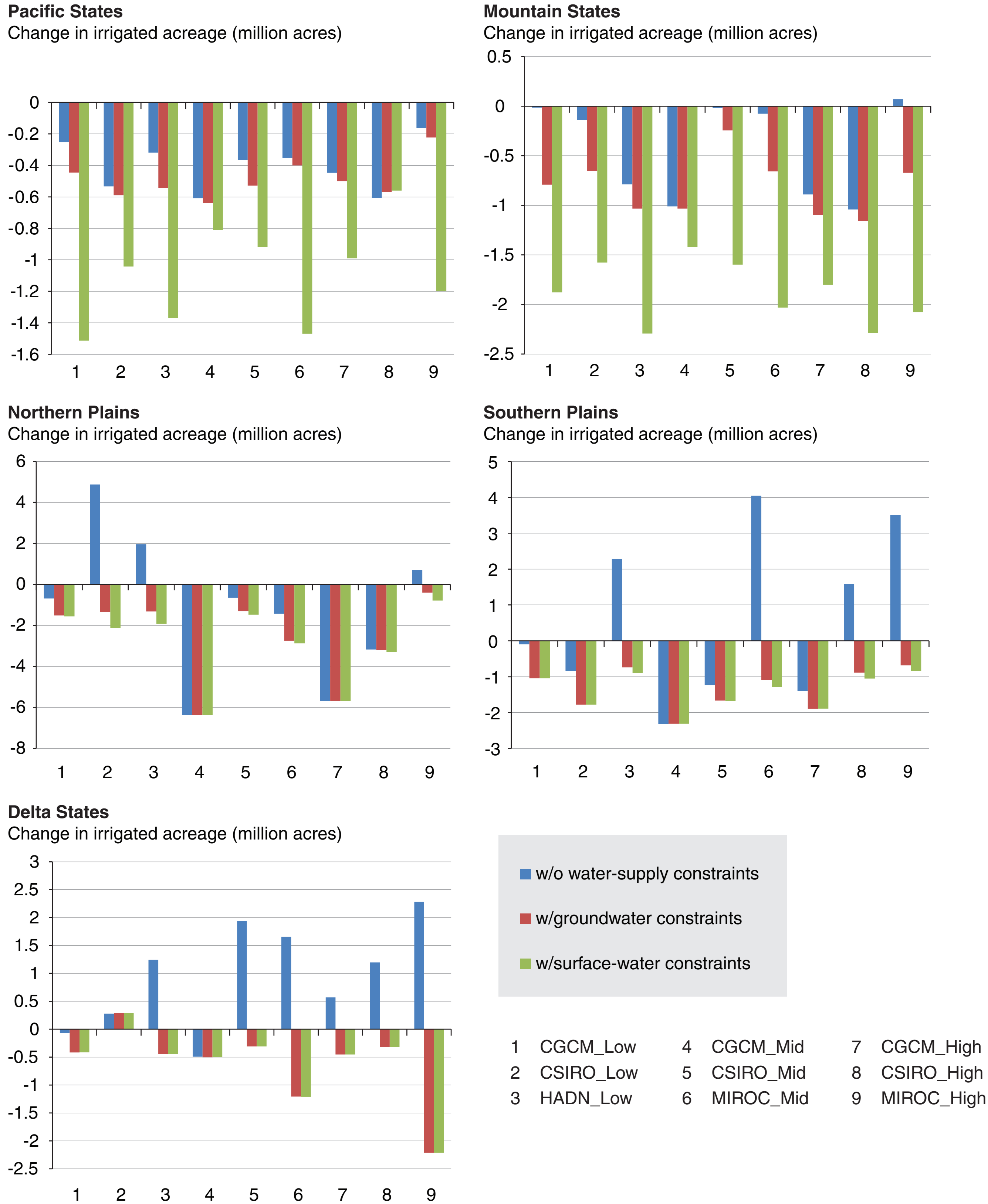
The projected decline in U.S. irrigated fieldcrop acreage reflects (1) the shift in relative profitability of irrigated cropping systems in many areas where precipitation is sufficient to support dryland production, (2) projected reductions in groundwater irrigation withdrawals due to regional groundwater depletion (fixed across climate projections), 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 shifting climate conditions over time, the yield response of irrigated and dryland crops, regional dependence on ground- versus surface-water irrigation, and climate-induced decreases in irrigation water supply. Figure 28 illustrates the relative importance of these drivers across Farm Production Regions, through differences in regional shifts in irrigated acreage with and without irrigation supply constraints in 2060. The change in bar height moving right represents the incremental effect of each of the three drivers on regional irrigated acreage change.

In the ***Pacific*** region, irrigated acreage declines or remains constant in the absence of water-supply constraints, while dryland acreage increases under all climate projections, suggesting a shift in the relative competitiveness of regional dryland production. This is particularly evident in the Pacific Northwest, where precipitation is often projected to increase and dryland wheat and hay production is concentrated. The picture differs in more arid irrigated areas—including California's Central Valley and southern coastal areas, as well as east-central Washington—where crop evapotranspiration demand is greater and growing-season rainfall is more limited. While the irrigation profit premium declines under most climate projections, irrigated acreage nevertheless holds fairly constant in the absence of water-supply constraints, indicating that returns to irrigated production remain high in those arid regions. Under warming and often wetter conditions across much of the central and northern Pacific Region, higher yields are projected for dryland wheat, hay, and cotton under most scenarios. The introduction of water-supply constraints in the southern-tier basins results in further reductions in irrigated acreage and additional expansion of dryland production. The impacts of reductions in groundwater withdrawal and constraints on irrigation volume (moving from the first to second bar) are relatively small; most of the decline in irrigated acreage reflects surface-water reductions attributable to climate change (as indicated by the shift between bars two and three).

Irrigated acreage in the ***Mountain*** region also declines under most climate projections, even in the absence of limitations in irrigation availability, reflecting the dual effect of declining relative returns to irrigation and increasingly limited water supplies in the central and southern basins. The decline in irrigated acreage spans all irrigated crops except for hay, which benefits from higher irrigated yields under climate change. As in the Pacific region, reduced irrigated area due to declining relative profitability of irrigation is most notable in the northern-tier Mountain subregions, reflecting increased precipitation and higher yields in dryland wheat and hay production at the northern end of that region. Despite a decline in irrigation returns in some areas, irrigation incentives remain strong across the southern and central Mountain region and, in the absence of growing water-supply scarcity, irrigated acreage remains fairly stable. The introduction of water-supply constraints results in a significant decline in irrigated acreage in the central and southern Mountain region across climate projections, with most of that acreage coming out of water-intensive irrigated hay production. Again, the impacts of projected groundwater withdrawal reductions and constraints on irrigation volume are generally small relative to the effects of surface-water constraints arising from climate change.

Figure 28

Change in irrigated acreage relative to reference case by climate projection for major irrigated regions in 2060



Note: Constraints on irrigation expansion are also applied whenever groundwater and/or surface-water constraints are imposed. See Appendix A for explanation of climate models.
Source: USDA, Economic Research Service.

The ***Southern Plains*** show mixed impacts on irrigated acreage in response to climate projections. In general, returns to irrigated production increase relative to dryland production in the northern and central subregions, with some increases observed in the Gulf Coast area. In the absence of water-supply constraints, irrigated acreage may expand or decline depending on the climate projection. A general increase in the acreage of irrigated corn, wheat, and hay suggests those production systems may gain a comparative advantage under changing climate. The introduction of water-supply constraints—which for the Southern Plains primarily reflect reduced groundwater withdrawals from the Ogallala Aquifer—results in a net decrease in irrigated acreage across all crops under all climate projections. Increasingly limited groundwater supplies, modeled independent of climate change in our study, represent the primary driver of changes in Southern Plains irrigated acreage.

The ***Northern Plains*** shows declining irrigated acreage under most climate projections, even in the absence of water-supply constraints. Increased precipitation, combined with reduced returns to irrigated corn and generally higher wheat and hay yields, drive an increase in the relative profitability of regional dryland production. However, dryland acreage also declines across several scenarios, reflecting declining yields in corn and soybean production. The introduction of water-supply constraints in the central Plains basins has a small incremental effect, as acreage declines are attributable primarily to shifts in the profitability of irrigated and dryland production. In fact, irrigated acreage ***expands*** in some areas in response to increased commodity prices. Climate-induced surface-water supply reductions (shown by the difference in second and third bars) have little effect on Northern Plains acreage.

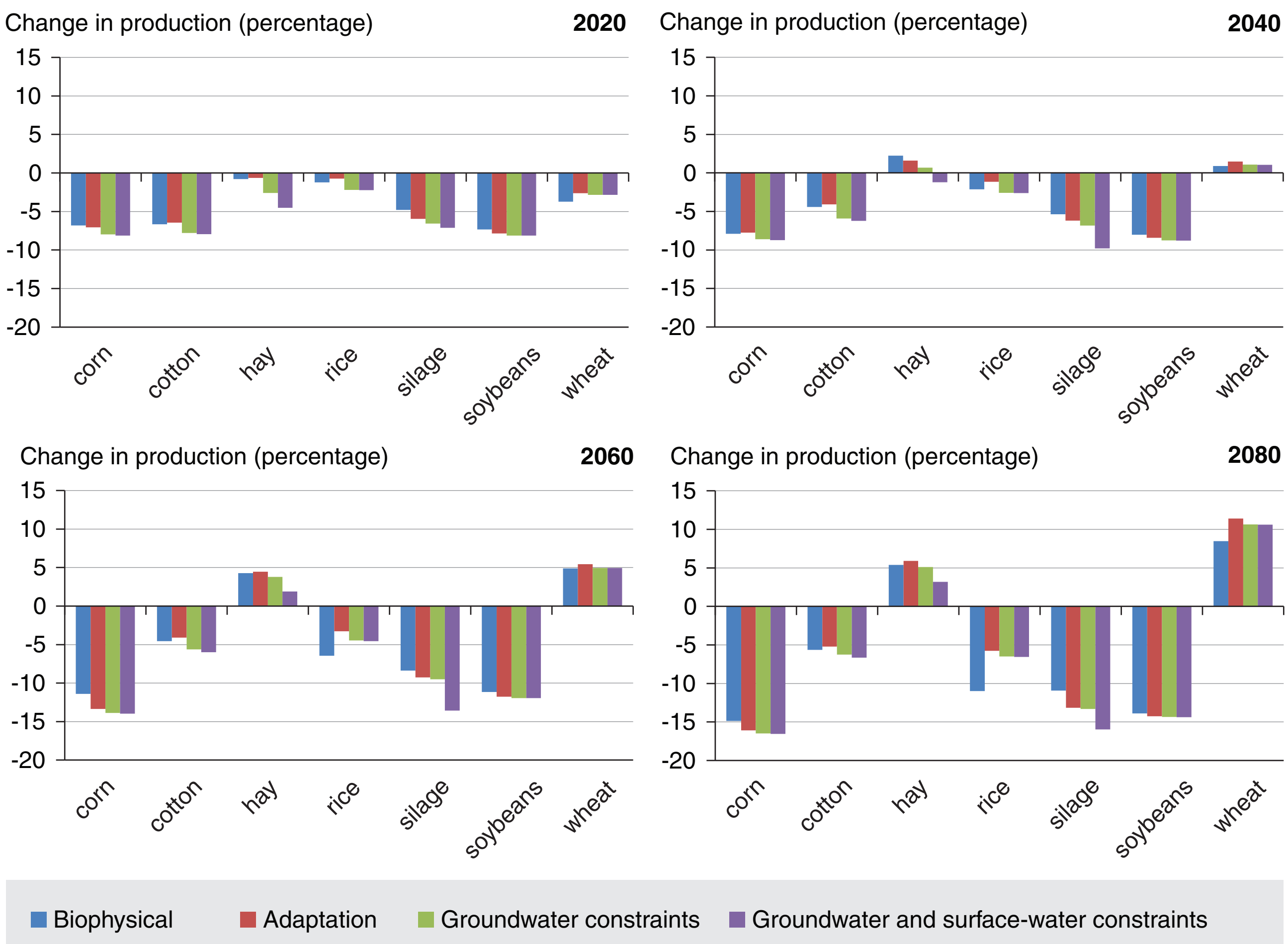
In the ***Delta States***, irrigated acreage expands under most climate projections in the absence of water-supply constraints, with dryland acres declining in all scenarios. Irrigated acreage increases across major irrigated crops (corn, cotton, rice, and soybeans), despite the general decline in irrigated yields. That expansion is driven, in part, by large declines in regional dryland yields which shift relative profitability toward irrigated production. When water-supply constraints are imposed, both irrigated and total acreage in production decline under most climate projections. The impact of water-supply constraints in the Delta region is entirely due to projected groundwater withdrawal reductions, as no additional surface-water reductions are projected for the region.

In the remaining production regions—the ***Corn Belt, Appalachia, Lake States, Southeast, and Northeast***—irrigated acreage accounts for a limited share of the cropland base. However, our results suggest a potential increase in returns to irrigation in some areas. A warming climate is projected to expand levels of irrigated acreage for the Corn Belt, Appalachian, and Northeast regions, with mixed impacts on the Southeast and Lake States. In some cases, the proportional expansion of irrigated acreage is large, with irrigated acreage more than doubling under some projections in the Corn Belt, and increasing five-fold in the coastal Appalachian region under one climate projection, when no expansion constraints are imposed.

Drivers of national production and price response

Most of the crops modeled experience increasingly large losses in aggregate production over time (relative to reference climate levels); notable exceptions are hay and wheat, which, despite slight production declines in 2020, respond to changes in growing conditions over the remaining years with increased yields and output. The production impacts associated with the biophysical yield changes under climate change (with and without adaptation) as well as the additional reductions generated by the irrigation constraints on national production are shown in figure 29. The impacts of changing climate conditions on production (without the adaptation response or irrigation constraints) are shown in the first bar column, with percent declines in output relative to the reference scenario. Changes in national production after adaptation are shown as the difference between the first and second columns, followed by the incremental impacts of groundwater and irrigation volume constraints (third column) and then surface-water constraints (fourth column).

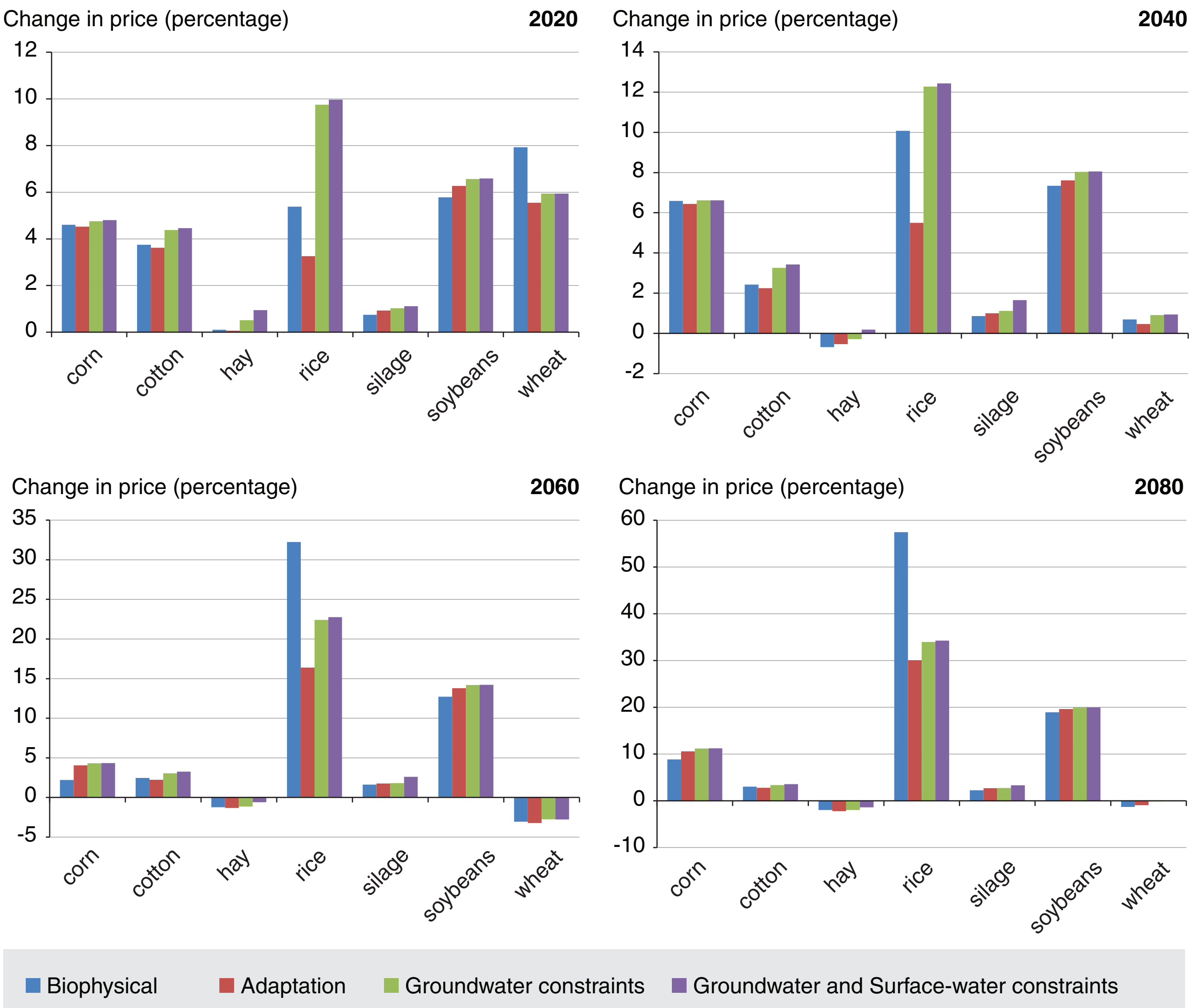
Figure 29
Impact of biophysical change, producer adaptation, and irrigation constraints on national production over 2020-2080



Note: Constraints on irrigation expansion are also applied whenever groundwater and/or surface-water constraints are imposed.
Source: USDA, Economic Research Service.

Across all periods and for most crops, the initial biophysical yield impacts associated with climate change are the most significant driver of national changes in production (fig. 29) and prices (fig. 30). Producer adaptation to these changes—and subsequent changes in relative returns to crops, regions, and production methods—generally results in an increase in national cotton, hay, rice, wheat, and oats production and a decline in corn, silage, soybean, and barley production. Constraints on the availability of irrigation water further affect production levels, although their relative importance changes over time. In 2020, for instance, constraints on groundwater significantly reduce production of hay and rice; by 2080, however, projected declines in groundwater withdrawals (relative to climate change-induced yield shifts) do not significantly alter national production for most crops.

Figure 30
Impact of biophysical change, producer adaptation, and irrigation constraints on national commodity price over each analysis period



Note: Constraints on irrigation expansion are also applied whenever groundwater and/or surface-water constraints are imposed.
Source: USDA, Economic Research Service.

A relatively small share of national fieldcrop production is irrigated, and this proportion changes with climate-change-induced shifts in the relative profitability of irrigated versus dryland systems. When groundwater constraints are imposed, dryland agriculture expands and redistributes to largely compensate for losses in irrigated production. Climate change remains a significant driver of national changes in production and price, and the vast majority of the climate change impact occurs through impacts on biophysical yield; except for silage and hay production, reductions in surface-water availability due to climate change have a relatively small impact on production and price.

The impacts of different drivers of commodity price largely mirror their impacts on production; the responsiveness of that relationship is informed by the price elasticity of demand for the commodity, as well as by the role of that commodity in livestock diets and model flexibility in substituting among livestock feedstocks as prices change. Wheat, for instance, experiences significant increases in production due to climate change in 2080 but only minor declines in price; the price impact of greater wheat production is buffered by a 400-percent increase in the use of wheat as a livestock feedstock. The price of rice reflects the changing relative importance of the different drivers over the analysis period. While irrigation constraints substantially increase rice prices in the early analysis periods, those same constraints have only a minor marginal impact on prices by 2080, when their impact is dwarfed by a significant biophysical decline in rice yields and production.

As a result of impacts on production and prices, climate change is generally projected to reduce both consumer and producer welfare, even in the short term. Climate change results in an increase in the production-weighted price index calculated across the 10 modeled REAP crops for almost all combinations of climate scenario and analysis year.[15] Despite the price increase, national producer welfare drops across most scenarios and time periods. Impacts on producers vary greatly across both crop sectors and regions; however, producers in the Corn Belt and Northern Plains experience per-acre losses across all future climate projections, while growers in the Delta, Northeast, and Pacific regions experience gains under four or more climate projections. Irrigation constraints can offset gains and exacerbate losses; while the aggregate magnitude of additional losses due to constraints on irrigation is moderate, regional impacts are more significant in those regions, like the Southwest, that experience water shortage. Climate change, and the evolving constraints and opportunities associated with water scarcity, also generate significant redistributions of returns among crop sectors.

[15]The CGCM model is the notable exception. For 4 of the 12 combinations of climate scenario (3) and analysis year (4), the CGCM model projected declines in an index of commodity fieldcrop prices.

Implications for research, technology development, and policy

Irrigation is widely viewed as an important adaptation to shifting production conditions under climate change. However, increasing water scarcity—driven by increased competition for available water supplies and climate-induced shifts in hydrologic systems—is a potential constraint on irrigation expansion at the farm level and production at the national level. Our results, however, suggest that the biophysical yield impacts associated with climate change may drive shifts in the relative profitability of irrigated versus dryland production that limit irrigation incentives even in the absence of water scarcity. While climate effects on water-supply availability contribute to increasing water scarcity across much of the arid West, declines in the relative profitability of irrigation appear to temper the irrigation response under many climate projections in the United States. The marginal impacts of climate-related surface-water supply constraints are regionally significant in terms of acreage change, but do not substantially affect national production levels or commodity prices.

Beyond 2020, per-acre applied irrigation demands decline under the climate change scenarios relative to the reference conditions for each analysis year. Such shifts in applied irrigation demand reflect changes in precipitation patterns under climate change, as well as offsetting factors: (1) increased crop evapotranspiration demands with warming temperatures, and (2) declining biomass due to increasing temperature stress on crop growth, which results in smaller plants and lower evapotranspiration rates over the growing season.

While increased irrigation can help mitigate the effect of higher growing-season temperatures, changing climate conditions may lower the marginal productivity of irrigation water in such a way that the yield premium achievable through irrigation declines. This analysis finds that, by late century, 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, even when irrigation supplies are nonconstraining. As a result of such shifts in relative profitability, which mute demand for irrigation in many regions, and given that much of the Nation's fieldcrop production is rainfed without irrigation, the impacts on agricultural prices and production of climate-induced reductions in irrigation water supply are projected to be small relative to the impacts of changing growing conditions—temperature, precipitation, and atmospheric CO_2 concentration—on yields.

Our estimate of temperature-induced declines in yield may be conservative; the biophysical simulation model used—EPIC—projects yield losses that respond smoothly to increases in temperature and does not capture the potential for sharp losses in yield when threshold temperatures are exceeded. The literature suggests, however, that such critical thresholds exist for several major crops. Based on an econometric analysis of the relationship between temperatures and U.S. crop yields for corn, soybeans, and cotton, Schlenker and Roberts (2009) estimated potential acreage-weighted average yield declines of 30-82 percent due to higher temperatures before the end of the century. An improved understanding of crop response to temperature, and the interaction of that response with water stress and water productivity, is also necessary to refine crop modeling and impact forecasting. Lobell and Burke (2008) found that for most crops and regions, uncertainties related to regional temperature change and subsequent crop response outweighed uncertainty related to precipitation and precipitation response.

Technology can increase agricultural resilience to climate change by improving both plant water-use efficiency (yield per unit of water uptake) and the efficiency of applied irrigation. In the United States, seed companies have recently released several corn hybrids developed for tolerance to drought (Heisey and Rubenstein, 2015). This analysis suggests, however, that effectively building resilience to climate change over the long term may require a greater investment in understanding the relationship between the timing and magnitude of temperature change and crop yield, and development of crop varieties whose yields are more robust to temperature stress, particularly during critical growth and grain-filling periods. The relationship between drought tolerance and temperature sensitivity is also critical; a plant variety developed for drought tolerance may not retain its improved drought tolerance under higher temperatures (Heisey and Rubenstein, 2015).

Due to changes in yields and shifts in relative profitability across dryland and irrigated production systems, this analysis also projects increased reliance on dryland production under climate change. Measures that strengthen the resilience of dryland agriculture will therefore also be critical in building agriculture's adaptive capacity. Such mechanisms include development and diffusion of crop cultivars more tolerant of heat and water stress, as well as soil management practices that improve soil moisture retention (e.g., conservation tillage, crop residue management, or cover crops); development of forecasting and decisionmaking tools that allow farmers to more closely align the timing of cropping operations with improved temperature and precipitation predictions, and insurance programs and other financial strategies that mitigate production risk (Wallander et al., 2014). Also critical to farmer decisionmaking will be information about interactions among these strategies and practices; differences in performance between traditional crop varieties and drought-tolerant varieties, for instance, may be influenced by whether best management practices for soil moisture retention are in place. The USDA's seven regional Climate Hubs are designed to coordinate region-specific outreach and technical support to agricultural producers and natural resource managers.[16]

In comparison to the substantial initial yield and production impacts projected for some fieldcrop sectors under climate change, the impacts on production of both farmer flexibility and adaptation (as a mitigation tool) and limits on the availability of irrigation water (as a constraint) are marginal. There is some potential to manage the initial crop response to changing climate conditions through development of new crop genetic resources, but such development is time consuming, expensive, and technically difficult (Heisey and Rubenstein, 2015).

A complementary strategy would be to minimize the temperature and precipitation changes to which crops are likely to be exposed. While the momentum of CO_2 accumulation in the atmosphere means that a certain amount of warming is inevitable at this point, long-term CO_2 concentrations, and resulting temperature increases, can still be moderated as part of a comprehensive strategy for tackling the long-term impacts of climate change on agriculture and food production.

Analysis limitations

Findings from our analysis are circumscribed by the capacity of the modeling framework, data availability, and project scope. In exploring the biophysical implications of climate change for U.S. fieldcrop production, this analysis focuses on the yield-related impacts associated with

[16]The Climate Hubs were established in 2014 to develop and disseminate science-based information and technologies to agricultural producers and natural resource managers to facilitate adaptation and decisionmaking under climate change.

projected changes in regional average temperature, regional average precipitation, and increased carbon dioxide concentration in the atmosphere. Relative return, production, and price projections are all derived from, and highly sensitive to, the underlying yield and biophysical impact results generated by the EPIC crop modeling. Research efforts such as the Agricultural Modeling Intercomparison and Improvement Project (AgMIP) are exploring and documenting the large variability among crop models that exists in estimating the impacts of changing growing conditions on crop growth. Our findings bolster their calls for improved understanding of how temperature and the timing of extreme temperature events affects crop phenology and yield, validation of that research under realistic field conditions, and improved crop models to capture that dynamic (Long and Ort, 2010; Hatfield et al., 2011; Walthall et al., 2012). A fuller understanding of elevated atmospheric CO_2 effects on plant water-use efficiency and yield productivity—including the interactions between CO_2 and temperature, and the differential impacts across cropping systems—is also needed. Strengthening our confidence in crop-level agronomic impacts, and how they are represented within crop modeling systems, is critical for robust economic modeling of climate impacts and adaptation in agriculture.

There is increasing evidence that disproportionate impacts to agriculture under climate change will arise from changes in the incidence and timing of extreme temperature and precipitation events (Melillo et al., 2014). The downscaled GCM results underlying our climate change projections did not allow us to estimate changes in the variability of daily temperature and precipitation, changes in the incidence of extreme weather events such as drought or storm-induced flooding, or specific changes in the timing or duration of extreme temperature or precipitation events. Changes in weather variability may also be a significant driver of yield and yield variability (Isik and Devadoss, 2006; Walthall et al., 2012) and may be an important factor in the adoption of irrigated production systems and other field practices as risk management strategies (Negri et al., 2005). In more humid areas of the United States, increased weather variability—including greater frequency and severity of drought—may spur irrigation investment in response to greater yield risk, even when the relative profitability of dryland cropping systems increases. Improved capacity within the climate community to forecast changes in the timing and duration of extreme weather events will be critical to improved behavioral and economic analysis of potential impacts and adaptation behavior.

This analysis also focuses on adaptation and impacts within fieldcrop sectors. While cropland and water supply constraints are modified to account for acreage and irrigation-water use in high-value specialty crops, adaptation and impacts in the specialty crop sector are not explicitly considered. Similarly, the model does consider livestock-sector impacts through changes in feedgrain markets, but the direct impacts of climate change on the livestock sector through changes in management and maintenance costs or livestock morbidity, mortality, and productivity are not incorporated into the analysis.

Other scope limitations to the analysis arise from data and model limitations. The report explores potential future constraints on irrigation water, but does not consider other factors that influence the extent and distribution of U.S. irrigated production. Factors including increasing costs of surface-water and groundwater access, sunk irrigation costs, water demands for new and emerging uses, potential for water-supply enhancement, and institutional/technological changes in water resource management and efficiency are not considered. Future investments in reservoir storage or basin transfers may mitigate climate-induced reductions in some areas, or enhance irrigation potential in areas with projected increases in streamflow. Additionally, while the water availability estimates developed for the irrigation constraint capture information about the increasing scarcity of water resources, we do not attempt to assess direct climate effects on groundwater resources, such as changes in recharge rates, or potential policy responses to water scarcity involving water-demand management and supply-enhancement measures.

The potential impacts of climate change on the supply and costs of other agricultural inputs—including energy, fertilizer, and labor—would also affect relative returns to different types of production and could create additional region-specific constraints on the adaptive strategies available to farmers. Potentially important secondary effects of climate change on agricultural industries and rural economies are not examined, nor are exogenous changes to land markets, including pressures on agricultural land arising from conversions to developed uses, forestry, or bioenergy production over the coming century, which could influence the incentives and constraints that farmers confront in responding to climate change. Similarly, continued declines in western irrigated acreage, driven by increasing competition for water and higher water prices that would be expected to occur independent of climate change, may affect irrigated acreage shifts reported here.

Adaptation options available to producers extend beyond those that we were able to incorporate into 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 important farm-level adaptation strategies, such as changing harvesting and planting dates or altering applied nitrogen rates in response to yield changes. We adjusted model parameters to minimize the impacts of fixed planting and harvest dates on yield, but nevertheless, with those adjustments, the growing season remained fixed, precluding us from exploring options such as double-cropping as a potential response to longer growing seasons and accelerated crop maturity in some regions.

Limited information also kept us from considering changes in the incidence, damage, and management costs associated with pests and diseases that might be attributable to climate change, though prior research indicates that such factors are likely to be costly (Malcolm et al., 2012; Walthall et al., 2012). Other climate factors expected to change over time—such as ground-level ozone concentrations and solar radiation—may also have an important effect on agricultural production but were beyond the scope of our biophysical impact modeling.

Future research

Several followup research projects are already under development using ERS's existing modeling capacity. An analysis of the environmental impacts associated with changes in agricultural production and resource use under climate change, not addressed in the current report, is underway. ERS researchers are also developing additional climate change scenarios to reflect the development and diffusion of drought-tolerant crops; that analysis will explore the potential for such cultivars to expand adaptation options for U.S. farmers.

The structure and scope of REAP are also being expanded to accommodate potential adaptation strategies (beyond land allocation) related to crop production patterns and practices. Expanded adaptation options within REAP/EPIC will include adjustments in harvest and planting dates to accommodate changes in growing-season length, as well as double-cropping or integrating cover crops in order to reduce environmental impacts and to improve soil moisture and health. REAP is also being expanded to include specialty crops, which account for roughly 15 percent of irrigation demand and are particularly vulnerable to reduced irrigation availability, especially in the Pacific and Southeast regions. Further REAP improvements will allow investigation of climate change impacts on animal productivity and forage/feed production systems.

This analysis explores the impacts on the agricultural sector of changes in average monthly precipitation and temperature by region. Recent evidence suggests, however, that climate change will also bring increased frequency of extreme precipitation and temperature events, including drought and heat spells (Melillo et al., 2014). Crop production is particularly vulnerable to the magnitude and timing of such extreme events. The variability of natural precipitation is also an important driver of irrigation adoption (Negri et al., 2005), as irrigation may be used increasingly to mitigate periodic drought in both arid and temperate growing regions. To accommodate a consideration of these critical factors, REAP is being modified to explore not only the impacts of average changes in climate indicators, but the impacts associated with the annual variability around those averages, including the potential effects of extreme weather events.

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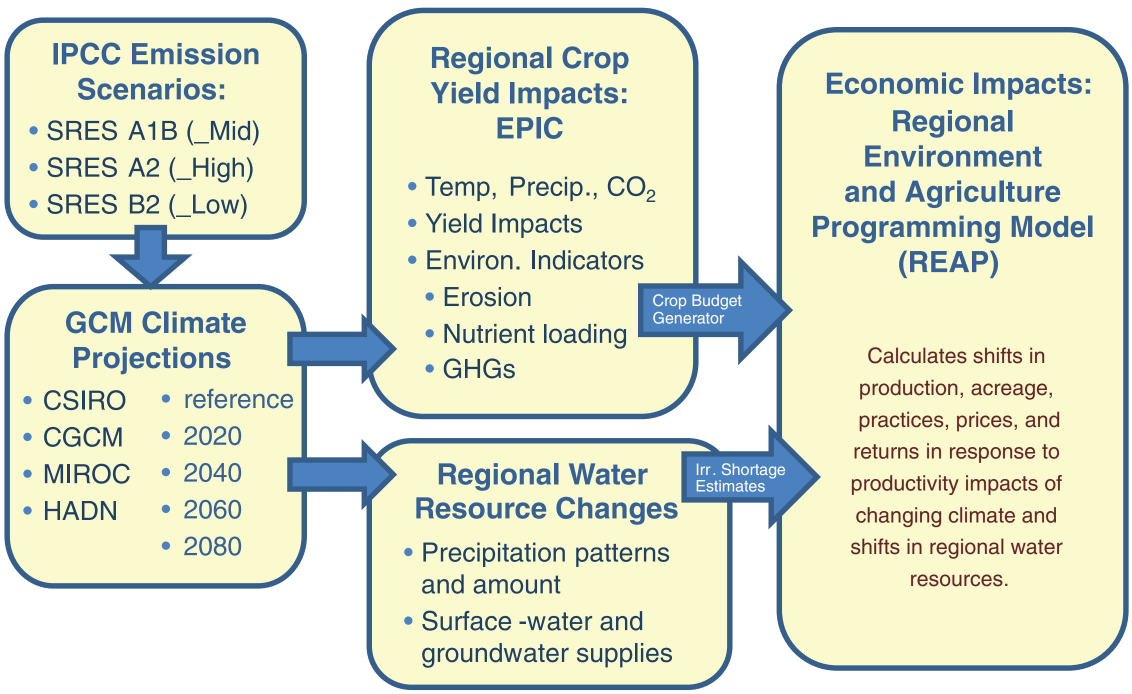
Appendix A: Detailed Research Methodology

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 (appendix figure 1). Downscaled climate data for the period 2000-2090 under several potential projections of climate change are used to estimate the regional biophysical impacts of changing climate conditions on yields, crop irrigation requirements, and indicators of the environmental impact of agricultural fieldcrop production. 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 results for regional and national estimates of production, prices, farm returns, and other measures of producer and consumer welfare.

Appendix figure 1

Analytic framework for examining interactions between climate change, water resources, and agricultural adaptation



Note: IPCC = Intergovernmental Panel on Climate Change, GCM = General Circulation Model, EPIC = Environmental Policy Integrated Climate Model, and GHG = Greenhouse Gases. See Appendix A for explanation of climate models.
Source: USDA, Economic Research Service.

Downscaled climate data, and the potential regional surface-water shortages associated with each scenario, were developed for the USDA Forest Service's Resources Planning Act (RPA) assessment of renewable natural resources (USDA Forest Service, 2012). Nine future climate projections were explored, which include three different General Circulation Models (GCMs) applied to each of three of the emissions scenarios in the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES)—the A1B, the A2, and the B2.[1] The three emissions scenarios considered each represent a distinct story line about potential future development and resulting carbon emissions. The SRES A1B emissions scenario is considered a "middle of the road" projection and is characterized by rapid economic growth, the introduction of energy-efficient technologies, and a balanced portfolio of energy sources (IPCC, 2007). The SRES A2 emissions scenario is a higher-emissions scenario characterized by rapid population growth and more fragmented, slower regional growth. The SRES 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 GCMs for a single emissions scenario, each emissions scenario was run through three separate GCMs to derive a range of possible climate sensitivities 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). See Joyce et al. (2014) for a discussion of why these models were selected for the RPA Assessment and more details on development of the downscaled climate projections.

Water demand and renewable water supply under 9 climate projections were estimated by Foti et al. (2012) for 98 water basins, or assessment subregions (ASRs), in the contiguous 48 States. ASRs coincide with either 4-digit hydrologic units or aggregations of those units (appendix figure 2). 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 et al., 2012). While our study focuses on climate-induced changes in surface-water supplies developed from USDA Forest Service estimates of renewable water-supply shortages, our estimates of irrigation availability under future climate projections also include rough groundwater supply projections, which are derived from U.S. Geological Survey data series and supporting literature and are assumed to be fixed across climate futures.

[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.

Appendix figure 2
Assessment subregions (Foti et al., 2012)

Source: USDA, Economic Research Service.

Our analysis considers climate impact and adaptation analyses for four future timeframes. Climate conditions for the 2020 timeframe are calculated as average conditions across projected years 2011-2030, those for 2040 are averaged across 2031-2050, those for 2060 are averaged across 2051-2060, and those for 2080 are averaged across 2071-2090. “Reference” climate conditions are defined by an average over 2001-2008 conditions for the CGCM_High estimation scenario.[2] See Foti et al. (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 projection and year of analysis. See Appendix B for detailed information on characteristics of the climate change projections used in this analysis.

Biophysical simulation modeling

Crop production for a given production region, soil type, and set of field operations is simulated using the EPIC (Environmental Policy Integrated Climate) biophysical simulation model. EPIC is a field-scale simulation 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.

[2] Because there are very small differences across estimation scenarios for the 2001-2008 timeframe, “reference” climate conditions were anchored to a single estimation scenario (CGCM_High). 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_High “reference” values to generate the projections associated with each of the other climate change projections.

EPIC is used to identify the change in crop yields and plant water use (including crop evapotranspiration and applied irrigation water) associated with each of the climate projections across the model regions. Appendix C provides detailed information on the crop modelling methodology and assumptions used in this analysis, including a breakdown of how crop yields respond to variation in the three major climate elements varied under the climate projections—temperature, precipitation, and carbon dioxide concentration.

For the simulation of crop production, our regional analysis divides crop production in the United States into 267 regions (Regional Environment and Agriculture Programming, or"REAP regions"), as defined by an overlay of the ASRs (defined by watershed boundaries), land resource regions, and farm production regions. While our system simulates crop production and optimizes acreage allocation at the level of the REAP region, most results are aggregated and presented at the farm production region (FPR) scale.

Changes in climate conditions and regional yields are likely to induce a cascading set of impacts on the agricultural sector—affecting production practices and rotations, input use and irrigation, production patterns and returns, commodity prices, export availability and trade, and, ultimately, producer and consumer welfare. In this project, we explore the potential dynamics of such impacts using the REAP model.

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 within the United States. REAP allocates production acreage among a discrete set of crop rotations available to each region (see Appendix D for a list of crop rotations by region), and allocates the resulting agricultural products among a set of markets, including feed use, other domestic use, various processing sectors, and exports, in order to maximize the sum of producer and consumer surplus resulting from that allocation. 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 to USDA's Farm Production Regions (FPRs) for this study (see figure 3 for REAP region and FPR boundaries).

Each REAP model region includes a set of production activities comprising crop rotation; no-till, reduced till, or conventional tillage; and 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 acreage distribution parameters that capture historically observed patterns of production.[3]

[3]For more information on the REAP modeling framework, see the technical documentation for the model at http://www.ers.usda.gov/publications/tb-technical-bulletin/tb1916.aspx.

To form a reference against which climate change impacts are measured in future time periods, we designed a set of agricultural production conditions in future time periods that reflect a world in which patterns of production continue to change in response to historically observed dynamics (involving changing population, diet, demographics, and other socioeconomic factors), but without climate change (i.e., assuming “reference scenario” conditions). Conditions for that reference scenario are developed for the analysis years 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 more information on the methodology and the specific assumptions embedded in the reference scenario, see Appendix F.) Such future reference scenarios are sensitive to many assumptions about uncertain future dynamics and behavior; analytical results relating to climate change impacts should therefore be interpreted not as predictions of absolute impact under any given scenario but as informative about the relative direction and magnitude of impact, both over time and across alternative climate futures.

For each analysis year, REAP’s acreage distribution parameters, and the crop yield 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 reflects changes in crop technology that are projected to occur in the intervening years and corrects for any yield biases that may have existed in the original EPIC outputs. Calibration of REAP’s reference acreage, production, and environmental impact assumptions incorporates information on irrigated cropping rotations from the NRI as well as supporting data on irrigated/dryland crop acreage (NASS/AgCensus), irrigation application rates (Farm and Ranch Irrigation Survey (FRIS), EPIC), irrigated costs (Agricultural Resource Management Survey, 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, crop-water requirements, and cost estimates for production enterprises that were derived using the climate change projections. The REAP modeling framework reallocates production acreage under each of the climate scenarios to optimize the sum of producer and consumer surplus given the changes in regional yield and crop water use. Farmers’ allocation decisions depend on changes in yields, irrigation costs (through changes in water use), and commodity price, which are also endogenous within REAP. As prices vary, consumer and producer surplus are also endogenous and are explored separately across the climate change scenarios.

While yield and water use are fixed by production activity for any given climate scenario, endogenous changes in aggregate production, production acreage, and irrigation demand emerge as a result of reallocation of cropland acreage across production activities. In addition to the drivers of land use re-allocation listed above, acreage reallocation under climate change may also be constrained by the regional availability of resources such as productive land and water. This analysis therefore incorporates constraints on total regional acreage in fieldcrop production; available cropland by region was estimated by aggregating working and idle cropland categories within the 2007 Census of Agriculture. Derivation of estimates for the regional availability of irrigation water under climate change is described below.

Analysis of irrigation water use and availability

Applied irrigation water is estimated in the EPIC crop-growth simulation model for each irrigated production activity under the reference climate conditions and separately across analysis years 2020, 2040, 2060, and 2080 for each climate change projection. Differences in irrigation requirements across production activities within the reference scenario capture variation in crop evapotranspiration (ET) requirements across crop rotation/tillage/soil-erodibility combinations as well as differences in regional precipitation. In estimating irrigation demand for crops, our parameterization of EPIC allows a small amount of plant water stress; when crop water stress exceeds the permitted threshold, however, an irrigation application is triggered. EPIC also assumes a fixed irrigation water-use efficiency (percentage of applied water that is consumed by the crop) of 75 percent.

Relative to the reference estimates for a given production activity, differences in applied water under modeled climate projections reflect the effect of changes in regional precipitation as well as differences in crop ET under changed growing conditions. Endogenous changes in regional irrigation demand arise as a result of the optimal reallocation of acreage among production enterprises under a climate projection, which can result in changes in both the extent and intensity of irrigation within a region.

The changing availability of water resources under climate change is captured by estimating reductions in irrigation water availability for each REAP region, analysis year, and climate projection that may arise due to changes in precipitation and temperature as well as changes in demand from agriculture and other water-consuming sectors. Reference levels of aggregate irrigation water use by REAP region are first estimated for each analysis year (2020-2080) based on reference crop model acreage allocations and EPIC-generated estimates of applied irrigation water per crop-rotation acre under the reference climate conditions. Relative to that reference case, projected reductions in irrigation water availability under each climate change projection are calculated as a percent reduction in available irrigation water by REAP region and year. Our analysis of irrigation availability is primarily focused on surface-water supplies (derived from USDA Forest Service renewable water-shortage estimates), which are most directly affected by climate-induced changes in precipitation and potential ET. However, because groundwater is an important water source in major irrigated areas of the United States, adjustments were made to water-supply assumptions to reflect the share of surface and groundwater currently used (USGS, 2005) as well as potential reductions in withdrawals by water source over time.

Declines in Groundwater Withdrawals Are Estimated Regionally

Changing climate conditions may affect groundwater supplies through changes in both aquifer recharge and groundwater withdrawals. While aquifer dynamics under climate change have received increasing research attention, we do not project changes in groundwater recharge under alternative climate futures for this analysis. Groundwater recharge is highly site specific, based on local soils and hydrologic systems, and the science of climate effects on groundwater is generally less well understood (Taylor et al., 2013). 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 (i.e., conjunctive hydrologic systems and water-source substitution), and institutional restrictions on groundwater management.

For purposes of this analysis, fixed declines in irrigation-groundwater withdrawals over time were projected for selected REAP regions. While rates of future decline in groundwater withdrawals are highly uncertain, projected reductions in groundwater withdrawals provide useful context for assessing the relative magnitude of climate-induced surface-water supply reductions derived from the RPA analysis. Sensitivity analysis performed by running model simulations with and without groundwater-decline assumptions confirm that our use of groundwater-withdrawal projections has a minimal effect on reported impacts attributed to climate change.

To identify model regions subject to declining groundwater withdrawals, we overlaid Moderate Resolution Imaging Spectroradiometer spatial irrigation data (MODIS, 2001) with USGS aquifer delineations and REAP region boundaries. This overlay provided a spatial representation of groundwater resources used for irrigation and allowed for area-weighting of irrigated acreage and groundwater use by REAP model region.

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 1990, 1995, 2000, and 2005 (USGS, 2013) and used to identify multi-county areas where irrigation groundwater withdrawals have declined over the 1990-2005 period. Withdrawal trends were then compared with 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 informed, where available, from estimates in the published literature (Steward et al., 2013; Scanlon et al., 2012; UCCHM, 2014).

For purposes of the study, we assume that declines in groundwater withdrawals are driven by declining water tables and resulting increases in pumping costs due to rising pumplifts and reductions in well yields. For selected irrigated regions experiencing both reduced irrigation-groundwater withdrawals and declining water tables over much of their land area, groundwater withdrawals for irrigation were assumed to decline in a roughly linear fashion over the coming decades.[4] 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 by up to 50 percent in 2080. Withdrawal reductions of up to 20-30 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.

Surface-Water Supply Reductions Vary by Region and Climate Scenario

Surface-water supply reductions for irrigated agriculture are derived from RPA water-supply shortage projections, based on basin-level renewable water yield and water demand estimates developed for the 2010 RPA Water Assessment (Brown et al., 2013). For each of the ASRs, regional water yield was projected annually through 2090 using downscaled estimates of temperature and precipitation by climate projection. Surface-water flows were simulated in a water-routing model of U.S. river systems that accounts for interannual reservoir storage and interbasin transfers. Water demand, a measure of projected water use (in the absence of annual water supply shortages), was estimated for

[4]In reality, groundwater withdrawals tend to increase in drought years, as high-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.

multiple use categories—public supply, domestic, industrial, mining, thermoelectric, livestock, aquaculture, and irrigation—to reflect both climate change and other exogenous demand drivers. The RPA estimates for irrigated agriculture draw on historical records of sector-level water withdrawals and consumptive use (based on USGS's 5-year schedule for water assessment reporting), as well as projections of water use drivers including irrigated area and applied water per acre (Foti et al., 2012). Potential regional water shortages are then calculated as the difference between projected water demand and renewable water supply by ASR, after instream flow requirements are met.

Irrigation water-use efficiency is an important factor affecting future water demand in the irrigated fieldcrop sector.[5] Irrigation system efficiencies have increased over recent decades in response to growing water scarcity, rising water prices, higher costs of labor and energy, and availability of improved technologies and management practices (CAST, 1996). However, the effect of higher irrigation efficiencies on aggregate irrigation demand is uncertain and likely to vary spatially. While improved efficiencies reduce water conveyance and application losses at the field level, higher crop-water consumptive use (through increased yields and expanded irrigated acreage) may increase irrigation water use at the basin level in the absence of institutional restrictions on expanded withdrawals (Pfeiffer and Lin, 2010; Huffaker and Whittlesey, 2003; Schaible and Aillery, 2012). In some areas, changes in regional cropping mix have also reduced applied water over time where water-intensive crops account for a declining share of irrigated cropland (Gollehon and Quinby, 2006). The RPA water-shortage projections reflect continued reductions in average withdrawals per irrigated acre based on observed trends from 1985 to 2005. More significant declines are projected for the Western States, with withdrawal rates falling from 2.7 acre-feet in 2005 to 2.4 acre-feet in 2060; withdrawals in the East are projected to decline from 1.35 acre-feet in 2005 to 1.30 acre-feet in 2060 (Foti et al., 2012). Regional assumptions in per-acre water demand from the RPA analysis, reflecting both trends in irrigation efficiency and cropping reallocations, are captured in the water-supply reduction estimates used to define water-supply constraints in the REAP model analysis.

The USDA Forest Service water-shortage projections in the RPA analysis further assume ongoing trends in the regional redistribution of irrigated area that are expected to occur irrespective of climate change. Irrigated acreage has declined in areas of the arid West in response to increasing competition for land and water and higher water prices, while irrigation is increasingly used in the Eastern States to supplement available moisture, particularly in drought years. In developing surface-water supply constraints for the REAP analysis, RPA water-shortage projections for the Western United States were adjusted to net out assumed reductions in agricultural demand due to projected declines in regional irrigated area. The effect is to tighten water-supply constraints in the REAP optimization analysis, which can be met in the model through changes in applied water at both the extensive margin (cropland under irrigation) and intensive margin (applied water per acre).

Reductions in irrigation surface-water supplies by REAP model region were based on a 20-year average of reported RPA annual (percent) shortages of renewable water supplies by ASR for 2020, 2040, 2060, and 2080 (Foti et al., 2012). (REAP regions generally follow ASR watershed boundaries.) In applying RPA water-shortage projections to irrigation surface-water supply reductions in the REAP model (after adjustments for Western irrigated acreage decline in the RPA analysis), we implicitly assume that the full water-supply shortfall by ASR is borne by the irrigated fieldcrop

[5]Irrigation water-use efficiency includes both water conveyance and field application efficiency. Water conveyance efficiency represents applied water at the field level as a share of total water withdrawal. Field application efficiency reflects the share of applied water that meets crop consumptive requirements and other beneficial uses.

sector. We believe this to be a reasonable working assumption as irrigated agriculture is generally the primary water use in areas facing significant water shortages, while the marginal value of water in irrigation is typically lower than for nonagricultural withdrawals. As irrigated agriculture accounts for the largest share of consumptive use in most river basins where water supplies are fully appropriated, nonagricultural demands during water-supply shortfalls will generally be met through reallocation of irrigation supplies.

Reductions in surface-water supplies are further adjusted in the REAP model analysis to reflect acreage in non-modeled crops. We assume that higher valued specialty crops—including vegetables, orchard, and berry crops not currently included in the REAP model—are unaffected by climate-induced reductions in surface-water supplies. Specialty crops account for approximately 12 percent of irrigated acreage nationally, with significantly higher acreage shares in various regions of the country. While our water allocation assumption is simplistic, prior assessments suggest that high-valued specialty-crop production is likely to account for a growing share of production where changing climate regimes contribute to increasing water scarcity (Howitt et al., 2010). We further assume that non-modeled field crops (e.g., dry beans, potatoes, sugar beets, peanuts, grass seed, etc.) and uncultivated pasture share regional water-supply shortfalls with modeled field crops. Thus, water-supply constraints in the REAP analysis reflect net adjustments in reported RPA supply reductions based on irrigated acreage shares in specialty crops and other non-modeled crops.

Under climate futures examined in the 2010 RPA Assessment, a changing climate is projected to have significant impacts on water supplies for irrigated production. Figure 4 shows surface-water supply reductions by REAP region for the CGCM_High climate projections, 2020 through 2080, derived from projected shortages in renewable supplies in the RPA analysis. (See Appendix G for maps of surface-water supply reductions under the remaining eight climate projections.) Surface-water supply reductions (relative to current agricultural surface-water use) 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 considerable consistency in the regional concentration of projected impacts. 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.

The study analysis is primarily focused on potential restrictions in surface-water use under changing climate regimes, consistent with the 2010 RPA Water Assessment. We do not explore the possibility of additional water-supply development that may limit irrigation supply shortfalls or enhance opportunities for irrigation expansion in some regions. Nor do we consider the capital costs of increased irrigation infrastructure. Expansion of irrigation in areas that are not projected to experience irrigation water-supply constraints is limited to an increase of 10 percent over reference-case irrigation volumes to avoid unreasonable levels of costless irrigation expansion. While the volume of available irrigation water supply is limited by REAP region, our model does allow for adjustments in regional irrigated acreage due to changes in relative returns under irrigated and dryland production, possible reallocation of applied irrigation water across crops, and/or changes in per-acre irrigated demand due to changing climate and growing conditions.

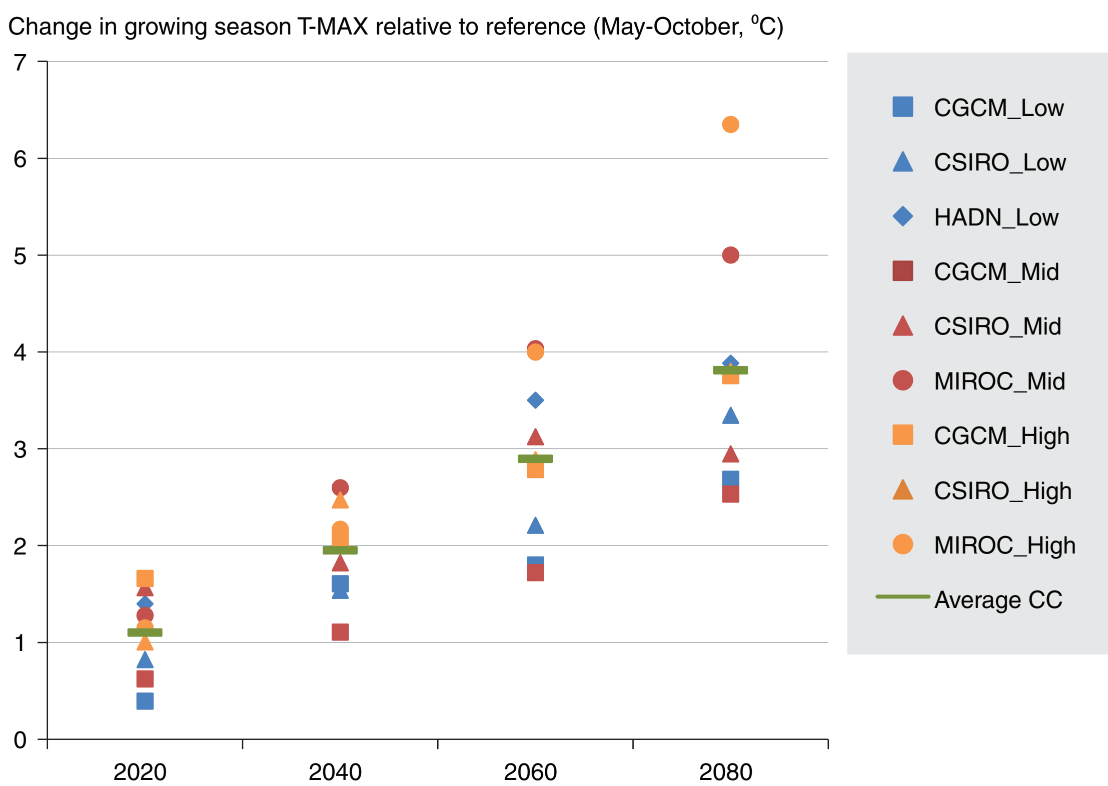
Changing climate conditions may affect the purchase price of surface water through shifts in market-supply conditions and capital expenditures associated with water-supply development. Climate change may also affect groundwater supplies through modified rates of aquifer recharge, as well as changes in groundwater demand with climate-induced adjustments in surface-water availability, with implications for groundwater costs. The costs of surface and groundwater access and institutional restrictions on groundwater and surface-water allocations will influence how irrigation water supply and shortages play out in real time. Unfortunately, such detailed hydrologic and institutional projections are beyond the scope of this analysis. Given the complexity of projecting surface-water pricing and aquifer drawdown, we do not estimate changes in cost per unit of water over time or climate scenario. We do not, therefore, account for the marginal impacts of irrigation water shortages on water price and, through that pathway, production costs and profitability under climate change. While the amount of applied water per acre varies, as does the resulting per-acre cost of irrigation, the cost per unit of water is assumed to be constant. Thus, reductions in water-supply availability create a physical constraint to adaptation, but there is no additional economic dynamic arising through increased marginal cost of water.

Appendix B: Characterizing Climate Change Projections

Climate characteristics for each of the crop analysis regions are derived from the underlying climate projections by averaging over the original climate data points and weighting points within the average based on the amount of cropland acreage they represent. The acreage-weighting procedure reduces the effect of microclimatic conditions in nonagricultural areas (e.g., urban heat islands, mountainous regions) that may bias estimates of ambient climate in agricultural areas. The downscaled General Circulation Model (GCM) monthly averages for minimum daily temperature (TMIN), maximum daily temperature (TMAX), and precipitation (PRCP) are first averaged across 10 years on both sides of the analysis date (i.e., 2011-2030 for analysis year 2020) and then reaggregated up to the scale of Regional Environment and Agriculture Programming (REAP) regions based on the cropland-weighted-average of climate conditions. A random weather generator within the Environmental Policy Integrated Climate (EPIC) model uses the average monthly climate information to generate daily weather patterns (temperature and precipitation) for each simulated year by crop production region.

The models and the Special Report on Emissions Scenarios (SRES) diverge in their projections of precipitation patterns and temperature change over the analysis period 2020-2080. While there is also considerable variability across regions and climate change projections, average metrics can provide some indication of differences in the magnitude and severity of climate change under the different climate projections. Changes in national cropland-weighted averages of growing season (May-October) maximum temperature are shown in appendix figure 3.

Appendix figure 3
Change in national cropland-weighted average for growing-season (May-October) maximum temperature, relative to the reference climate, under each climate projection



Note: Legend displays climate change models. See Appendix A for explanation of climate models.
Source: USDA, Economic Research Service.

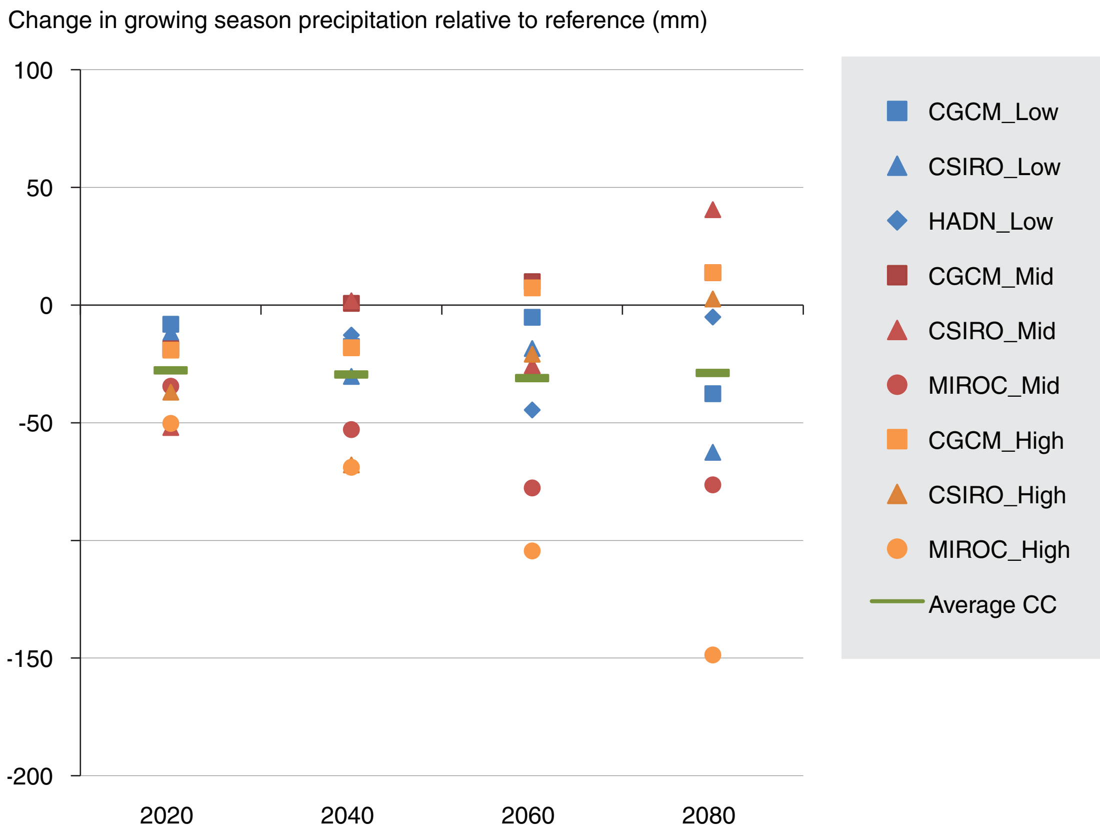
As the model projections diverge in late-century, the MIROC model projects the warmest future for U.S. cropland—more than a 6°C increase under the A2 (High) emission scenario. The CGCM model projects the coolest average May-October maximum temperature. There is considerable overlap among the emissions scenarios; both model and emissions scenario are important in determining relative warming. Generally, however, the B2 (Low) projections fall toward the cooler end of the temperature spread.

While temperature increases are fairly consistent across climate projections, projections of precipitation vary in magnitude and direction of change in annual and seasonal precipitation, as well as in the spatial distribution of precipitation across regions. National cropland-weighted averages of growing-season (May-October) precipitation are shown in appendix figure 4.

Appendix figure 4 illustrates how climate model projections for precipitation change increasingly diverge through 2080, though when averaged across climate models, national precipitation change appears to remain stable over time. Considerable overlap among precipitation projections associated with different emissions scenarios (_Low, _Mid, and _High) exists; the high emissions scenario (_High or A2) produces one of the lowest precipitation measures when run through the MIROC model, but one of the highest when run through the CGCM model. The middle emissions scenario (_Mid or A1B) scenario has a similar spread in projected growing-season precipitation. A few observations about growing-season precipitation projections emerge, however:

Appendix figure 4

National cropland-weighted average of growing season (May-October) precipitation relative to the reference climate under each climate projection



Note: Legend displays climate change models. See Appendix A for explanation of climate models.
Source: USDA, Economic Research Service.

- All scenarios are, on average, drier than (or roughly equivalent to) the reference scenario for the analysis years 2020 and 2040.

- Variation and uncertainty increase over the analysis horizon.

- Climate change projections are generally drier over the analysis horizon, with the exception of the CGCM_Mid scenario and the CGCM_High scenarios, which on average suggest wetter conditions toward the latter part of the century.

- The MIROC model results are among the driest scenario results for all time periods.

- The CSIRO_Mid scenario exhibits a surge in average precipitation for the analysis year 2080; in general, the CSIRO_Mid scenario exhibits wide swings from one analysis year to the next.

- All _Mid (B2) climate change projections are, on average, drier than the reference climate for all analysis years.

- Several climate change projections exhibit nonmonotonic precipitation change over time, with declines in average precipitation followed by increases in subsequent time periods or vice versa.

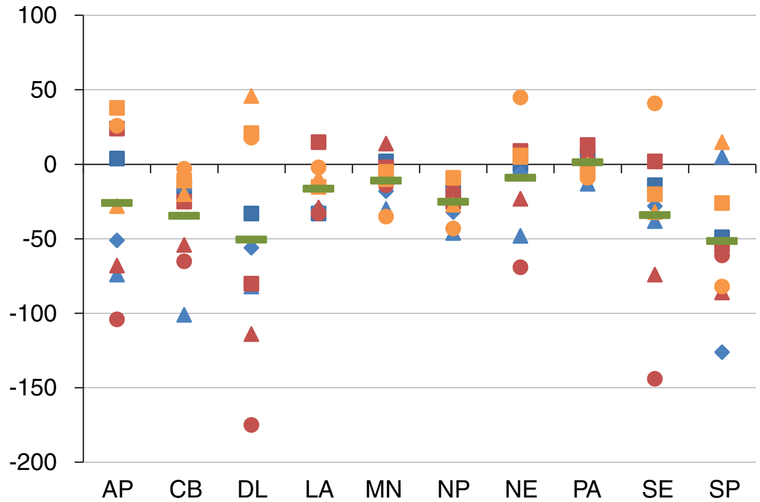
National averages mask large variation across regions. Changes in acreage-weighted growing-season precipitation levels at the FPR level are shown in Appendix Figure 5 for each of the analysis periods.

Appendix figure 5

Cropland acreage-weighted growing-season precipitation at the farm production region level for each climate change projection in each analysis year

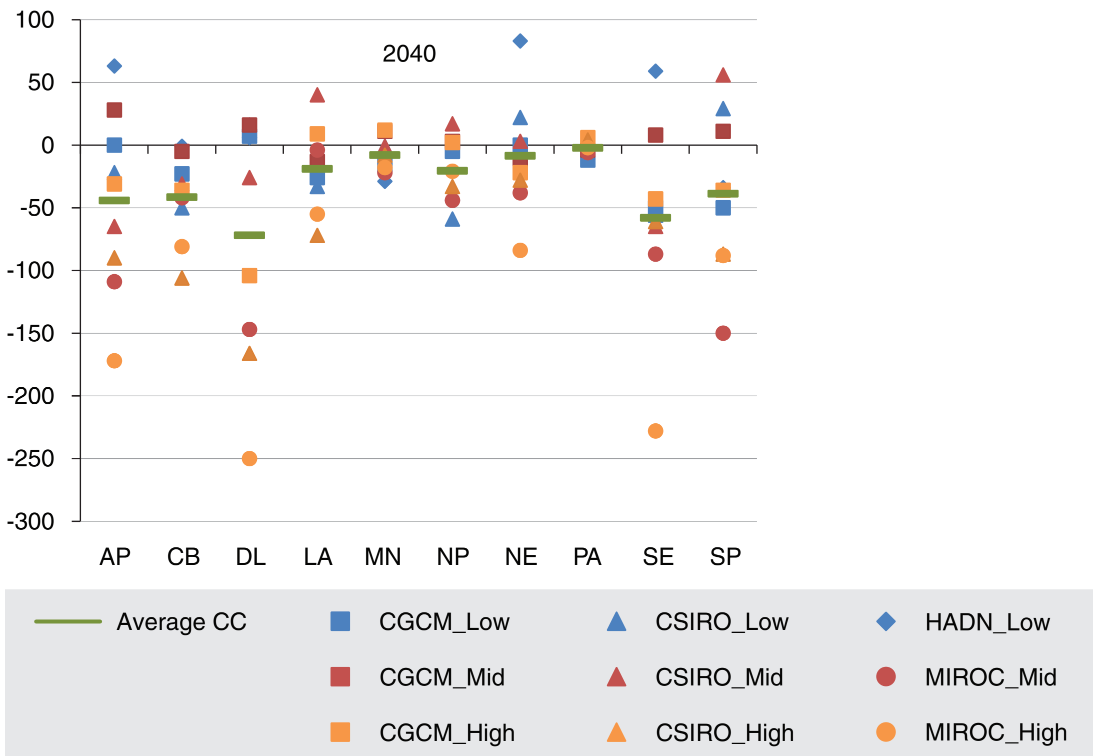
2020

Change in growing season precipitation relative to reference (May-October, mm)



2040

Change in growing season precipitation relative to reference (May-October, mm)



Note: AP = Appalachia, CB = Corn Belt, DL = Delta States, LA = Lake States, MN = Mountain States, NE = Northeast, NP = Northern Plains, PA = Pacific, SE = Southeast, and SP = Southern Plains.
See Appendix A for explanation of climate models.
Source: USDA, Economic Research Service.

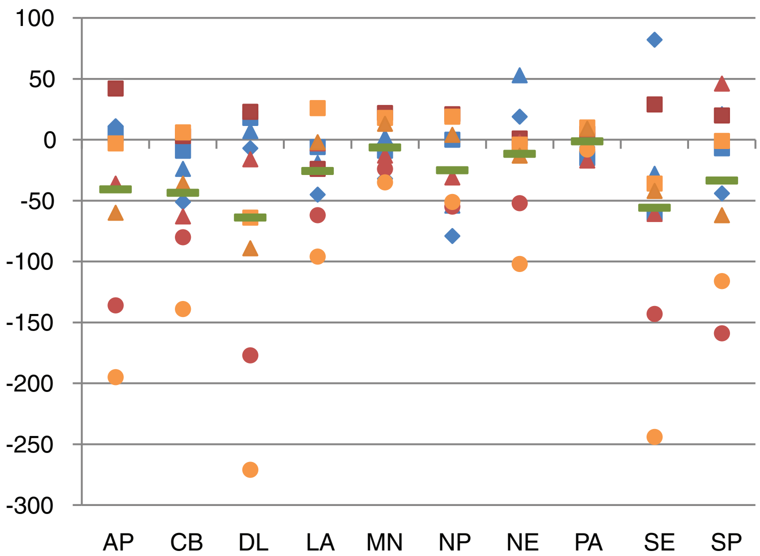
continued—

Appendix figure 5 (continued)

Cropland acreage-weighted growing-season precipitation at the farm production region level for each climate change projection in each analysis year

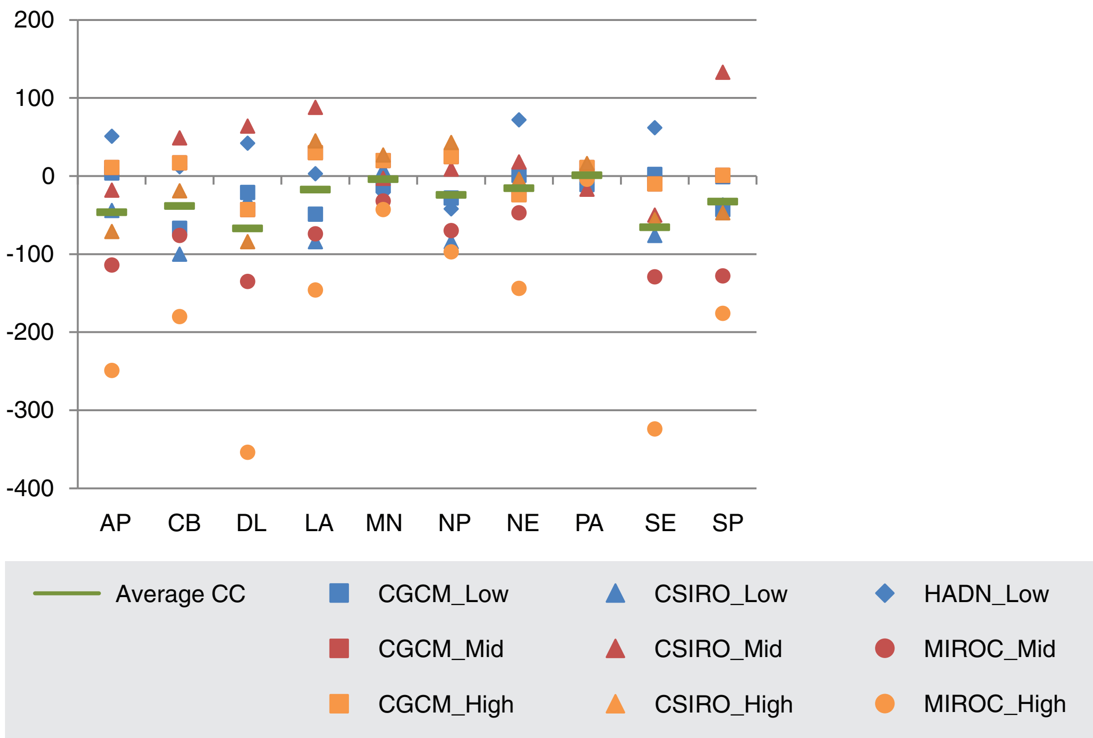
2060

Change in growing season precipitation relative to reference (May-October, mm)



2080

Change in growing season precipitation relative to reference (May-October, mm)



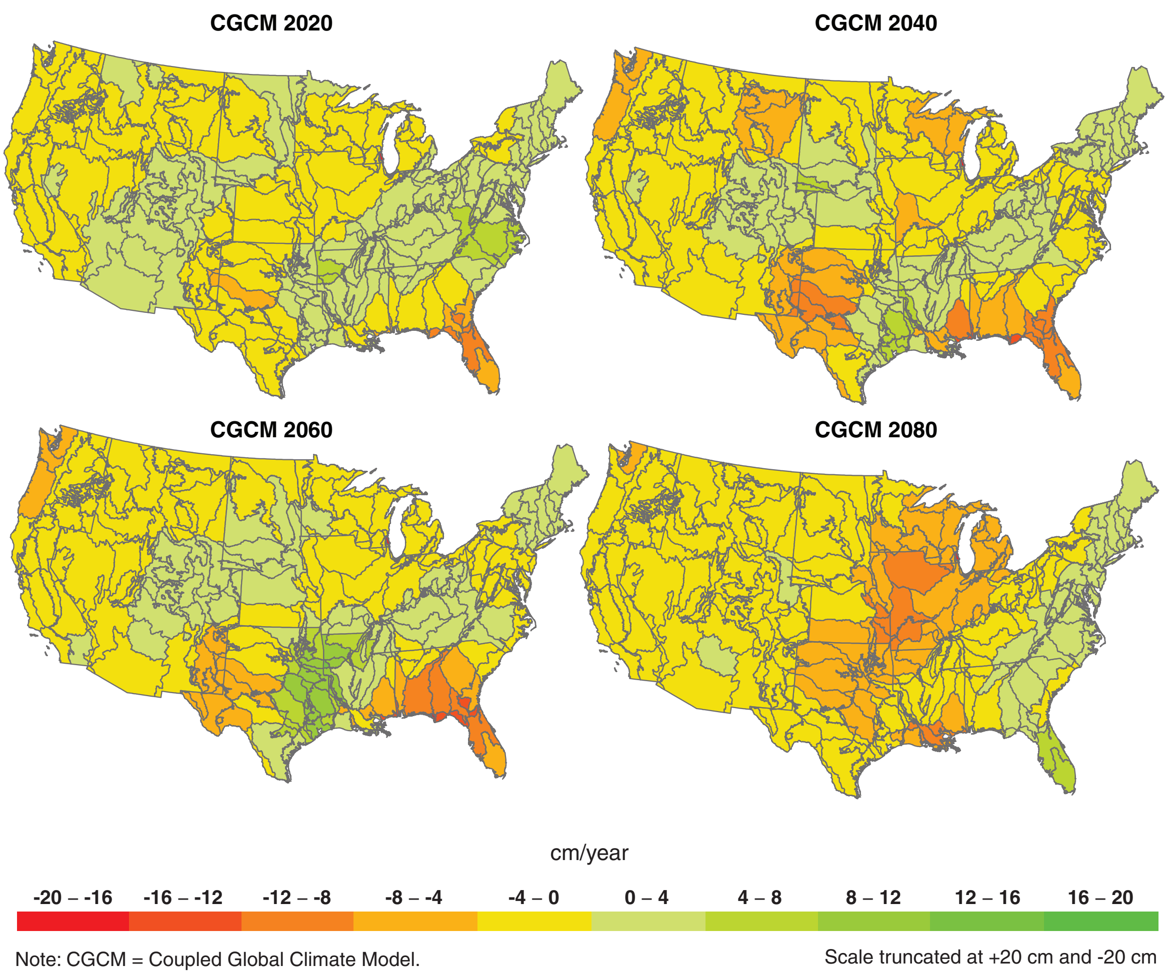
Note: AP = Appalachia, CB = Corn Belt, DL = Delta States, LA = Lake States, MN = Mountain States, NE = Northeast, NP = Northern Plains, PA = Pacific, SE = Southeast, and SP = Southern Plains.
See Appendix A for explanation of climate models.
Source: USDA, Economic Research Service.

Precipitation impacts vary widely across climate projections and across analysis years for most regions; precipitation projections are, however, less variable in the arid Pacific and Mountain regions, due in part to lower levels of growing-season rainfall. While CGCM and CSIRO generally predict more moderate impacts than MIROC, their predictions vary as to which regions will experience precipitation increases and which will suffer precipitation losses. The MIROC climate model generally produces the most extreme (hot and dry) climate projections within an emissions scenario.

Changes in estimates of May-October precipitation (relative to the reference level) at the scale of the REAP crop production region are shown in map form for each of the analysis time periods in appendix figure 6 to appendix figure 14.

Appendix figure 6

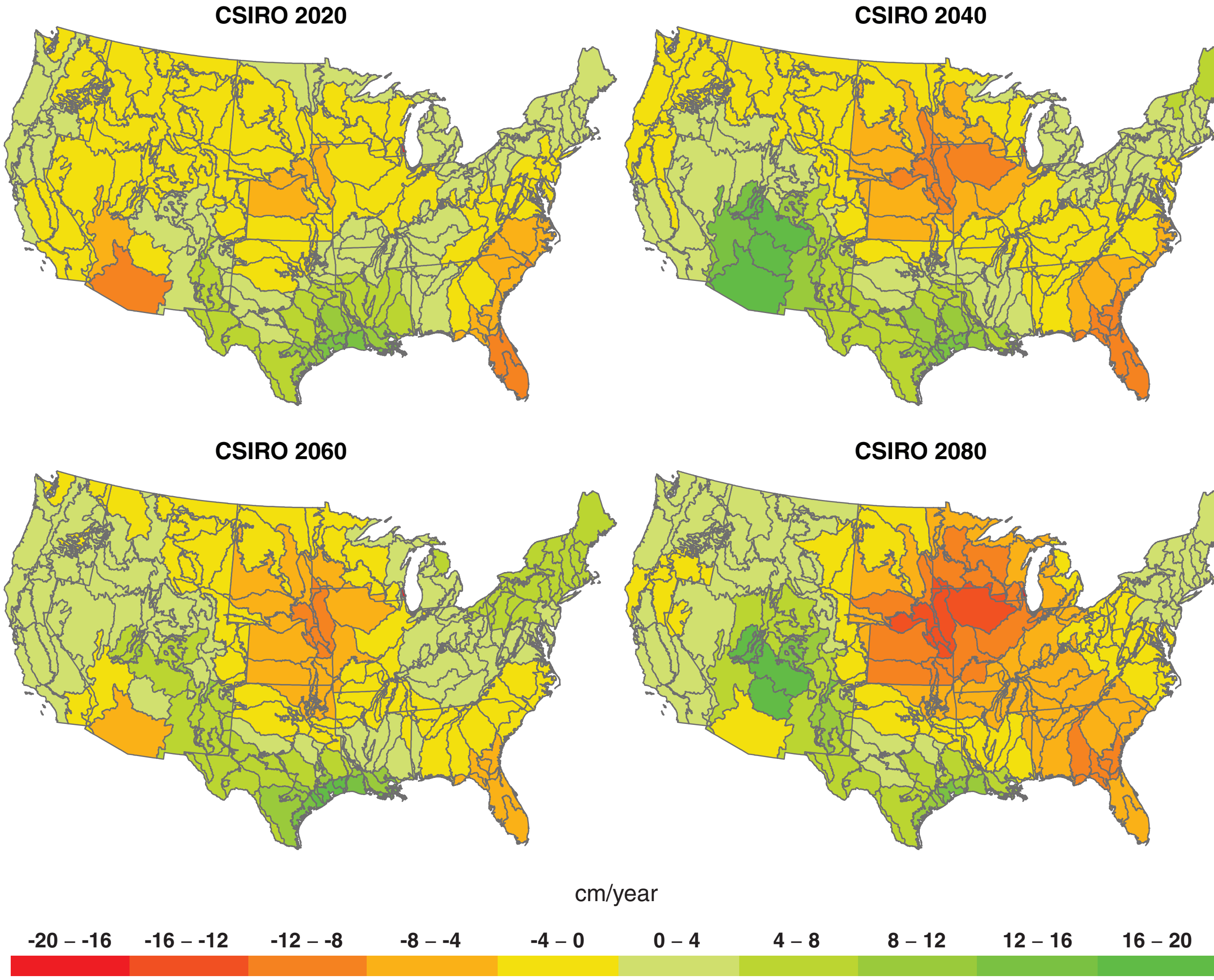
Change from reference in mean growing-season precipitation (May-October) for the CGCM_Low projection



Note: CGCM = Coupled Global Climate Model.
Source: USDA, Economic Research Service.

Appendix figure 7

Change from reference in mean growing-season precipitation (May-October) for the CSIRO_Low projection

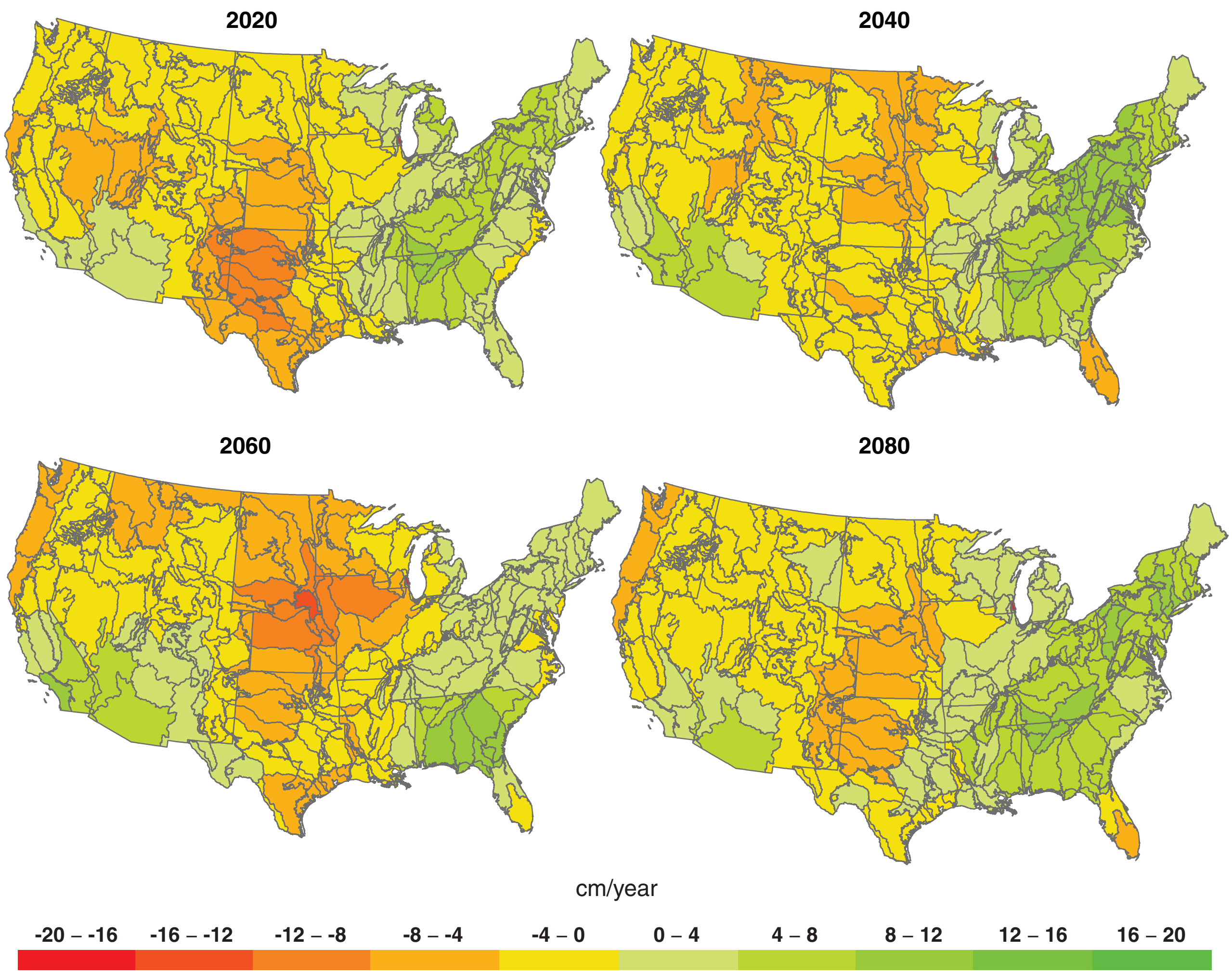


Note: CSIRO = Australian Commonwealth Scientific and Industrial Research Organization Mark 3.5 Climate System Model.
Source: USDA, Economic Research Service.

Scale truncated at +20 cm and -20 cm

Appendix figure 8

Change from reference in mean growing-season precipitation (May-October) (cm/year) for the HADN_Low projection



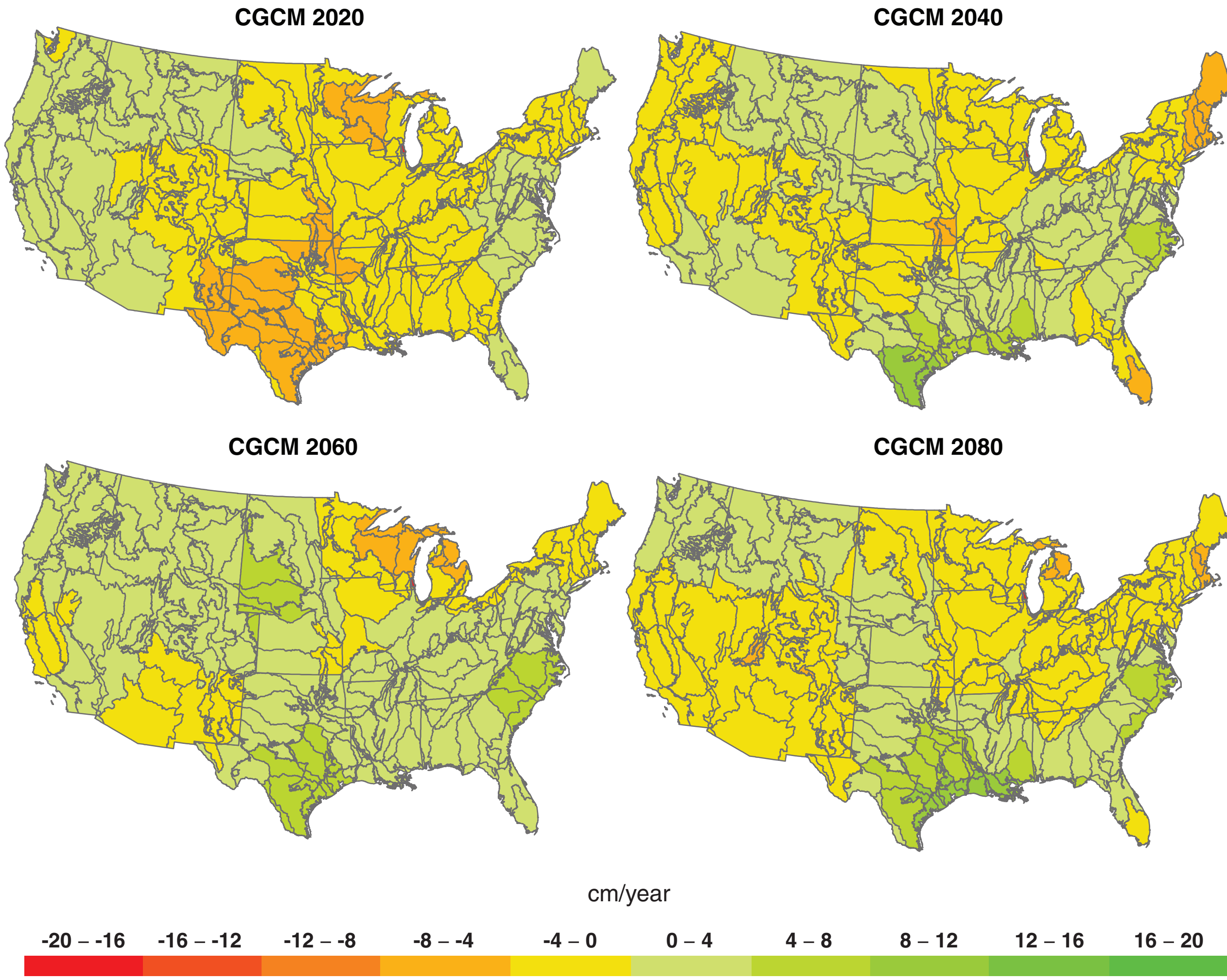
Note: HADN = United Kingdom Met Office Hadley climate model

Scale truncated at +20 cm and -20 cm

Source: USDA, Economic Research Service.

Appendix figure 9

Change from reference in mean growing-season precipitation (May-October) (cm/year) for the CGCM_Mid projection



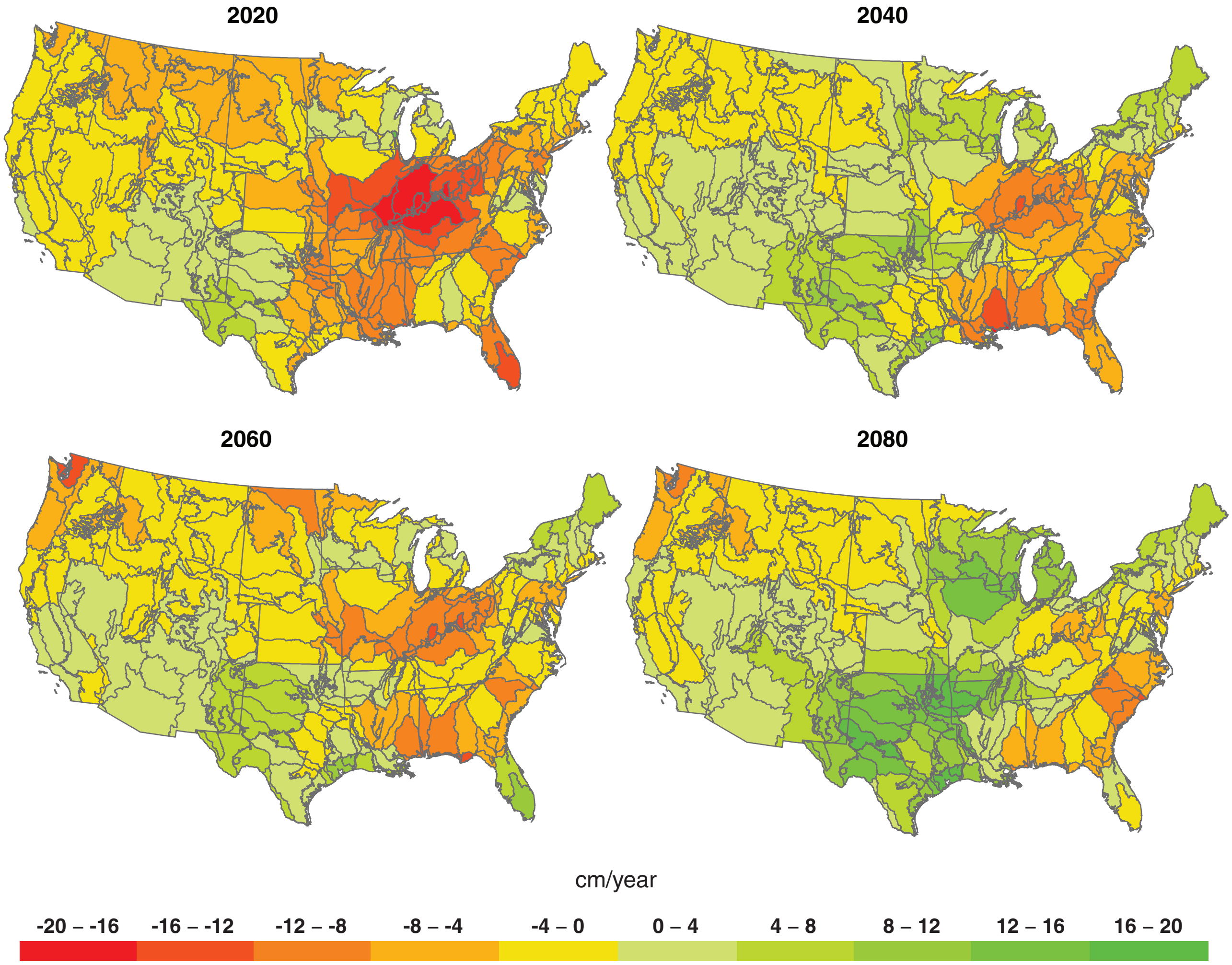
Note: CGCM = Coupled Global Climate Model

Scale truncated at +20 cm and -20 cm

Source: USDA, Economic Research Service.

Appendix figure 10

Change from reference in mean growing-season precipitation (May-October) for the CSIRO_Mid projection

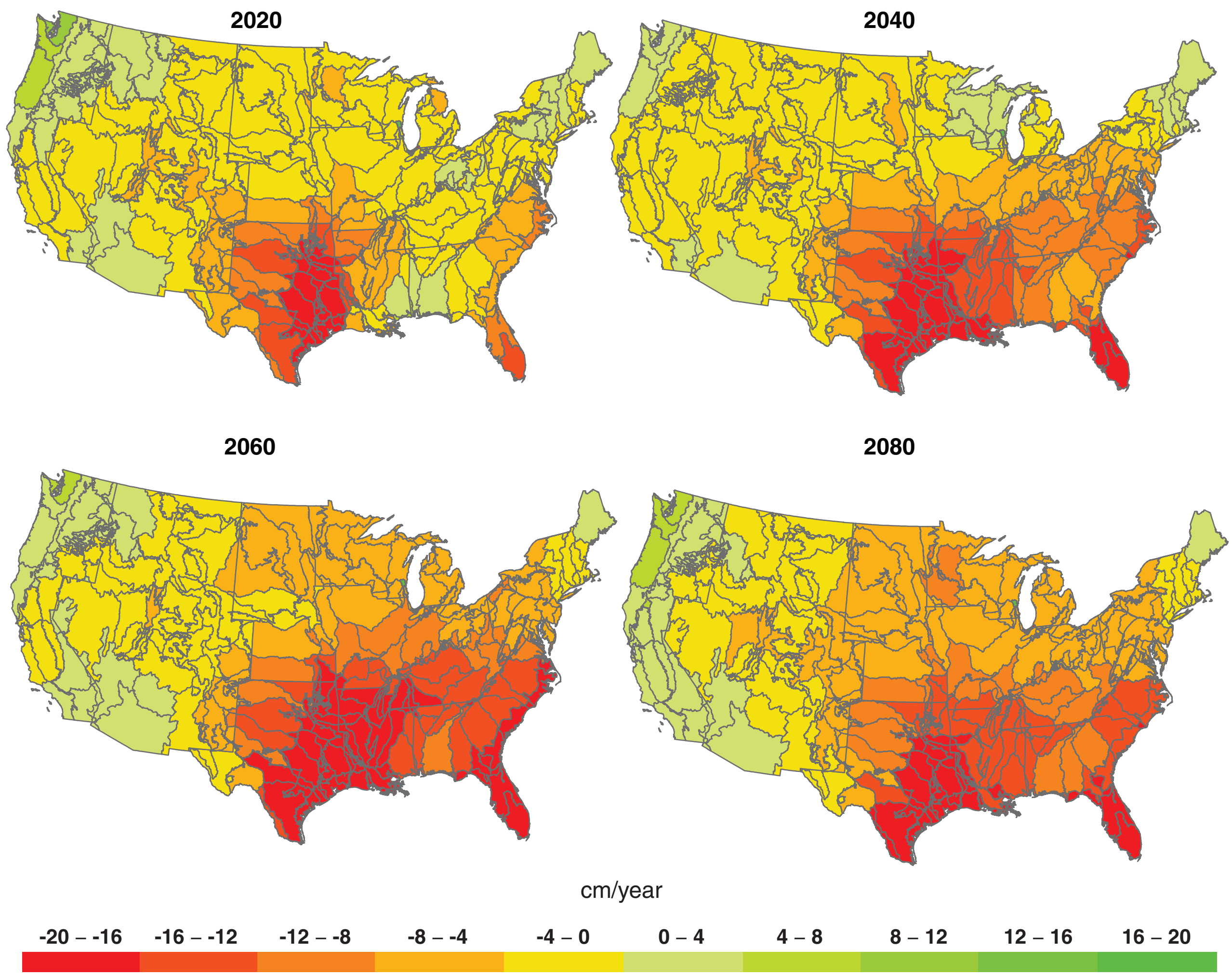


Scale truncated at +20 cm and -20 cm

Note: CSIRO = Australian Commonwealth Scientific and Industrial Research Organization Mark 3.5 Climate System Model
Source: USDA, Economic Research Service.

Appendix figure 11

Change from reference in mean growing-season precipitation (May-October) (cm/year) for the MIROC_Mid projection



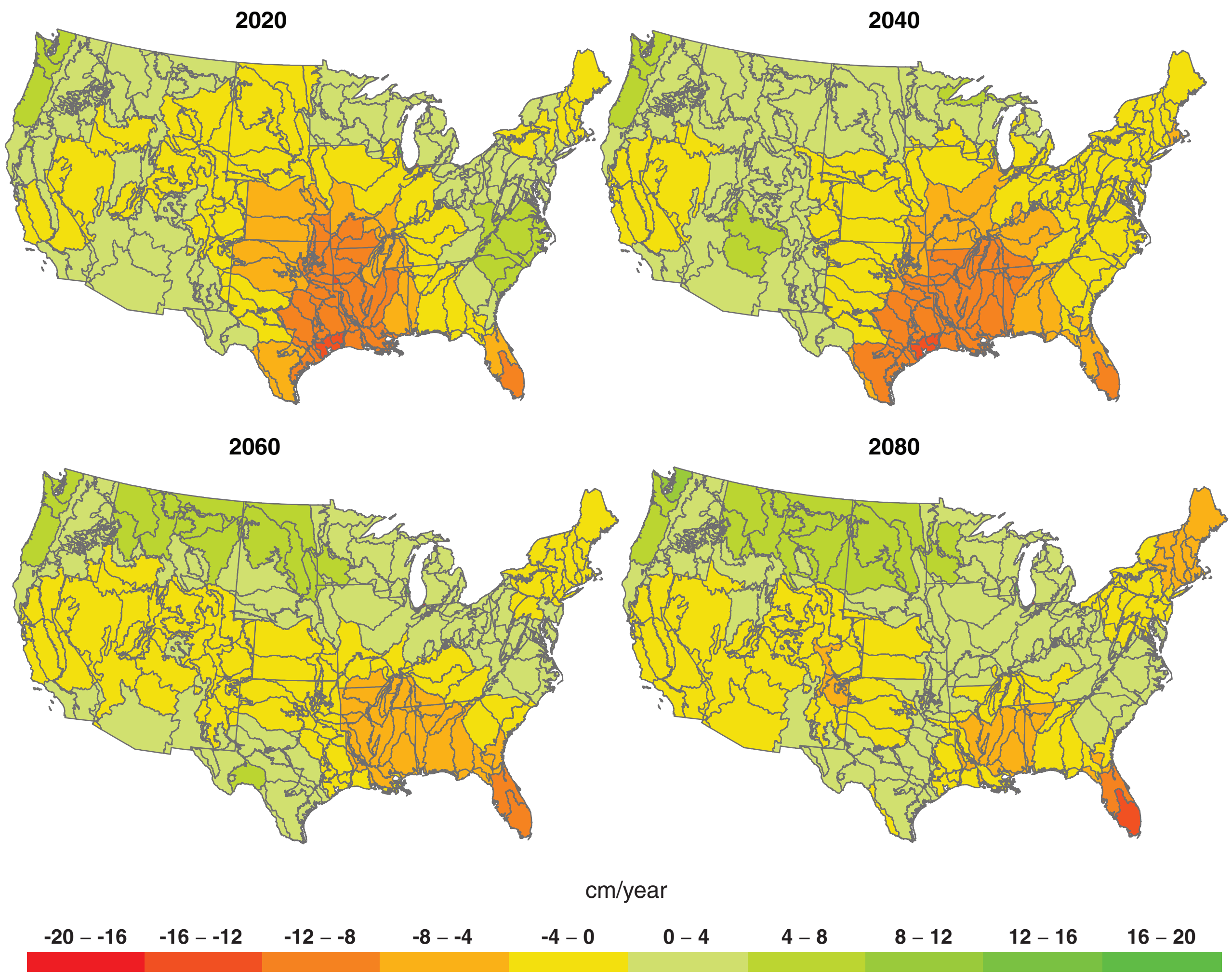
Note: MIROC = Japanese Center for Climate System Research Model

Scale truncated at +20 cm and -20 cm

Source: USDA, Economic Research Service.

Appendix figure 12

Change from reference in mean growing-season precipitation (May-October) for the CGCM_High projection



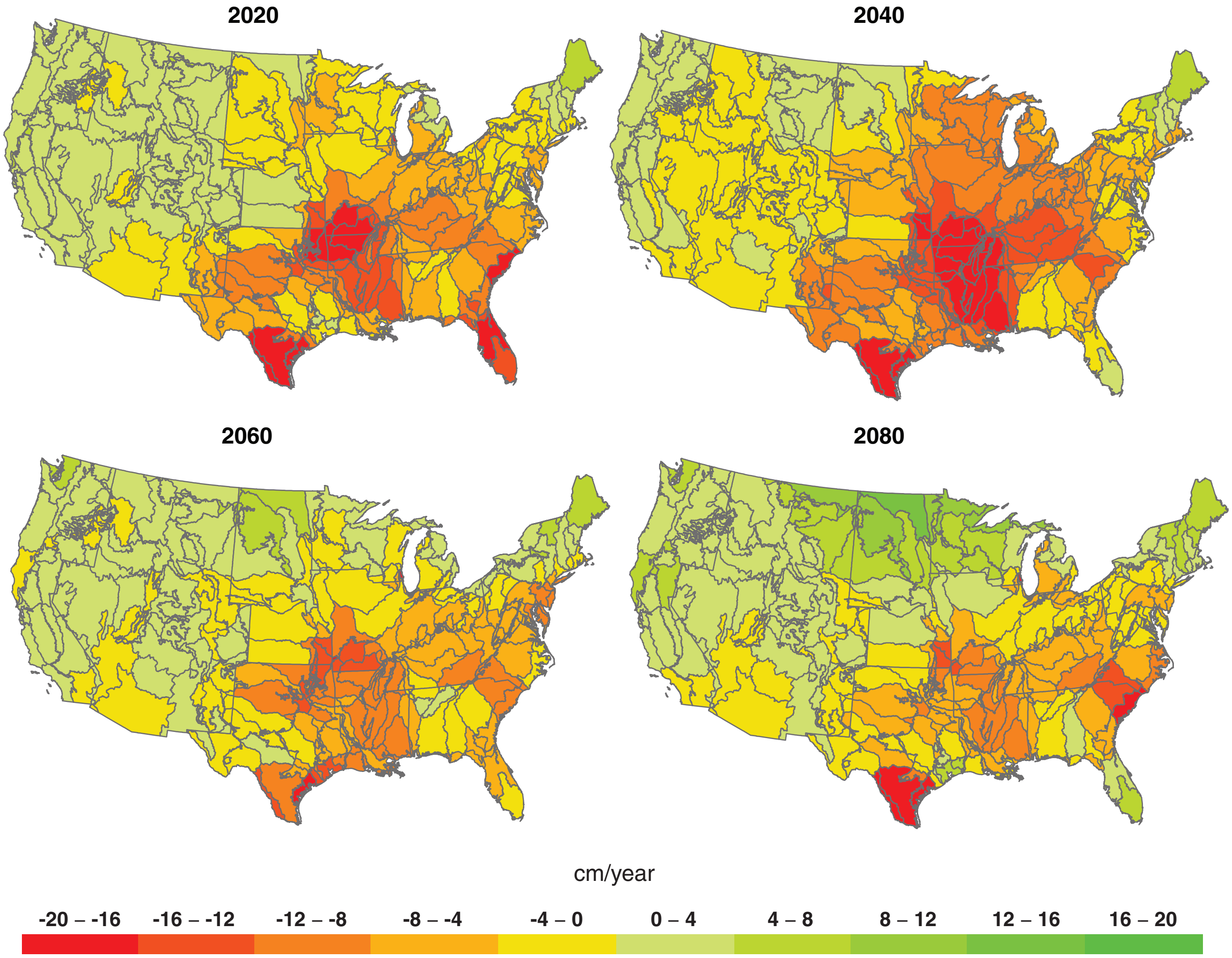
Note: CGCM = Coupled Global Climate Model

Scale truncated at +20 cm and -20 cm

Source: USDA, Economic Research Service.

Appendix figure 13

Change from reference in mean growing-season precipitation (May-October) for the CSIRO_High projection

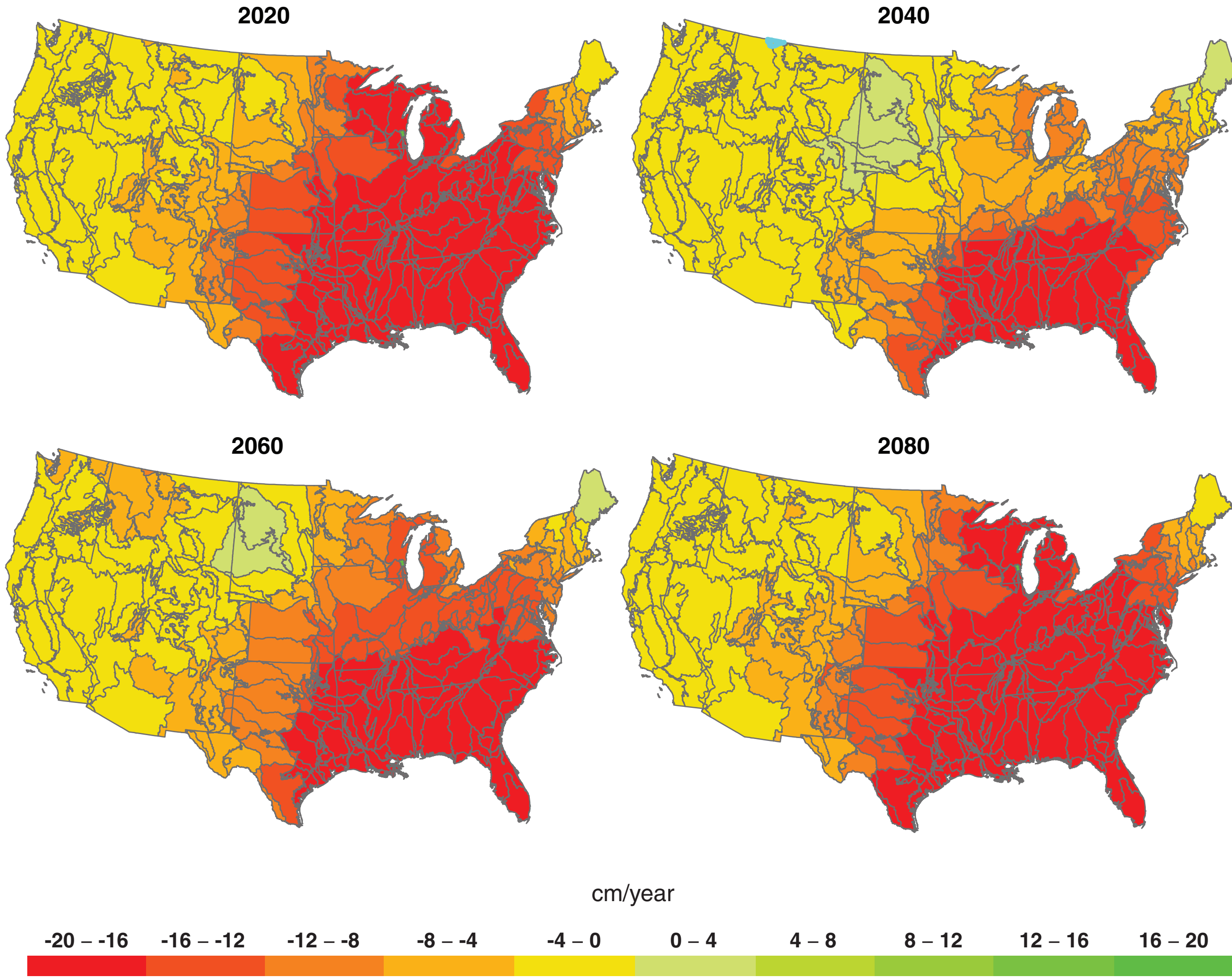


Note: CSIRO = Australian Commonwealth Scientific and Industrial Research Organization Mark 3.5 Climate System Model
Source: USDA, Economic Research Service.

Scale truncated at +20 cm and -20 cm

Appendix figure 14

Change from reference in mean growing-season precipitation (May-October) for the MIROC_High projection



Note: MIROC = Japanese Center for Climate System Research Model

Scale truncated at +20 cm and -20 cm

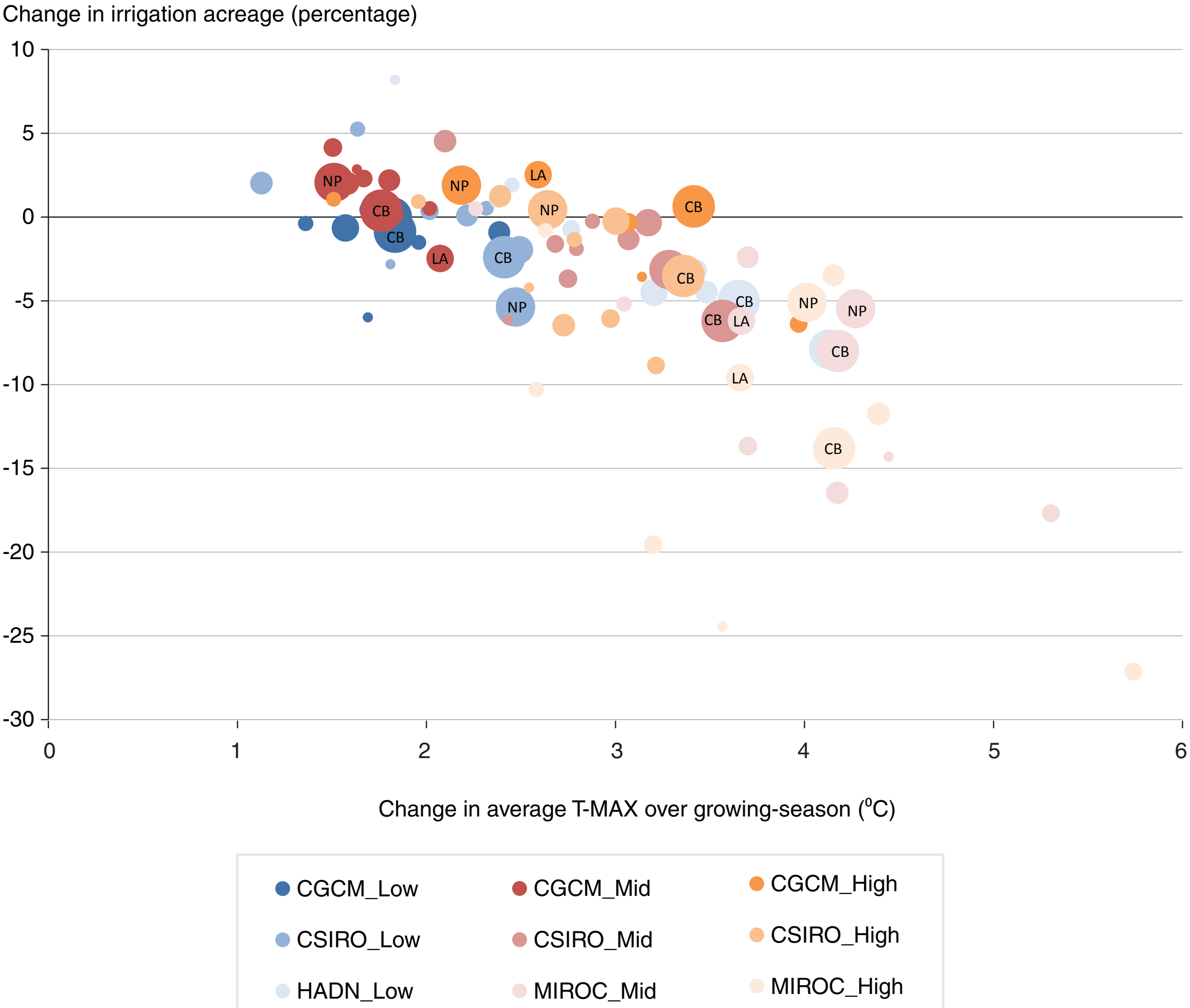
Source: USDA, Economic Research Service.

Regional changes in temperature and precipitation

Graphing regional changes in growing-season temperature versus changes in growing-season precipitation provides additional information about how regional aridity (reflecting a combination of increased temperature and decreased precipitation) is projected by the different models and scenarios. Appendix figure 15 illustrates for analysis year 2060 how the regions fall out along two dimensions—one representing change in precipitation and the other reflecting change in temperature—for each of the different climate projections. The size of the bubbles reflects the amount of production acreage in each region under the reference scenario and is therefore constant across climate projections. Most major production regions are generally projected to be both drier and warmer, with the darker bubbles (the CGCM model) projecting more moderate increases in temperature and declines in precipitation, and the lighter bubbles (primarily the MIROC model) projecting greater growing-season temperature increases and precipitation declines in major agricultural production areas.

Appendix figure 15

Change in regional growing-season climate conditions in the year 2060 under each of the climate projections



Note: See Appendix A for explanation of climate models.
Source: USDA, Economic Research Service.

Shifts in seasonal precipitation

Future crop growth will be affected by changes in both the magnitude and timing of regional precipitation. The climate analyses thus far have focused on growing-season precipitation (defined as May-October precipitation), but winter precipitation can also affect crop growth, both for crops grown through the winter (such as perennial hay and winter-grown wheat, barley, and soybeans) and for annual warm-season crops through impacts on stored soil moisture and nutrients. Appendix Figure 16 illustrates for 2060 the percent change in annual precipitation versus the percent change in winter precipitation by farm production region. Points to the right of the dashed 45^{o} line indicate those regions experiencing a shift in precipitation toward winter precipitation, because (1) the increase in winter precipitation exceeds that for annual precipitation (QI), (2) winter precipitation declines proportionately more than annual precipitation (QIII), or (3) winter precipitation increases despite annual precipitation declines (QII). Generally, the major agricultural production regions experience a shift toward winter and early-spring precipitation. This seasonal shift can exacerbate the impacts of precipitation change on growing-season water availability in drier regions as well as alter relative changes in crop-water availability across warm-season and cold-season crops.

Climate change impacts on aridity

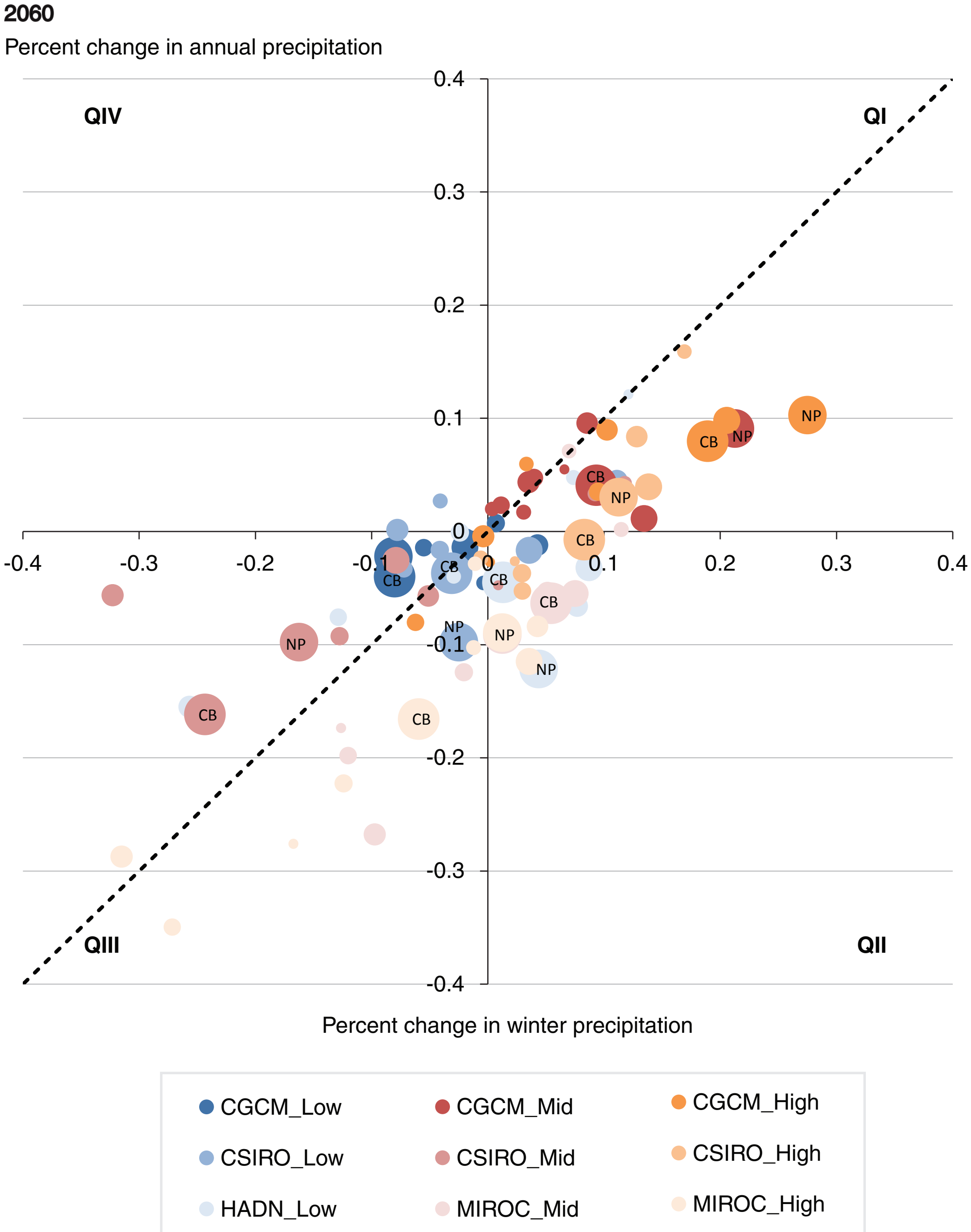
The agricultural significance of the relationship between temperature and precipitation may be reflected in measures of aridity. One widely used aridity index is the ratio of precipitation to potential evapotranspiration (PET). As precipitation increases, the aridity index declines; as PET increases, the aridity index increases. PET information is available for each of the climate projections that were used in this analysis. Appendix figure 17 shows the change in annual, national cropland-weighted aggregate PET and precipitation from the reference scenario to 2080. A change in PET and in precipitation in the same direction by the same amount does not change the aridity index. However, the magnitudes of PET changes are much greater than precipitation changes for all climate change projections, leading to a much more arid landscape. The degree of aridity changes varies under the climate change projections; the range is reflected by the distance from the "constant aridity" line.

The aridity classification (appendix table 1) adopted by the United Nations Environment Programme (UNEP) is useful to visualize the scope of agricultural impact as a function of regional changes in aridity under each climate projection. Appendix figure 18 shows that for all scenarios, every region either retains its aridity category or moves into a more arid category. Under the MIROC_High scenario, most of the Eastern United States jumps two aridity categories, becoming semi-arid.[6]

[6]The delineation of categories is arbitrary. The actual change in index for a situation with no category change could be much greater than a change that results in a category change. The objective here is to illustrate the variation in potential impact of the climate change projections.

Appendix figure 16

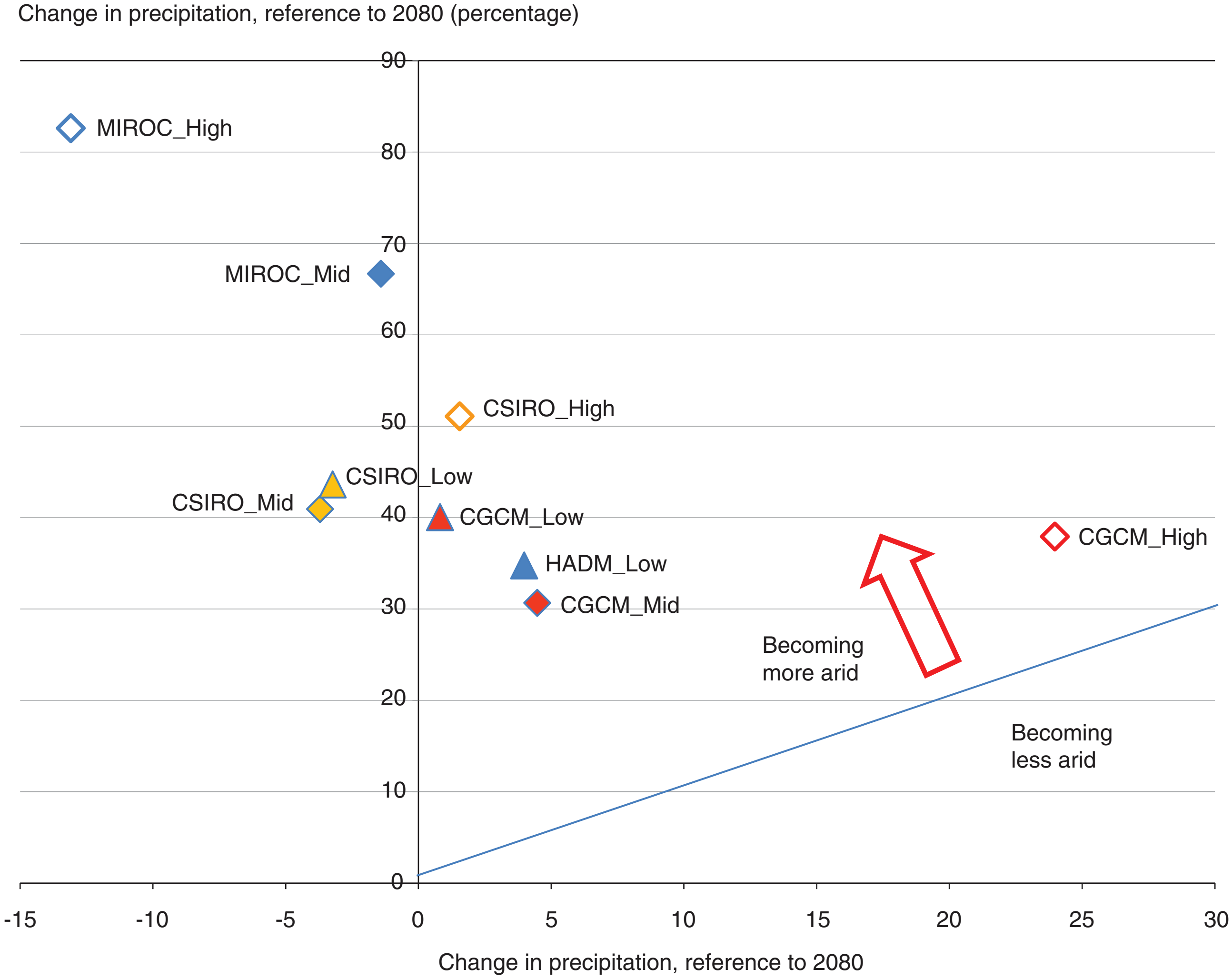
Change in annual precipitation versus change in winter precipitation for each climate projection in the year 2060



Note: Legend displays climate change models. See Appendix A for explanation of climate models.
Source: USDA, Economic Research Service.

Appendix figure 17

National cropland-weighted change in precipitation and potential evapotranspiration, relative to the reference, in 2080



Note: Legend displays climate change models. See Appendix A for explanation of climate models.
Source: USDA, Economic Research Service.

Appendix table 1

Aridity Classification (UNEP, 1992)

Classification	Aridity Index
Hyperarid	AI < 0.05
Arid	0.05 < AI < 0.20
Semi-arid	0.20 < AI < 0.50
Dry subhumid	0.50 < AI < 0.65
Non-arid	AI>0.65

Source: USDA, Economic Research Service.

Appendix figure 18

Regional change in annual aridity classification for 2080

Color of Region column indicates aridity class of region in the reference scenario.

Note: AP = Appalachia, CB = Corn Belt, DL = Delta States, LA = Lake States, MN = Mountain States, NE = Northeast, NP = Northern Plains, PA = Pacific, SE = Southeast, and SP = Southern Plains.
See Appendix A for explanation of climate models.
Source: USDA, Economic Research Service.

The timing of precipitation and temperature changes is an important factor affecting the aridity faced by crops with different growing seasons. Appendix figure 19 shows how the climate projections influence the aridity of warm-season growing conditions (May-October). With the exception of the Southern Plains and Northeast, regions increase their aridity categorization by at least one category. The Delta region under the MIROC_High scenario moves three categories.

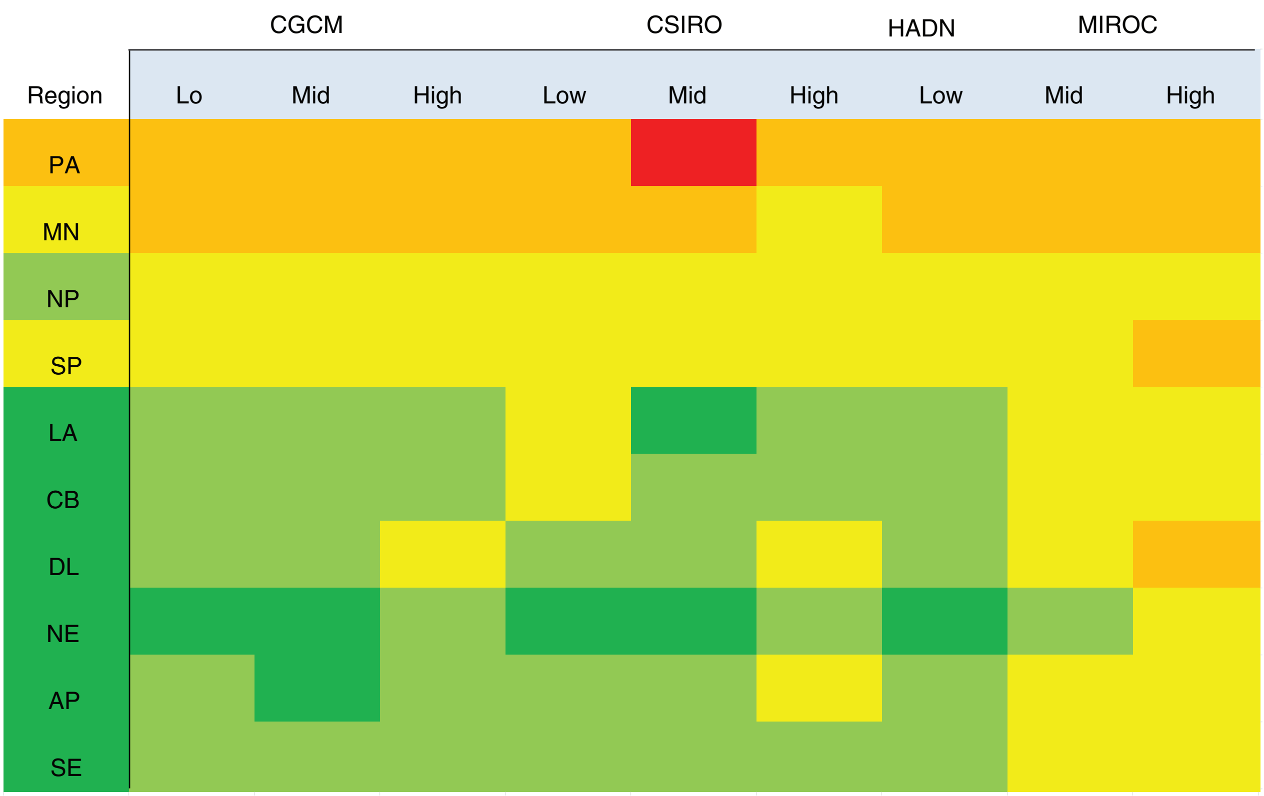
Because the regional and temporal variation in climate parameters differs widely between the scenarios, it isn't possible to rank the climate change projections by their aridity impact in a way that is consistent across regions. The MIROC_High and MIROC_Mid scenarios clearly show the greatest potential impact. The low emissions (B2) scenarios are generally more benign than the middle emissions (A1B) scenarios, which are in turn more benign than the high emissions (A2) scenarios. However, there are important exceptions to this generalization; for example, the CSIRO_Low scenario projects a two-category shift in the Corn Belt and Lake States, a phenomenon that only occurs in the MIROC_Mid and MIROC_High scenarios.

The GCM models and emissions scenarios provide a broad indication of the severity of climate change impact. All other things equal, a more arid environment is likely to reduce the productive capacity of dryland crop production; however, the specific outcome of coarse weather changes depends on the relative changes to crop yields within and between regions. The REAP economic model assesses how climate impacts translate into land use and price changes and the environmental consequences resulting from new crop production distributions.

Appendix figure 19

Regional change in growing-season (May-October) aridity classification for 2080

Color of Region column indicates aridity class of region in the reference scenario



Note: AP = Appalachia, CB = Corn Belt, DL = Delta States, LA = Lake States, MN = Mountain States, NE = Northeast, NP = Northern Plains, PA = Pacific, SE = Southeast, and SP = Southern Plains.
See Appendix A for explanation of climate models.
Source: USDA, Economic Research Service.