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Climate Change Impacts on Agriculture in the U.S.: Potential Constraints to Adaptation Due to Shifting Regional Water Balances

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Preliminary Analysis: Please Do Not Cite

Introduction

Projected climate change due to greenhouse gas emissions will likely have important water resource impacts, with broad implications for U.S. agriculture. Both vulnerability and the capacity to adapt to changing hydrologic conditions are likely to vary regionally, given the variation in projected temperature and precipitation patterns under a warming climate. Shifts in the extent and distribution of irrigated and dryland production are a potentially important adaptation response to climate change. Irrigated and dryland production systems differ significantly in yield productivity, input use, and environmental effects, all of which are influenced by local weather factors. Climate-induced changes in hydrologic conditions may have an important impact on crop-water demand and water availability for both dryland and irrigated agriculture. Potential shifts in the distribution of irrigated and dryland acreage will depend on regional adjustments in crop-water demand and supply, the viability and relative profitability of irrigated and dryland production systems both within regions and nationwide, and potentially competition for water from other non-agricultural sectors.

This research applies a national agricultural production model called the Regional Environment and Agriculture Programming (REAP) model to explore the implications of shifting regional water balances for agricultural production under a variety of potential climate change scenarios. Recent Economic Research Service (ERS) research on agricultural adaptation using REAP suggests that yield impacts under changing temperature and precipitation lead to substantial reallocation of acreage among crops and crop rotations (Malcolm et al, 2012). This analysis broadens the adaptation options within REAP to include adjustments in irrigated production and expands the research scope to consider constraints to and opportunities for adaptation arising from changing patterns of precipitation and projected shifts in the end-use water demand of various sectors.

This research seeks to address the following questions:

- How might changes in temperature and precipitation affect patterns of production and profitability for dryland and irrigated agriculture?
- How might farmers alter land-management practices (including irrigation decisions) and crop and crop rotation choice when faced with a new production regime shaped by climate change?

- How binding might constraints on water availability be on farmers' ability to adapt to climate change through changes in irrigations and crop choice?
- How would prices, production, and exports respond to projected changes in the pattern and methods of production?
- What would be the impact of such changes on farmer income and how might such changes vary by region?

Agricultural water supply

Rising temperatures and shifting precipitation patterns are likely to affect water availability for crop production. Dryland production may be particularly sensitive to shifting climatic factors, as changes in precipitation and evaporation during the growing season directly affect soil moisture available for crop growth. The net effect of climate shifts on soil moisture would vary regionally, depending on whether higher evaporative losses are offset or exacerbated by changes in precipitation. Increases in the variability of precipitation would also have particularly important implications for dryland systems. Heightened storm intensity increases field water runoff, reducing the share of precipitation that infiltrates the crop root zone (SWCS, 2003).[1] In areas subject to warmer and drier conditions, projected increases in drought frequency and severity may increase the annual variability of dryland yields.

Under irrigated production, natural soil moisture deficits may be replenished during the growing season through applied irrigation water. In arid areas of the western U.S. where soil moisture reserves are generally low and crop-water demands are high, irrigation provides the significant share of crop-water requirements in most years. In more humid areas of the U.S., irrigation is used to supplement available soil moisture reserves, particularly during periods of below-normal rainfall. While irrigation reduces the risk of uncertain seasonal rainfall associated with dryland production, irrigators may be subject to variability in the cost and availability of purchased water supplies.

Sources of irrigation water may be differentially affected by climate change as well. Surface-water sources account for roughly 58 percent of water withdrawals for irrigated crop production nationally, with the remaining 42 percent supplied by groundwater (Kenny et al. 2009). Climate change is likely to have an especially important impact on surface-water resources, given the importance of weather factors on surface runoff. Annual streamflow may increase in the northern and eastern U.S. where annual precipitation is projected to increase. Precipitation declines in the Southern Mountain and Southern Plains regions would likely result in reduced streamflow, with a shift in seasonal flow volumes to the wetter winter months (USDI, 2011).

[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, 2011).

Snowpack is an important factor in the magnitude and timing of seasonal runoff and stored water reserves used for irrigated crop production. Changes in snow accumulations and timing of meltoff can have profound impacts on surface-water resources where snowmelt represents a significant element of the regional hydrologic system. This is a particular concern in the West, where much of the surface-water runoff is derived from mountain snowmelt. Higher temperatures will restrict the length of the snow storage season, resulting in reduced snow accumulations and earlier spring meltoff (Knowles, 2006). Stored water reserves are projected to decline in many river basins, especially in the critical summer growing-season months when crop-water demands are greatest (USDI, 2011).

The effect of precipitation changes on surface-water flows may be offset or compounded by temperature-induced shifts in potential evapo-transpiration (PET). Higher temperatures under a warming climate are projected to increase evaporative losses from land and water surfaces and increase transpiration losses from non-crop land cover, potentially lessening annual runoff and streamflow for a given level of precipitation.[2]

Relatively less research attention has focused on climate impacts on groundwater systems. Groundwater is a primary water source for irrigation in the Plains States and an important irrigation water supply for the eastern U.S, as well as areas of the Mountain and Pacific West. While groundwater aquifers are generally less influenced in the short term by weather patterns, changing climate effects on precipitation, streamflow, and soil evaporation can affect groundwater systems over time through impacts on groundwater recharge rates (Dettinger and Earman 2007).

Across the U.S., expanding water demands for economic and environmental purposes has increased the competition for available surface and groundwater supplies. As irrigated agriculture accounts for the largest share of consumptive use in many river basins where available water is fully appropriated, emerging water demands in other sectors will be met primarily through a reallocation of agricultural supplies. Competition for water is likely to intensify in regions where climate change results in warmer and drier growing-season conditions. Where annual precipitation and runoff are projected to increase, or where adequate reservoir capacity exists to capture and store seasonal shifts in peak runoff, pressures on agricultural supplies may be lessened.

Agricultural water demand and irrigation under a changing climate

Climate change has important implications for the future extent and regional distribution of U.S. irrigated crop production. Irrigated sector adjustments will depend on climate impacts on

[2] Other factors—including precipitation, radiation, cloud cover, humidity, wind velocity, and atmospheric carbon—affect rates of evapo-transpiration, and an understanding of how factors would interact under a changing climate is incomplete.

regional water resources and implications for the viability and competitiveness of irrigation production. However, changes in irrigation water supply and demand are difficult to predict at a scale sufficient to quantify acreage and production responses (Adams and Peck 2008).

A number of studies have examined potential shifts in crop irrigation requirements and water supply, and implications for national and regional irrigated acreage (Reilly et al., 2001, Izaurralde et al. 2003, Thomson et al. 2005). Predicted acreage response has varied, due in part to differing modeling frameworks and regional water-supply assumptions under alternative climate projections. Potential shifts in the frequency and severity of drought are also likely to contribute to changing demand for irrigation (Negri et al. 2005). We briefly discuss two important determinants of irrigated acreage response: 1) water-supply availability for agriculture, and 2) relative returns to irrigated and dryland crop production.

Water-supply availability. Irrigated agriculture requires access to water supplies for crop production. In water-limited areas, the effect of climate change on regional water supplies is likely to drive irrigated acreage response. Under a warming climate, agriculture may become increasingly water-constrained across the central and southern portions of the Mountain and Pacific West (USDI, 2011), where irrigated production accounts for 37 percent of harvested cropland, including most of the region's high-valued specialty crop production (USDA-NASS, 2007). Higher temperatures with reduced summer rainfall would increase soil aridity during the growing season. At the same time, reduced mountain snowmelt in the Southwest and central Rockies is likely to constrain stored surface-water reserves that provide much of the region's irrigation supply, potentially limiting the scale of farm production within the Sacramento-San Joaquin, Upper Rio Grande, and Middle/Lower Colorado river basins. Projected increases in precipitation in the northern Rockies and Pacific Northwest, on the other hand, could expand water supplies within the Columbia and Upper Missouri river basins (USDI, 2011).

A heavy reliance on groundwater from the Ogallala Aquifer may help to shield the Plain States' irrigated sector in the short term from annual and seasonal shifts in water availability. However, groundwater pumping in excess of natural recharge has caused significant water table declines over much of the region, and increased water demands due to climate change may intensify pressures on groundwater resources. Agricultural water supplies in the Southern Plains—including the Lower Rio Grande and Texas/Gulf basins—are likely to be further constrained over the long term, while shifting precipitation patterns may potentially increase soil moisture and surface water availability in the Lower Missouri and Platte river basins of the Northern Plains (USDI 2011, Ojima, D. et al. 1999, Scanlon, B. et al 2013).

Significant groundwater aquifer declines have also occurred in California's Central Valley region, where much of the nation's high-valued fruit and vegetable production is concentrated (Scanlon, B. et al. 2013), Reliance on groundwater is particularly important in dry years when surface-water supplies are often limited. In the Southeast and Mississippi Delta regions,

irrigated acreage accounts for nearly a third of harvested irrigated, with groundwater as the primary water source. The region has seen a significant expansion in irrigated production since 1980, with much of the growth occurring in the Delta region. However, conflicts over water-supply shortfalls due to drought underscore the growing competition for regional water resources. While climate projections differ fairly widely for the U.S. Southeast (Hatch et al. 1999), projections used in this study—with precipitation declines in three of four GCM scenarios—suggest increasing irrigation demand with perhaps more limited potential for irrigated expansion.

In the more northern regions of the Corn Belt, Appalachia, Lake States, and Northeast, water availability is generally adequate for dryland production in normal rainfall years. Irrigated acreage accounts for just 3 percent of harvested cropland, although irrigation has expanded steadily in recent decades. While projected increases in precipitation would help sustain surface and groundwater supplies, irrigation expansion will depend on relative returns to dryland production.

Relative returns to dryland versus irrigated crop production. Changing climate patterns are likely to result in a shift in relative returns across irrigated and dryland production. Where growing-season precipitation is generally sufficient to support dryland production, irrigated acreage response may be more sensitive to shifts in relative returns than to changes in water availability. We discuss the effect of climate change on two drivers of crop returns: production costs and crop yields.

Production costs. In general, average costs for irrigated production are substantially higher than dryland production, reflecting both the costs of irrigation water access and distribution, and more intensive input use in irrigated cropping systems. The largest cost differentials occur in the southern-tier states, where irrigation applications account for a comparatively large share of crop-water requirements. Returns above variable costs provide a measure of the relative competitiveness of irrigated and dryland production. In the more arid portions of the U.S. corn-producing region—including the Mountain and Plains regions—irrigated returns generally exceed returns to dryland production. In the more humid Southeast, Cornbelt, Appalachian and Northeast regions, dryland production is relatively more competitive under prevailing production conditions.[3]

Climate change may affect relative returns to irrigated and dryland production through changes in production costs. A shift in the availability of surface and groundwater, for example, may have an important bearing on the cost of irrigation water. Regional effects would vary widely,

[3] Aggregate regional returns mask considerable intra-regional variation, as local returns to irrigation vary depending on local production systems, soils, water supplies, and micro-climatic factors. Returns to irrigation may also vary significantly across years, depending on weather and price conditions. Under drought conditions that increase the differential between dryland and irrigated yields, relative returns to irrigation are likely to expand.

depending on climate interactions with irrigation water supplies and marginal costs of applied water. Climate change may also affect energy costs in agricultural production.[4] Energy cost adjustments would have a relatively large impact on irrigation returns due to water pumping and pressurization requirements and other energy-intensive operations. Regional effects would reflect, in part, the predominant energy source used. Nationally, per-acre energy costs for irrigated corn ($102/ac) and wheat ($107/ac) in 2009 were substantially greater than for dryland corn ($18/ac) and wheat ($8/ac) (based on unpublished ARMS survey estimates). Higher costs of petroleum-based nitrogen fertilizer may also have a disproportionate effect on irrigated returns, due to increased use of chemical fertilizers. Fertilizer costs per acre for irrigated corn ($138/ac) and wheat ($79/ac) in 2009 generally exceeded dryland corn ($132/ac) and wheat ($52/ac).[5]

Crop yields. Climate change will also affect crop revenue through differential impacts on yields under irrigated and dryland production. Changes in crop yield will depend on the relative sensitivity of crops to climatic factors (crop physiology), and the coincidence of regional climatic shifts with geographic patterns of production (stress factors by crop location). Climate-induced change in irrigation requirements—represented by the difference between evapotranspiration (ET) for a well-watered crop and ET based on available soil moisture during the growing season—has important implications for yield response in irrigated and dryland cropping systems. Where crop ET rises relative to the change in growing-season precipitation, irrigation requirements are increased and dryland yields generally decline. An increase in normal precipitation above ET, in turn, would reduce crop irrigation requirements while favoring dryland production.

Adaptation to changing water resource conditions

Adaptation to changing water-supply regimes under climate change can help mitigate potential costs to the irrigated sector. This is particularly true of areas of the Western U.S. facing growing water scarcity and a potential contraction of irrigated acreage.

At the producer level, where groundwater reserves are adequate, groundwater may be used as a backup supply to meet surface-water supply shortfalls. Improved irrigation technologies increase the efficiency of water conveyance and field application, enhancing the productivity of limited water supplies. Irrigation improvements include an array of physical upgrades to gravity and pressurized systems as well as improved water management practices. Other practices—such as conservation tillage, water catchments, and snow fences—can help capture and retain natural soil moisture for both irrigated and dryland production. Cropping pattern shifts represents an

[4] Climate change may influence energy costs in many ways, such as through changes in energy demand, hydropower generation costs, and climate mitigation policy.

[5] Comparisons of national aggregate costs may mask more significant differences in irrigation and dryland production costs at a local level. Fertilizer costs for dryland corn largely reflects production in the Corn Belt, while irrigated corn captures production in the Plains States and Southeast.

important adaptation to water scarcity. Crop substitutions favoring less water-intensive or higher-valued crops can enhance returns to limited water supplies. As California agriculture becomes more water-constrained under a warming climate, high-valued specialty crops are likely to account for an increasing share of irrigation water use (Howitt et al. 2010, Schlenker et al. 2007). Development and diffusion of drought-tolerant cultivars may also help to reduce crop-water requirements.

To explore the potential impacts of shifting water regimes on the agricultural sector and its ability to adapt to climate change, this research uses a crop growth simulation model to estimate regional crop yields for several major U.S. field crops under a variety of different management schemes and several projected future climate and emissions scenarios. The regional crop yield estimates, and the resulting shifts in comparative advantage of production that they represent, are then entered into a partial equilibrium model of the U.S. agricultural sector to project how patterns and methods of production, as well as resulting production levels and prices, might react under changing climate conditions. While irrigation expansion represents a potential adaptation strategy for several regions facing potentially hotter and drier growing conditions, the capacity for expansion depends on the availability of water. This research uses estimates of potential irrigation water shortages, given changes in both climatic factors precipitation and in non-agricultural demand, to place regional constraints on the extent to which irrigation expansion can serve as an adaptation strategy. Potential shifts in the distribution of irrigated and dryland acreage will depend on regional adjustments in crop-water demand and supply, as well as on the viability and relative profitability of irrigated and dryland production systems.

Methodology

Projections of future climate scenarios and potential regional water shortages associated with those projections were developed by Colorado State University and the USFS Rocky Mountatin Research Station in support of the 2010 Water Resources RPA (Foti et al, 2012). Water supply and demand under 9 climate scenarios were estimated for 98 water basins, or Assessment Sub-regions (ASRs), in the contiguous 48 U.S. states. ASRs coincide with either 4-digit hydrologic units or aggregations of those units (Figure 1).

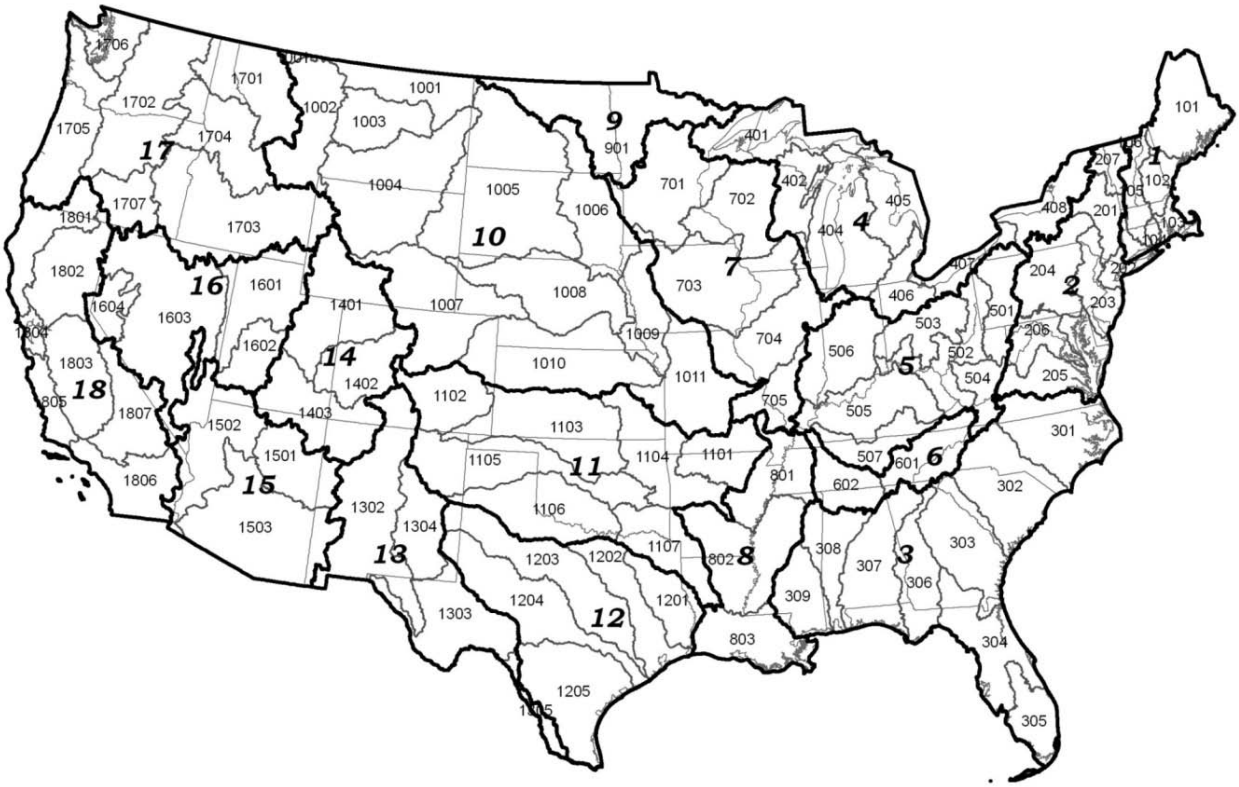


Figure 1: Assessment subregions (Foti et al, 2012).

The nine climate projections used in deriving water shortage estimates represent 3 potential carbon emissions scenarios, and 3 potential climate projections emerging from different General Circulation Models (GCMs) for each emissions scenario. The three emissions scenarios considered—A1B, A2, and B2—each represent a distinct storyline about potential future development and resulting carbon emissions. Of the three scenarios, the A2 scenario represents the most extreme emissions scenario and B2 the least extreme; the RPA report projects that by 2100 the surface warmings of the B2, A1B and A2 scenarios are 2.4ºC, 2.8ºC and 3.6ºC, respectively (Figure 2). Economic analysis of the extreme scenarios is ongoing, but this paper presents prelininary results associated with the middle emissions A1B path. The climatic implications of the A1B emissions path 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).

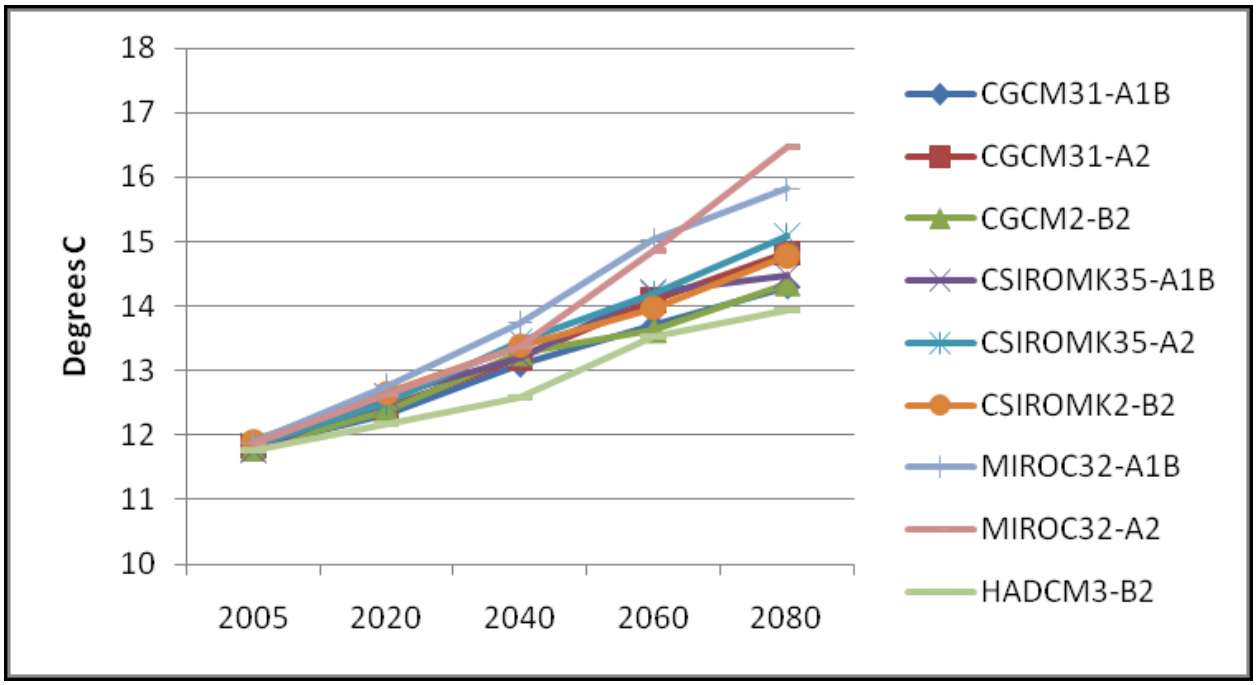
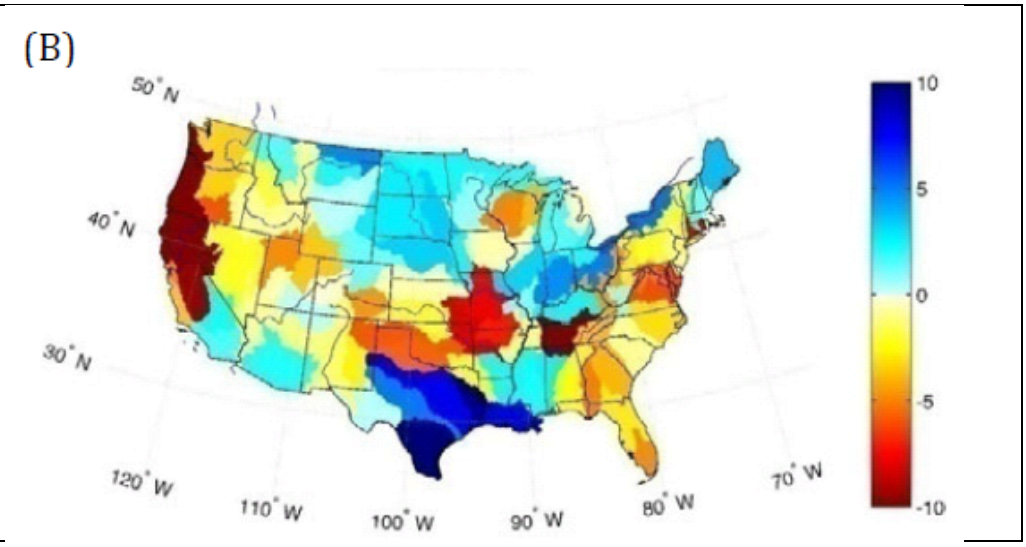


Figure 2: Mean annual temperature in the U.S. (Source: Foti et al, 2012)

The GCM results were downscaled by the RPA researchers 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). Regional precipitation impacts are shown in Figure 3. While CGCM and CSIRO generally predict more moderate impacts than MIROC, they vary in their predictions of which regions will be potentially positively impacted (by precipitation increases) and which are projected to suffer precipitation losses. The MIROC scenario generally represents the most extreme (hot and dry) future, though precipitation in the Corn Belt and the Lake States region is notably increased.

CGCM Results, A1B-2040



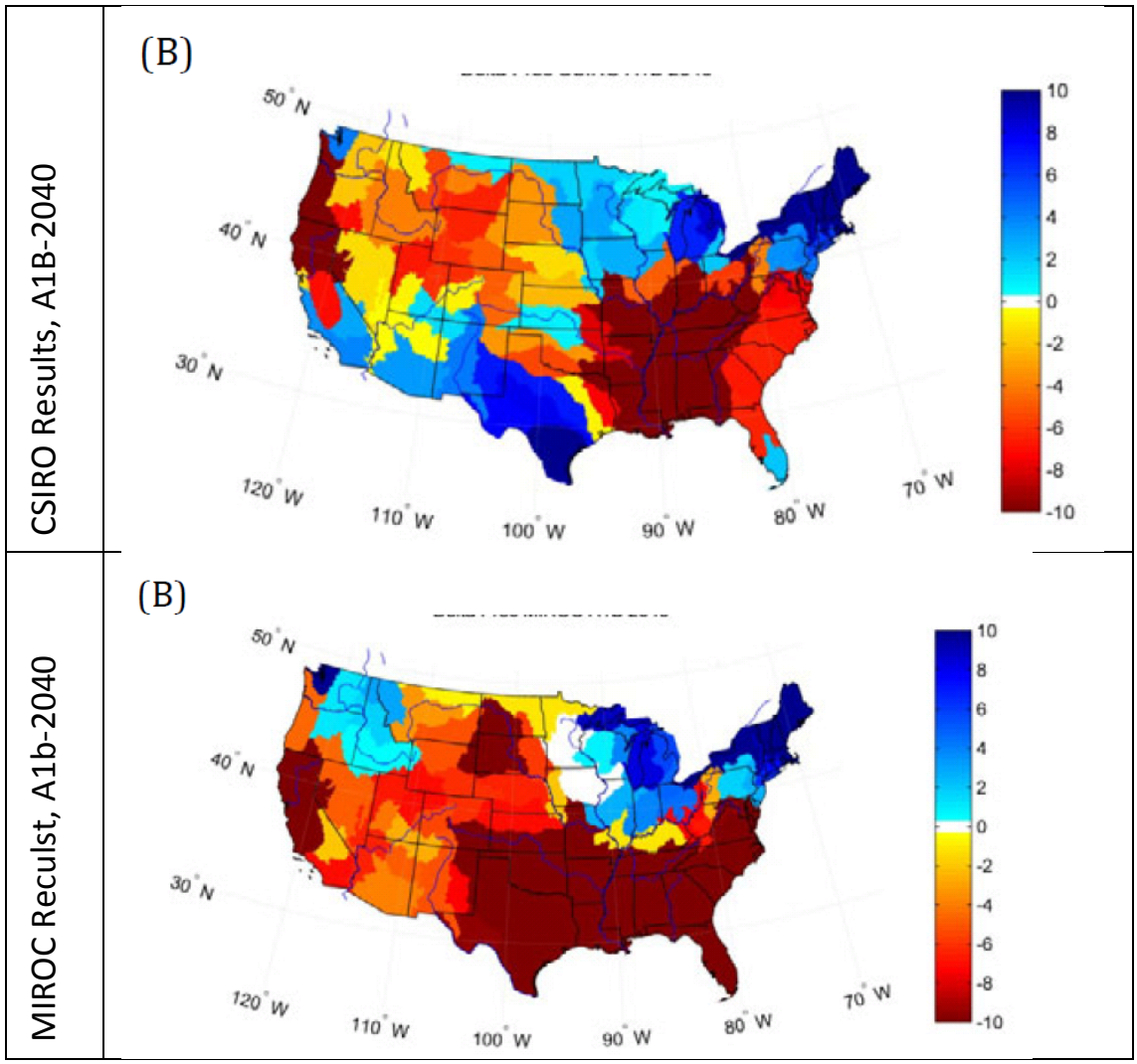


Figure 3: Change from current condition in mean precipitation (cm/year), with scale truncated at +10 cm and -10 cm. (Foti et al, 2012).

Regional water yield was then estimated annually through 2090 based on downscaled estimates of temperature and precipitation. Water demand, a measure of desired consumptive use, was estimated based on the USGS' five-year schedule for estimating water withdrawals, which uses historical records of sector-level water withdrawals and consumption use proportions as well as projection of water use drivers and rates of withdrawal per driver (Foti et al, 2012). Potential regional water shortages are then calculated as the difference between estimated water demand and water yield.

Such changes in climate conditions, regional yields, competing demands, and water shortages 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 Regional Environment and Agriculture Programming model (REAP). REAP is a static, partial equilibrium model of the U.S.

agricultural sector that 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 inputs. REAP allocates production acreage among a discrete set of production enterprises available to each region, and allocates the resulting agricultural products among a set of markets, including feed use, other domestic use, and exports, in order to maximize the sum of producer plus consumer surplus resulting from that allocation.

The optimal allocation of acreage in REAP is sensitive to climate through the impact 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. To assess the impact of changing climate conditions on yield, we use the biophysical simulation model EPIC (Erosion-Productivity Impact Calculator) to calculate for each REAP production region the crop yields arising from a set of production enterprises representing potential farmer choices for that region, which comprise combinations of tillage, crop, rotations, and irrigation and fertilizer use, under the different climate scenarios. 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.

REAP divides crop production in the United States into 267 regions, as defined by an overlay of ASRs (with hydrologic boundaries), land resource regions, and farm production regions (Figure 4). Each region is divided into production on highly erodible land (HEL) and non-highly-erodible land (NHEL), and each land type (HEL or NHEL) is represented by one or more soil series, depending on the amount of cropland in each region. Regions with less than one million acres of cropland are generally represented by a single soil type, with (roughly) an additional soil brought in for every additional million acres.

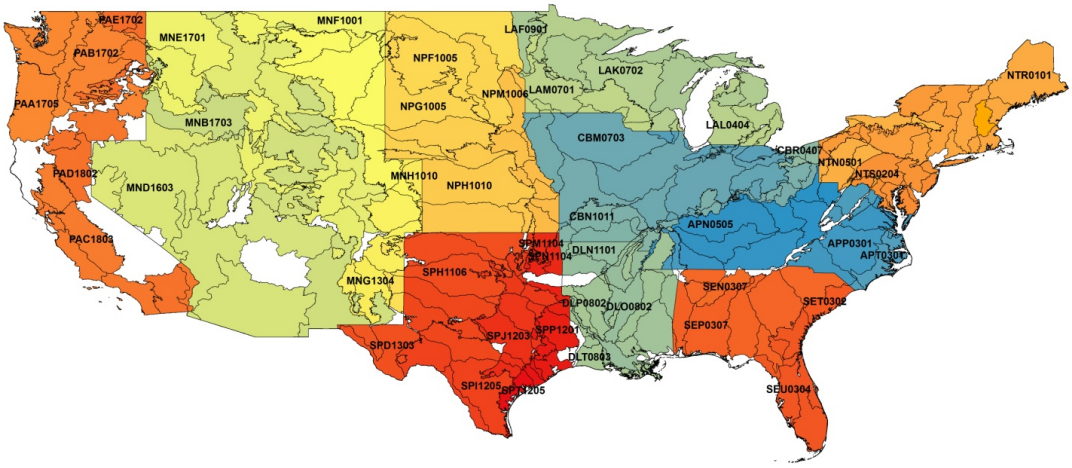


Figure 4: Lines delineate the 267 regions used in the EPIC calculations and REAP optimization. Regions with insignificant crop area in REAP crops are shown in white and are not included in the analysis.

Soil characteristics for each region and soil type are calculated using an overlay of the NASS cropland data layer and the SSURGO database. The cropland data layer identifies cropland within each REAP region, and the SSURGO database is used to divide that regional acreage into highly erodible (HEL) and non-highly-erodible (NHEL) map units and to characterize the soil types underlying those map units and the crops within them. Soils series chosen to represent each region are based on a consideration of soil series extent as well as importance for predominant crops within the region.

Crop production for a given region and soil type is simulated using the biophysical simulation model EPIC. EPIC uses the downscaled GCM information (re-aggregated up to the REAP regions based on a cropland-weighted-average of climate conditions) as the basis for generating the weather series that affects simulated crop growth. A random weather generator within EPIC uses the average monthly climate information derived from the GCMs – minimum daily temperature (TMIN), maximum daily temperature (TMAX), and precipitation (PRCP) – to generate daily weather patterns (temperature and precipitation) for each simulated year of growth in each REAP region. Changes in resulting crop yields are attributable to differences in average temperature, precipitation and atmospheric carbon dioxide concentration. Because estimates of the variability of future weather cannot be derived from either the original or the downscaled GCM climate data, the variability of weather, and therefore the relative incidence of extreme weather events, is held constant in this analysis between the baseline and future weather scenarios.

To disaggregate commodity production into particular cropping systems without overspecialization at the level of rotation and tillage, REAP uses a set of nested constant elasticity of transformation (CET) constraints to distribute production acreage among rotation, tillage, and irrigation options. The irrigation demand for each of REAP's irrigated production enterprises is estimated using EPIC, assuming that irrigation is triggered by a small amount of crop water stress.

This analysis uses a reference scenario that projects patterns of crop productivity, production, and prices out to 2040. Based on a combination of expert input, literature, and a modified extrapolation of current patterns, this reference scenario is a counterfactual representation of a future with changing population, demographics, diet, and other socioeconomic factors, but without the impacts of a changing climate. Calibration of REAP's dryland and irrigated production sectors incorporates information on irrigated cropping rotations from the National Resources Inventory as well as supporting data on irrigated/dryland crop acreage (NASS/AgCensus), irrigation application rates (FRIS/EPIC), irrigated costs (ARMS), water-supply source (USGS), tillage and fertilizer use (ARMS), and environmental impact coefficients (EPIC).

We then introduce three potential climate change scenarios, which are derived from three different general circulation model climate projections for emissions scenario A1B. All future climate scenarios are run through EPIC to determine regional climate impacts on crop yields and irrigation demand. These yield impacts, and the changing costs associated with irrigation, are then introduced into REAP, together with regional constraints on irrigation water availability, to determine how farmers' production decisions are likely to change under each of the climate scenarios with altered patterns of crop productivity and irrigation demand by region. Implications of climate change for price, production, income, exports, and consumer and producer surplus are generated for the year 2040 using climate conditions that represent a 20-year average around that year drawn from the climate model projections (2031-2050).

Results

EPIC Yield Impacts

The results of the EPIC runs for average crop yields for several major crops under the reference climate and the three different 2040 climate scenarios (for emissions scenario A1B) are shown in Tables 1-3. These averages are calculated using an acreage weighting based on 2007 NRI acreage in each rotation. As expected given the large regional variability in climate impacts across GCMs, there are significant differences in regional yield impacts across GCMs as well as across crops.

Table 1: Acreage-weighted yield results for corn in 2040 emerging from the EPIC analysis (red indicates declining yields relative to reference scenario).

Corn_A1B_2040 (bu/acre)					
FPR	METHOD	Reference	CGCM 2040	CSIRO 2040	MIROC 2040
Appalachia	D	143.47	155.08	154.36	139.11
Appalachia	I	195.63	203.8	214.59	213.9
Corn Belt	D	151.18	162.26	161.46	164.33
Corn Belt	I	205.97	212.58	210.03	206.96
Delta States	D	163.66	171.84	178.88	144.8
Delta States	I	192.4	203.53	243.17	215.13
Lake States	D	136.43	146.84	153.5	150.22
Lake States	I	164	175.99	175.06	177.33
Mountain Region	D	47.39	50.34	50.92	38.39
Mountain Region	I	161.14	168.42	169.87	154.75
Northern Plains	D	96.99	106.12	112.95	87.89
Northern Plains	I	183.38	191.7	196.33	184.83
Northeast	D	121.09	130.84	125.16	126.83
Northeast	I	191.81	199.54	197.91	201.32
Pacific States	D	35.28	39.52	43.66	42.86
Pacific States	I	166.33	160.32	169.49	156.08
Southeast	D	130.67	134.63	136.99	139.62
Southeast	I	211.39	213.09	220.91	232.29
Southern Plains	D	66.54	60	72.29	41.46
Southern Plains	I	160.58	148.17	168.64	166.48

Table 2: Acreage-weighted yield results for soybeans in 2040 emerging from the EPIC analysis (red indicates declining yields relative to reference scenario).

Soybeans_A1B_2040 (bu/acre)					
FPR	METHOD	Reference	CGCM 2040	CSIRO 2040	MIROC 2040
Appalachia	D	55.29	64.45	51.78	34.49
Appalachia	I	65.57	74.23	65.77	55.77
Corn Belt	D	46.29	48.49	41.39	38.38
Corn Belt	I	51.75	53.43	45.26	39.11
Delta States	D	45.24	42	37.44	22.66
Delta States	I	50.74	48.81	46.32	30.38
Lake States	D	42.78	40.73	44.77	35.9
Lake States	I	45.14	43.38	44.51	37.53
Mountain Region	D	11.89	14.44	11.91	8.97

Soybeans_A1B_2040 (bu/acre)					
FPR	METHOD	Reference	CGCM 2040	CSIRO 2040	MIROC 2040
Mountain Region	I				
Northern Plains	D	31.74	32.46	35.5	28.39
Northern Plains	I	51.61	48.06	50.97	44.66
Northeast	D	49.43	56.12	48.1	42.45
Northeast	I	62.06	71.78	64.18	62.55
Pacific States	D				
Pacific States	I				
Southeast	D	64.12	71.75	62.01	42.34
Southeast	I	86.9	89.78	85.46	73.42
Southern Plains	D	34.02	31.52	37.2	21.77
Southern Plains	I	59.08	56.32	57.63	58.32

Table 3: Acreage-weighted yield results for wheat in 2040 emerging from the EPIC analysis (red indicates declining yields relative to reference scenario).

Wheat_A1B_2040 (bu/acre)					
FPR	METHOD	Reference	CGCM 2040	CSIRO 2040	MIROC 2040
Appalachia	D	45.22	47.22	43.25	44.64
Appalachia	I	54.31	61.39	49.87	57.75
Corn Belt	D	50.36	51.8	51.65	54.45
Corn Belt	I	48.5	47.59	45.92	45.07
Delta States	D	34.23	35.53	38.43	38.31
Delta States	I	35.6	38.17	40.82	39.68
Lake States	D	47.65	51.21	51.91	50.7
Lake States	I	45.66	49.05	49.75	50.46
Mountain Region	D	24.78	30.74	24.34	23.88
Mountain Region	I	82.27	86.32	83.37	85.57
Northern Plains	D	44.17	45.78	42.88	38.31
Northern Plains	I	50.25	52.08	50.68	53.52
Northeast	D	36.6	39.22	40.48	41.34
Northeast	I	49.46	51.29	48.8	51.74
Pacific States	D	27.92	29.5	35.41	37.26
Pacific States	I	72.29	75.14	73.69	73.17
Southeast	D	28.75	31.71	32.15	22.84
Southeast	I	35.75	35.6	34.69	25.61
Southern Plains	D	21.45	24.43	21.78	21.09

Wheat_A1B_2040 (bu/acre)					
FPR	METHOD	Reference	CGCM 2040	CSIRO 2040	MIROC 2040
Southern Plains	I	43.21	45.1	39.12	45.09

For corn, increases in yields are estimated for both dry and irrigated rotations under CGCM and CSIRO climate projections, while impacts under the MIROC projections vary widely, with the Delta region and Southern Plains suffering losses in dryland yields, and others experiencing slight increases. For wheat, CGCM again consistently results in yield gains, but CSIRO projects precipitation (and yield) losses in significant wheat production regions like the Northern Plains. The MIROC projections are also mixed, with heavy yield losses in the Northern Plains and Southeast states but some gains experienced in the Northeast and Pacific states. Impacts on soybeans yields are mixed across both CGCM and CSIRO projections, though CGCM impacts are expected to be positive in the key production region of the Corn Belt. Simulations under the MIROC scenario estimate steep soybean yield losses for dryland production in most regions.

The results of the EPIC runs estimating water demand on irrigated acres for corn, soybean, and wheat under the reference climate and the three different 2040 climate scenarios (for emissions scenario A1B) are shown in Tables 4-6. The direction of change again varies by region, GCM, and crop. Corn's irrigation demand drops in the key Corn Belt region across all GCMs, but increases across all GCMs in the southeast. While the change in irrigation demand is often inversely related to the region's change in precipitation, that is not always the case. In the Mountain Region, for instance, corn's irrigation demand drops sharply despite a drop in precipitation; this is likely because irrigation is triggered by plant demand, and temperature impacts are driving down both yields and resulting crop-water requirements in that region.

The results for soybean and wheat irrigation demand are similarly varied. It's interesting to note that for the Delta region, soybean irrigation demand declines across all GCM scenarios while for wheat it increases across all GCM scenarios. As mentioned above, such differences reflect the different response of the crops to other changes in climate conditions, particularly temperature in this analysis, since precipitation impacts are buffered on irrigated land. Soybean yields, and irrigation demand, drop s in the region while wheat yields, and irrigation demand, increase.

Table 4: Estimated acreage-weighted water demand on irrigated corn acres in 2040.

Irrigation_Corn_A1B_2040 (acre-in)					
FPR	METHOD	Reference	CGCM 2040	CSIRO 2040	MIROC 2040
Appalachia	I	15.56	14.44	14.99	16.86
Corn Belt	I	15.18	13.73	13.92	14.2
Delta States	I	18.97	17.95	19.64	22.35
Lake States	I	12.59	11.57	11.33	12.05
Mountain Region	I	40.39	36.51	36.6	35.73

Irrigation_Corn_A1B_2040 (acre-in)					
FPR	METHOD	Reference	CGCM 2040	CSIRO 2040	MIROC 2040
Northern Plains	I	25.22	22.62	21.28	22.83
Northeast	I	13.08	11.6	13.52	14.43
Pacific States	I	48.88	47.31	50.78	47.73
Southeast	I	21.63	22.35	22.93	23.52
Southern Plains	I	37.05	32.8	31.56	37.86

Table 5: Estimate acreage-weighted water demand on irrigated soybean acres in 2040.

Irrigation_Soybeans_A1B_2040 (acre-in)					
FPR	METHOD	Reference	CGCM 2040	CSIRO 2040	MIROC 2040
Appalachia	I	12.46	11.51	13.03	14.83
Corn Belt	I	12.64	11.53	11.85	11.89
Delta States	I	13.48	12.3	12.64	14
Lake States	I	10.79	10.09	8.85	9.87
Mountain Region	I				
Northern Plains	I	22.82	20.44	18.94	19.01
Northeast	I	11.15	9.27	12.19	13.37
Pacific States	I				
Southeast	I	19.3	16.36	18.95	22.02
Southern Plains	I	24.34	22.07	21.8	30.99

Table 6: Estimated acreage-weighted water demand on irrigated wheat acres in 2040.

Irrigation_Wheat_A1B_2040 (acre-in)					
FPR	METHOD	Reference	CGCM 2040	CSIRO 2040	MIROC 2040
Appalachia	I	10.17	9.58	8.82	9.65
Corn Belt	I	8.95	7.94	8.46	7.97
Delta States	I	7.85	8.02	8.2	7.97
Lake States	I	10	9.27	8.75	9.46
Mountain Region	I	19.08	17.46	17.41	17.37
Northern Plains	I	17.19	15.51	16.69	17.99
Northeast	I	9.25	9.63	9.59	9.69
Pacific States	I	13.28	12.89	12.37	11.97
Southeast	I	8.66	8.96	8.16	8.64
Southern Plains	I	13.63	14.54	12.7	12.64

Economic Impact Results

The pattern of biophysical impacts estimated in response to changing climate conditions (illustrated above) represents an input into the REAP agricultural production model. Those impacts elicit a set of economic responses that includes regional changes in crops grown and rotations and production practices used as well as economy-wide changes in commodity prices, consumption, and availability of exports. The process of adaptation among both producers and consumers buffers the initial biophysical impact of climate change on crop yield by redistributing production among areas whose patterns of comparative advantage with respect to particular crops have changed and by shifting consumption among potential goods whose prices have changed. In this analysis we focus on the production response. While the feasibility of potential adaptive responses among producers will be dependent in large part on farmers' access to technical information, credit, and other resources, as well as on changing infrastructure and support in agriculture-related sectors, in this analysis we focus on the potential implications of resource constraints, particularly availability of irrigation water, on the impacts of climate change and the flexibility of agriculture to respond to changing conditions.

Future climate impacts on agricultural production are estimated relative to a "reference" case, which represents a hypothetical pattern of production, demand, acreage use, and exports that simulates future conditions in the absence of climate change. This research project involves development of a set of hypothetical reference scenarios for the years 2020, 2040, 2060, 2080, to correspond to the yield impact years that are being analyzed with EPIC and future climate conditions over those years. For the preliminary analysis described in this paper, however, the future reference conditions describe a future pattern of production that was developed for 2030; the final reference numbers for 2040 may differ slightly from the 2030 numbers (based on extrapolations such as a declining domestic demand for raw cotton, for instance), but the dynamics of production changes relative to those numbers due to climate change should be consistent across analyses.

Scenario 1: No irrigation constraints

In the absence of potential constraints on irrigation, agriculture in all regions is free to switch production between dryland and irrigated production at whatever scale is necessary to maximize the economic surplus associated with production nationwide under the climate conditions estimated by each GCM in 2040. National realized yields for the REAP commodities under those assumptions are shown in Table 7. These figures represent the EPIC output illustrated earlier, but calibrated and adjusted for technology change within REAP (as shown in the "reference" estimates), and then re-averaged based on the changing patterns of acreage and rotation used (as shown in the subsequent scenario estimates).

Table 7: National realized yields for REAP crops under reference and three future climate scenarios.

Crop	Region	Reference	CGCM	CCIRO	MIROC
BARLEY	US	68.19	73.78	71.46	65.37

CORN	US	184.17	196.52	200.39	199.80
COTTON	US	1.89	2.11	2.27	2.56
OATS	US	73.04	70.77	67.14	63.90
RICE	US	83.90	90.45	91.61	91.97
SILAGE	US	14.27	14.90	14.76	14.65
SORGHUM	US	55.16	52.91	61.12	63.87
SOYBEANS	US	50.33	51.93	48.11	41.34
WHEAT	US	42.48	45.91	42.37	42.57

Aggregate production of REAP commodities are estimated for each GCM and and changes in aggregate production relative to the reference scenario are shown in Table 8. Impacts of future climate conditions on aggregate production vary across crops, though corn production increases across all the climate futures explored for this time period. Soybeans and wheat production both increase under the CGCM scenario and then decline under the CSIRO and MIROC scenarios. Impacts on other small grains are mixed, with sorghum generally increasing in production and barley generally decreasing. Cotton production, whose yields respond well to warmer conditions with higher atmospheric CO_2 conditions, increases across all the climate scenarios explored.

Table 8: Change in aggregate production of REAP commodities under three future climate scenarios (relative to reference scenario).

	CGCM	CSIRO	MIROC
Corn (Mill. Bu.)	5.79%	7.21%	4.74%
Soybeans (Mill. Bu.)	3.32%	-3.46%	-18.28%
Wheat (Mill. Bu.)	9.71%	0.67%	-2.56%
Sorghum (Mill. Bu.)	-9.66%	10.79%	5.30%
Barley (Mill. Bu.)	5.79%	3.52%	-3.77%
Oats (Mill. Bu.)	-11.62%	-12.17%	-19.16%
Rice (Mill. Cwt)	10.02%	12.45%	11.51%
Cotton (Mill. Bales)	14.12%	16.37%	14.51%
Silage (Mill. Tons)	4.73%	5.44%	1.68%

The price changes associated with REAP commodities under those assumptions are shown in Table 9. The price of most commodities drops or remains stable as a result of the climate conditions forecast for 2040, with the exception of soybeans, whose price increases under all but the most benign forecast. Price drops do not always coincide with increases in production; the price of wheat, for instance, drops over all scenarios, though production is also projected to fall under two of the three climate futures. That dynamic reflects the effects of feed-switching within the livestock sector; the increasing availability of low-cost corn and sorghum shifts the demand for wheat, so that, even with a declining price, less wheat is demanded.

Table 9: Estimated prices for REAP commodities under reference and three future climate scenarios.

	Reference	CGCM	CSIRO	MIROC
Corn ($/bu)	3.65	3.21	3.07	3.24
Soybeans ($/bu)	9.30	8.99	9.72	11.92
Wheat ($/bu)	5.32	5.12	5.30	5.40
Sorghum ($/bu)	4.16	3.95	3.95	4.02
Barley ($/bu)	3.93	3.61	3.96	4.16
Oats ($/bu)	2.27	2.15	2.19	2.24
Rice ($/cwt)	16.76	16.65	16.63	16.64
Cotton ($/bale)	355.20	333.80	330.38	333.21
Silage ($/ton)	21.06	20.75	20.70	21.03

Although declining prices increase consumer welfare, they do not benefit producers unless accompanied by sufficiently large increases in yields or production (or decreases in cost) to increase returns to farming despite the declining prices. Because climate yield impacts are expected to vary regionally, so too will impacts on production and farmer returns. In this preliminary analysis, we look at gross value of production as a proxy for the potential distributional implications of changing climate conditions. Change in gross value of crop production by region (relative to the reference scenario) under the three future climate scenarios is shown in Table 10. While value of production increases across all scenarios in the Northeast and Pacific States, impacts in other regions are variable across climate futures. The Corn Belt and Northern Plains, which are ranked first and second in total value of production for REAP crops, experience declines under two of the three climate futures.

Table 10: Change in gross value of crop production by region.

Region	CGCM	CSIRO	MIROC
Northeast	8.59%	1.37%	10.27%
Lake State	-4.09%	4.06%	5.61%
Corn Belt	-2.85%	-10.03%	1.46%
Northern Plains	-4.08%	0.66%	-8.24%
Appalachia	6.96%	-3.68%	-11.99%
Southeast	11.80%	6.88%	-6.87%
Delta States	2.81%	4.65%	-8.86%
Southern Plains	-9.80%	-3.26%	7.78%
Mountain States	6.14%	-1.21%	-1.32%
Pacific States	18.81%	30.32%	28.87%
U.S. Average	-1.20%	-2.33%	-0.53%

Scenario 2: Irrigation constrained by proportional change in precipitation

For the purposes of this preliminary analysis, while the more information on water-supply shortages (from the water RPA) is being processed for use in the final analysis, a simple irrigation constraint will be explored. Under this scenario, irrigation water demand in the reference scenario is calculated and used to establish a reference level of irrigation availability by region. Irrigation water is then assumed to become more or less available by an amount proportional to the change in annual precipitation within a region. According to this assumption, regions that have not previously had irrigation cannot establish irrigated production, regardless of precipitation change, while regions that are irrigated in the reference scenario become more or less constrained depending on the direction and magnitude of change in annual precipitation.

To explore the impacts of the irrigation constraint, we focus on the results of the CSIRO climate scenario and compare the unconstrained results emerging from scenario 1 (under the CSIRO climate projection) to the results of the same climate projection with the irrigation constraint imposed. Figure 5 highlights those regions for which the irrigation constraint is binding under scenario 2.

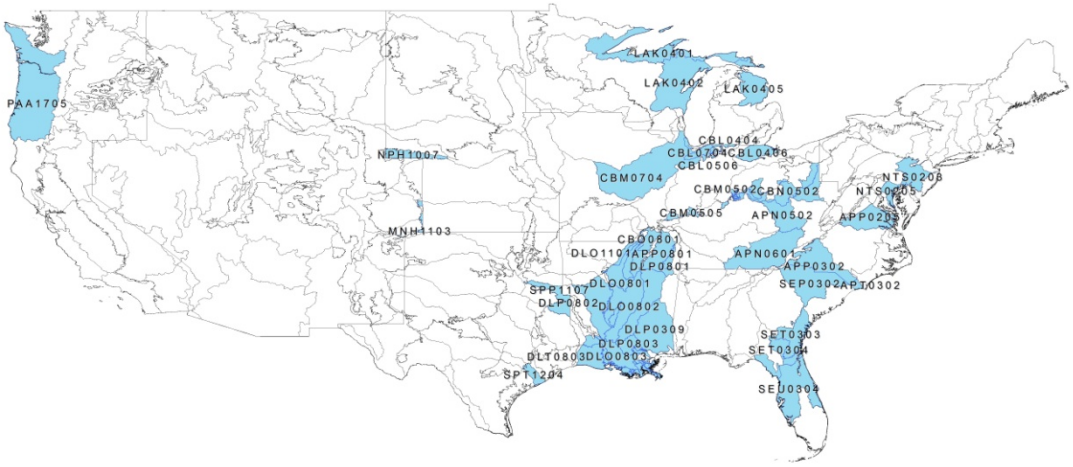


Figure 5

The implications of the irrigation constraint for realized national yield are shown in Table 11 for the major REAP crops. Table 12 then illustrates the regional differences across corn, wheat, and cotton.

Table 11: Realized national yields for the CSIRO scenario (2040) with and without the irrigation constraint.

Crop		CSIRO with no Irrigation Constraint	CSIRO with Irrigation Constraint
BARLEY	(Bu/acre)	71.46	59.75
CORN	(Bu/acre)	200.39	197.01
COTTON	(Bales/acre)	2.27	1.97
HAY	(Tons/acre)	3.05	2.98
OATS	(Bu/acre)	67.14	65.98
RICE	(Cwt/acre)	91.61	88.00
SILAGE	(Tons/acre)	14.76	15.18
SORGHUM	(Bu/acre)	61.12	59.81
SOYBEANS	(Bu/acre)	48.11	47.90
WHEAT	(Bu/acre)	42.37	40.98

Table 12: Realized national yields, broken down by region, for the CSIRO scenario (2040) with and without the irrigation constraint.

	Corn (Bu/acre)		Wheat (Bu/acre)		Cotton (Bales/acre)	
Region	No Irrigation Constraint	With Irrigation Constraint	No Irrigation Constraint	With Irrigation Constraint	No Irrigation Constraint	With Irrigation Constraint
Appalachia	196.66	195.88	52.79	52.70	2.62	2.62
Corn Belt	211.52	210.80	50.22	50.14	2.70	2.67
Delta States	265.93	251.66	37.23	39.19	3.34	3.27
Lake States	201.89	200.92	56.94	56.89	2.46	2.47
Mountain Region	192.23	114.03	38.55	33.95	***	***
Northern Plains	184.63	180.81	47.63	46.99	***	***
Northeast	169.99	167.35	44.23	44.19	***	***
Pacific States	217.81	172.26	49.71	43.70	2.84	2.03
Southeast	171.80	167.63	38.27	38.37	3.15	3.14
Southern Plains	151.31	147.05	24.01	23.66	1.50	1.24
US	200.39	197.01	42.37	40.98	2.27	1.97

The realized national yields of some crops (e.g. barley and cotton) are significantly impacted by potential constraints on irrigation water availability arising from changing precipitation patterns. The highest-valued REAP crops (corn, soybeans, and wheat) are less substantially affected at the national level, but are nevertheless significantly impacted within certain regions that are not their

primary production areas. Yields are particularly impacted in areas that are already irrigation constrained—including the Mountain and Pacific regions. The realized yield for corn, for instance, drops in the Mountain region from 192.23 bu/acre to 114.03 bu/acre when irrigation is constrained. Interestingly, the overall irrigation constraint is sometimes not binding in those regions (see Figure 5); subsequent analysis will explore this finding, but it suggests that when irrigation is constrained in those regions, water is reallocated away from the crops shown. Silage yields, for instance, increase in the Mountain region when an irrigation constraint is imposed, suggesting that it gains a comparative advantage of production relative to corn when water is scarce.

The impacts of changing water availability on the price of REAP crops is shown in Table 13. With the exception of sorghum, all crops prices increase (or remain the same). Despite the decline in national average yield, sorghum is the only crop whose aggregate production increases under the water-constrained scenario, suggesting that despite losses in yield, it gains a comparative production advantage when water is scarce in at least a portion of its production range. Cotton's price increase is small given the size of the national average yield drop; despite a 13% declin in national average yield, the acreage allocated to cotton increases nationally from 12.2 million acres to 13.8 million acres, and cotton's aggregate production falls by only 2%.

Table 13: Crop prices under CSIRO (2040) scenario with and without limits on available irrigation water.

Crop Price	CSIRO with no Irrigation Constraint	CSIRO with Irrigation Constraint
CORN ($/bu)	3.07	3.10
SORGHUM ($/bu)	3.95	3.93
BARLEY ($/bu)	3.96	4.10
OATS ($/bu)	2.19	2.19
WHEAT ($/bu)	5.30	5.30
RICE ($/cwt)	16.63	16.92
SOYBEANS ($/bu)	9.72	9.76
COTTON ($/bale)	330.38	333.72
SILAGE ($/ton)	20.70	22.37

The changes in regional gross value of crop production arising from constraints on the availability of irrigation water are shown in Table 14. Under the CSIRO climate scenario for the analysis year 2040, the change in national gross value of production is a slight decline of 1%, but the decline in historically irrigation-constrained regions—the Mountain states and the Pacific states—is as high as 38.47%. In the Mountain states, lost value of production for cotton, hay, and silage are responsible for 40%, 25% and 24% of the total loss, respectively. In the Pacific region, rice, silage , corn, and hay account for 70%, 12%, 11% and 11% of the total loss, respectively. Subsequent analysis will explore and troubleshoot the reasons that those areas, which are

severely impacted by imposition of the irrigation constraint, nevertheless fail to exhaust their available irrigation water (thereby creating a binding irrigation constraint—Figure 5). Potential explanations include increasing costs of irrigation or other impacts on relative returns between dryland and irrigated production in those regions as well as simply changes in production acreage overall.

Table 14: Change in gross value of crop production by region when limits to available irrigation water are imposed.

Region	Change in Gross Value of Production from Crops
Appalachia	1.51%
Corn Belt	1.01%
Delta States	-2.29%
Lake States	0.90%
Mountain Region	-20.71%
Northern Plains	0.92%
Northeast	1.93%
Pacific States	-38.47%
Southeast	0.20%
Southern Plains	2.21%
US	-1.14%

Conclusions

The results of this preliminary analysis suggest that limits on the availability of irrigation water may play an important role in constraining the ability of certain regions to respond to changing climate conditions, even in the near- to mid- term. The current analysis is being expanded to include additional future climate scenarios, improved estimates of water-supply shortages under the study scenarios based on work done by the U.S. Forest Service and Colorado State University in support of the 2010 Water RPA (Foti et al, 2012), and longer term analyses to address potential conditions for the years 2060 and 2080. As this research is ongoing, figures reported in this paper are preliminary numbers and should not be cited.

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