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Is Current Irrigation Sustainable in the United States? An Integrated Assessment of Climate Change Impact on Water Resources and Irrigated Crop Yields

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At the heart of much of the program's work lies MIT's Integrated Global System Model. Through this integrated model, the program seeks to discover new interactions among natural and human climate system components; objectively assess uncertainty in economic and climate projections; critically and quantitatively analyze environmental management and policy proposals; understand complex connections among the many forces that will shape our future; and improve methods to model, monitor and verify greenhouse gas emissions and climatic impacts.

This reprint is intended to communicate research results and improve public understanding of global environment and energy challenges, thereby contributing to informed debate about climate change and the economic and social implications of policy alternatives.

—Ronald G. Prinn and John M. Reilly,
Joint Program Co-Directors

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Is Current Irrigation Sustainable in the United States? An Integrated Assessment of Climate Change Impact on Water Resources and Irrigated Crop Yields

Élodie Blanc[1,2], Justin Caron[3], Charles Fant[1] and Erwan Monier[1]

Abstract: While the impact of climate change on crop yields has been extensively studied, the quantification of water shortages on irrigated crop yields has been regarded as more challenging due to the complexity of the water resources management system. To investigate this issue, we integrate a crop yield reduction module and a water resources model into the MIT Integrated Global System Modeling (IGSM) framework, an integrated assessment model that links a model of the global economy to an Earth system model. While accounting for uncertainty in climate change, we assess the effects of climate and socio-economic changes on the competition for water resources between industrial, energy, domestic and irrigation; the implications for water availability for irrigation; and the subsequent impacts on crop yields in the US by 2050. We find that climate and socio-economic changes will increase water shortages and strongly reduce irrigated crop yields in specific regions (mostly in the Southwest), or for specific crops (i.e. cotton and forage). While the most affected regions are usually not major crop growers, the heterogeneous response of crop yield to global change and water stress suggests that some level of adaptation can be expected, such as the relocation of cropland area to regions where irrigation is more sustainable. Finally, GHG mitigation has the potential to alleviate the effect of water stress on irrigated crop yields—enough to offset the reduced CO_2 fertilization effect compared to an unconstrained GHG emission scenario.

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1. Introduction

Growing populations and dietary changes will require increases in food production. Irrigated land, which currently amounts to only 20% of total cultivated land, supplies 40% of global food production thanks to crop yields that are on average 2.7 times larger than their rainfed counterparts (UNESCO, 2012). Expanding irrigation can contribute to increasing global production, but can be costly and have serious environmental impacts (Reilly and Schimmelpfennig, 1999). The main constraint, however, is freshwater availability. Food production is the largest user of freshwater, with 70% of global withdrawal (UNESCO, 2012), and many areas are already water stressed (Wada *et al.*, 2011). Climate change is feared to exert further pressure on irrigation capabilities by altering water resources and water uses. More specifically, it is expected to affect water availability by altering the geographic distribution of water resources (Arnell, 1999, 2004) as well as its temporal distribution (Middelkoop *et al.*, 2001). It is also expected to impact irrigation water requirements (Fischer *et al.*, 2007; Konzmann *et al.*, 2013; Wada *et al.*, 2013). Under those conditions, are current irrigation patterns sustainable? Which regions will be most affected? What will be the consequences of water shortages on irrigated crop production?

While the impact of climate change on crops has been extensively studied, both at the regional level (e.g. Tao *et al.*, 2012; Blanc, 2012; Lobell *et al.*, 2011; Auffhammer *et al.*, 2012) and at the global level (e.g. Deryng *et al.*, 2014; Teixeira *et al.*, 2013; Arnell *et al.*, 2013), understanding the effect of climate change on irrigated crop yields is more challenging due to the complexity of the system to consider. Biophysical crop models are specifically designed to estimate crop yields under different climatic conditions, but they usually only consider two irrigation scenarios: no irrigation (rainfed yield) or full irrigation with no restriction on irrigation water availability (Rosenzweig *et al.*, 2014). Water resource system models account for competing water uses but are not capable of estimating the effect of the resulting potential water limitations on crop yields. In the most extensive assessment to date, Elliott *et al.* (2014) assess the impact of future irrigation water availability on crop productivity at the global level using an ensemble of water supply and demand projections from 5 global climate models, 10 global hydrological models and 6 global gridded crop models—thus accounting for the uncertainty in climate change, hydrology and crop modeling. This study, however, only considers a single GHG concentration scenario and does not simulate the possible benefits of abatement policies. Also, it considers water use and resources without spatial or temporal optimization of water allocation. The lack of optimization is a crude assumption that is not representative of current water management. Focusing on the US, Hejazi *et al.* (2015) do include a river routing and reservoir operations models in an integrated assessment framework, but only consider two simulations from a regional climate model and thus do not account for any uncertainty in climate change other than the GHG emissions scenario.

In this US-focused study, we evaluate the direct and indirect impacts of climate change and socio-economic stressors on water resources and crop production using a large ensemble of scenarios. To this end, we use the Water Resource System for the United States (WRS-US, Blanc *et al.*, 2014) within the MIT Integrated Global System Model-Community Atmosphere Model (IGSM-CAM) modeling framework (Monier *et al.*, 2013). We extend the WRS-US model to include a yield impact module that estimates the effect of irrigation water shortage on crop yields. This framework allows for a spatially detailed analysis by covering 99 river basins in the US. Our study is driven by a large ensemble of 45 integrated economic and climate scenarios developed for the US Environmental Protection Agency's Climate Change Impacts and Risk Analysis (CIRA) project (Waldhoff *et al.*, 2014), which includes three different GHG mitigation scenarios, different global climate response and initial conditions to account for the large uncertainty in climate change projections.

While our modeling framework allows us to track the impact of climate change and socio-economic stressors on irrigated crop yields, we choose to keep irrigated areas fixed. We project changes in crop production that will be caused by climate stress and increases in water demand by other sectors such as energy production and municipal use, but in the absence of adaptation in the agricultural sector. This allows us to identify regions where we can expect future transitions in irrigated agriculture—either to different crops or rainfed crops, or where agricultural production will decrease or disappear.

2. Methods

2.1 Integrated assessment framework

In the IGSM-WRS-US framework (Blanc *et al.*, 2014), which forms the basis of the present analysis, the interaction of water resources and anthropogenic water requirements is analyzed using an integrated set of economic and Earth system models. A schematic of the framework is provided in **Figure 1** with input from the IGSM-CAM on the left hand side and the water resources system on the right hand side.

Within the integrated assessment framework, the global economy is represented by the Emissions Prediction and Policy Analysis (EPPA) model (Paltsev *et al.*, 2005).

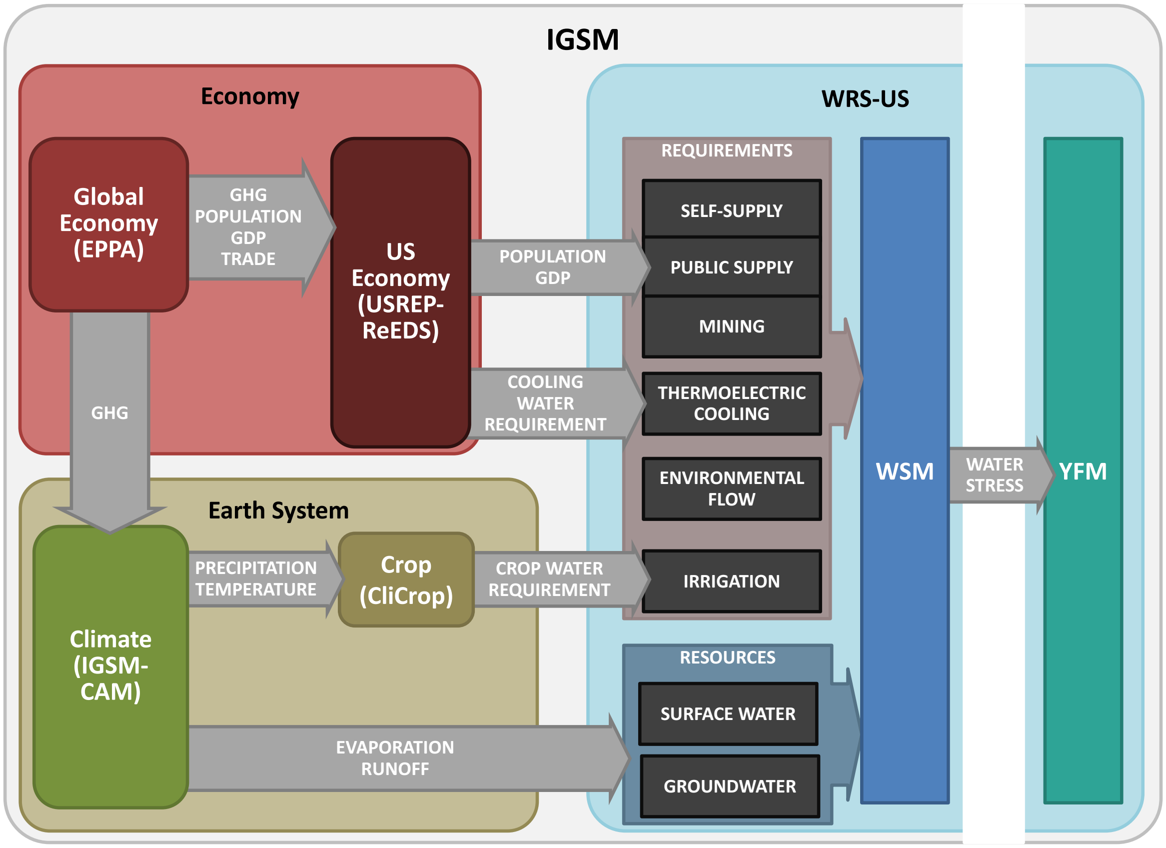

Figure 1. Schematic of the IGSM-WRS-US framework illustrating the connections between the different components of the IGSM framework and the WRS-US components

This general equilibrium model, in addition to providing projections of global GHG emissions contributing to the simulated changes in climate, provides projections of economic output with and without global climate change mitigation policies.

US national-level economic projections from EPPA are used to provide boundary conditions to the US Regional Energy Policy (USREP) model (Rausch *et al.*, 2010), a general equilibrium model of the US economy with sub-national detail. USREP is used to provide projections of economic activity in different regions of the US (including GDP, population and mining output), which are then used to determine water requirements, as detailed below. The USREP model is also coupled with the National Renewable Energy Lab's (NREL) Regional Energy Deployment System (ReEDS) model (Rausch and Mowers, 2012). ReEDS (Short *et al.*, 2009) is a long-term capacity-expansion model of electricity generation. It provides highly resolved (in terms of geographical and technological detail) projections of electricity production and the corresponding withdrawal and consumption of water for thermal power generation cooling.

The Earth system component of the integrated assessment framework includes land surface, atmospheric and ocean processes, and provides the required variables to estimate crop water needs and geophysical water availability. The right hand side of Figure 1 describes the water system components of the framework, the WRS-US model version 2.0 (Blanc *et al.*, 2014; Blanc, 2015). WRS-US simulates water resources and requirements for 99 river basins following the Assessment Sub-Regions (ASR) delineation set out by the US Water Resources Council (USWRC, 1978). A spatial representation of the ASR structure is provided in the Appendix (see **Figure A1** and **Table A1**).

The water resources considered in WRS-US are composed of runoff (estimated using IGSM-CAM) and groundwater resources. Groundwater resources are estimated to remain constant at 2005 levels unless groundwater extraction is greater than groundwater recharge. To estimate groundwater recharge, we use USGS (2003)'s 1-kilometer resolution dataset of mean annual natural groundwater recharge. We also account for water recharge from reservoirs using surface storage recharge shares from IFPRI's IWSM model.

Water requirements are composed of anthropogenic and environmental requirements. Anthropogenic water requirements are estimated for five sectors: irrigation, thermoelectric cooling (estimated directly by the ReEDS model), public supply, self-supply (mostly industrial) and the mining sector.[1] Changes in requirements from the last three sectors are estimated econometrically using water data collected at the county level by USGS (2011): public supply withdrawals are estimated as a function of population and GDP per capita projections from USREP; self-supply and mining withdrawals are determined by sectoral value-added projections from USREP.

We estimate water withdrawals for irrigation using the CliCrop model (Fant *et al.*, 2012), which simulates daily crop water requirements to maximize crop yields. CliCrop is driven by daily accumulated precipitation, daily mean temperature and daily temperature range from the IGSM-CAM. The representation of the crop phenology and irrigation requirements are based on the methodology used in the Food and Agriculture Organization's (FAO) CropWat model (Allen *et al.*, 1998) and on the Soil and Water Assessment Tool (SWAT, Neitsch *et al.*, 2005) for soil hydrology. The effect of increased atmospheric CO_2 concentrations on crop water use is accounted for by (i) modeling stomatal closure in CliCrop by adjusting crop evapotranspiration demand (Allen *et al.*, 1998) and crop growing stage durations (Wahaj *et al.*, 2007); and (ii) adjusting water demand depending on biomass development using estimates from Sue Wing *et al.* (2015). These crop water requirements account for management practices as well as conveyance and field efficiency. These efficiencies are assumed to remain constant over time to be consistent with our objective of estimating the effect of climate change without adaptation in the irrigation sector. Environmental water requirements are representative of policies protecting water ecosystems through the regulation of water levels and flows. See Fant *et al.* (2012) and Blanc *et al.* (2014) for further details regarding calculations of irrigation requirements.

The estimated water resources and requirements are inputs to a Water System Management (WSM) module. For each ASR, the model allocates available water among users, each month, while minimizing annual water deficits (i.e., water requirements that are not met) and smoothing deficit across months. The allocation of water is solved simultaneously for all months of each year, and for all ASRs while respecting upstream/downstream relationships. This solving structure captures cooperation across basins by optimizing water allocation depending on water requirements and resources across all basins within the same water-shed (Blanc, 2015).

Irrigation is a residual user and water is allocated to this sector once the requirements of all the other sectors have been met. Water deficit is represented by the water Supply-Requirement Ratio (SRR), which is calculated monthly as the ratio of total water supplied over total water required for all sectors (including irrigation). This water stress indicator represents physical constraints on anthropogenic water use. Stress to the irrigation sector in particular is represented by the SRR for irrigation, *IR_SRR*, calculated monthly as the ratio of water supplied for irrigation over water required by this sector. This stress indicator is used to calculate irrigated yield reductions due to lack of irrigation caused by water shortages.

2.2 Yield factor module

As shown in the right hand part of Figure 1, the WRS-US modeling framework was extended with a new Yield Factor Module (YFM) in order to estimate the effect of irrigation water shortages on crop yields. Following the FAO's CropWat model (Allen *et al.*, 1998), the 'relative yield reduction is related to the corresponding relative reduction in evapotranspiration'. The yield factor, YF, is then calculated for each crop and growing season, gsc, as:

$$YF_{crop,gsc} = \left(\frac{Ya_{crop}}{Yx_{crop}}\right) = 1 - Ky_{crop,gsc}\left(1 - \frac{ETa_{crop}}{ETx_{crop}}\right) \quad (1)$$

where the ratio of actual yield, Ya, and maximum yields, Yx, representing the yield factor are a function of actual and maximum crop evapotranspiration (ETa and ETx, respectively). Ky is a yield response factor and represents the sensitivity of crop yields to a reduction in evapotranspiration due to water shortage. Values for this parameter are also sourced from FAO's CropWat model and reported in Appendix (**Table A2**). For crops very sensitive to water shortage, Ky >1 and the yield reduction is proportionally larger than the reduction in water use. Ky <1 applies to crops that are more tolerant to water deficits and for which yields decrease less than proportionally to water use reduction. Crop water requirements depend on the crop growing stage (Brouwer *et al.*, 1989). Out of the four stages usually considered, the third 'mid-season' stage, corresponding to the flowering and yield formation, is the period of greatest water need. Therefore, a water shortage within this season will have the largest detrimental effect on crop yields. We therefore use values of Ky which are specific to each of the four growing stages, gsc. The values are consistent with those employed by the CliCrop model that provides growing stages and water requirements to the YFM.

When considering water stress due to lack of water availability for irrigation at the river basin level (asr), the yield factor, YF, is calculated annually as:

$$YF_{crop,asr,year} = \frac{\sum_{cnt}\left(\prod_{gsc=1,\dots,4}\left(1 - Ky_{crop,gsc}\left(1 - \frac{ETaS_{crop,cnt,gsc}}{ETx_{crop,cnt,gsc}}\right)\right) IRarea_{crop,cnt}\right)}{IRarea_{crop,asr}} \quad (2)$$

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[1] See Blanc *et al.* (2014) for a detailed description of each sector.

where *IRarea* at the county level, *cnt*, is the crop-specific irrigated area (USDA, 2003; USGS, 2011); see Blanc *et al.* (2014), Blanc (2015) for further details. Crop evapotranspiration under water stress, *ETaS*, is calculated using the SRR for irrigation, *IR_SRR*, estimated by WSM:

$$ETaS_{crop,cnt,gsc} = ETa_{crop,cnt,gsc} + (ETx_{crop,cnt,gsc} - ETa_{crop,cnt,gsc}) * IR\_SRR_{cnt,gsc} \tag{3}$$

where *IR_SRR* is calculated for each growing stage, using the monthly *IR_SRR* estimated by WSM prorated by the share of each month within each growing stage. The term $(ETx_{crop,cnt,gsc} - ETa_{crop,cnt,gsc})$ represents crop irrigation requirements at the root to obtain maximum yield. An *IR_SRR*=1 would imply that all the water required for irrigation is available. On the other hand, an *IR_SRR*=0 means that none of the water necessary for irrigation is available and therefore irrigated crop yields are similar to rainfed crop yields. Each of the various crops considered are affected equally by a shortage of water for irrigation, i.e. no specific crop has priority access to water over another crop.

2.3 Scenarios

Water uses and resources are projected out to 2050 using a large ensemble of integrated economic and climate simulations from the IGSM-CAM modeling framework (Monier *et al.*, 2013) prepared for the EPA's CIRA project (Waldhoff *et al.*, 2015). This ensemble comprises three consistent socioeconomic and GHG emissions scenarios: a reference scenario (REF) with unconstrained emissions (similar to the Representative Concentration Pathway RCP8.5 (van Vuuren *et al.*, 2011)), and two greenhouse gas mitigation scenarios—POL4.5, a moderate mitigation scenario consistent with reaching 4.5 W m−2 by 2100 (similar to RCP4.5), and POL3.7, a more ambitious mitigation scenario consistent with reaching 3.7 W m−2, corresponding to an intermediate stabilization scenario between RCP4.5 and RCP2.6.[2] For each emission scenario, the IGSM-CAM is run with three different values of climate sensitivity (CS=2.0, 3.0 and 4.5°C) obtained via radiative cloud adjustment.[3] For each set of emissions scenarios and climate sensitivity, a five-member ensemble is created with a different representation of natural variability through initial condition perturbation.[4] Contrary to Elliott *et al.* (2014), this ensemble is derived using a single climate model. However, Monier *et al.* (2016) shows that the range of agro-climate projections from the IGSM-CAM ensemble is similar to that of the CMIP5 multi-model ensemble. That is because the IGSM-CAM ensemble samples key sources of uncertainty, namely the emissions scenarios, the global climate response (using different values of climate sensitivity) and the natural variability.

In this study, we mainly focus on simulations with a climate sensitivity of 3.0˚C (CS3.0) to identify the benefits of GHG mitigation. We present results from the five-member ensemble mean to filter out noise associated with natural variability and thus extract the anthropogenic signal. Nonetheless, we identify the range of projections associated with uncertainty in natural variability. We also provide a brief analysis of the impact of the uncertainty in climate sensitivity for the unconstrained emissions scenario.

3. Results

3.1 Water resources and requirements projections

To determine future water allocation across sectors and subsequent stress, the WRS-US model considers projections of water resources and water uses. Runoff projected by the IGSM-CAM is bias-corrected to better match the observations for the present-day period. **Figure 2** provides the range of projected changes in total natural runoff by mid-century (not including inflows from upstream basins) for each emissions scenario. In this figure and in the remainder of the text, we will refer to the present as the 2005–2014 period and as the future as the 2041–2050 mid-century period. A time series for the full ensemble of simulations is provided in Appendix (**Figure A2**). The ensemble-mean total runoff is projected to increase on average for all emissions scenarios, but individual simulations can project decreases. There is, thus, evidence of a large role for natural variability to affect precipitation trends, especially by mid-century—a finding in agreement with the analysis of Hawkins and Sutton (2011), Deser *et al.* (2012) and Monier *et al.* (2015).

Water requirements for the thermoelectric cooling, public supply, self-supply and mining sectors are simulated using predictions of changes in population, total GDP and value added of the mining sector. These inputs are predicted by the USREP model under the three GHG emission scenarios. Population is projected to increase steadily over the 2005–2050 period with no difference between scenarios, but with considerable differences between regions of the US. As a result, total non-irrigation water requirements over the US are projected to increase by between 135% and 140% (see **Figure A3** in the Appendix). Irrigation water requirements projected using the CliCrop model are driven indirectly through the effect of the different policy scenarios on CO_2 and cli-

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[2] More details on the emissions scenarios and their economic implications are given in Paltsev *et al.* (2015).

[3] See Sokolov and Monier (2012).

[4] More details on the design of the climate ensemble and the analysis of the projections of temperature and precipitation changes over the United States can be found in Monier *et al.* (2015).

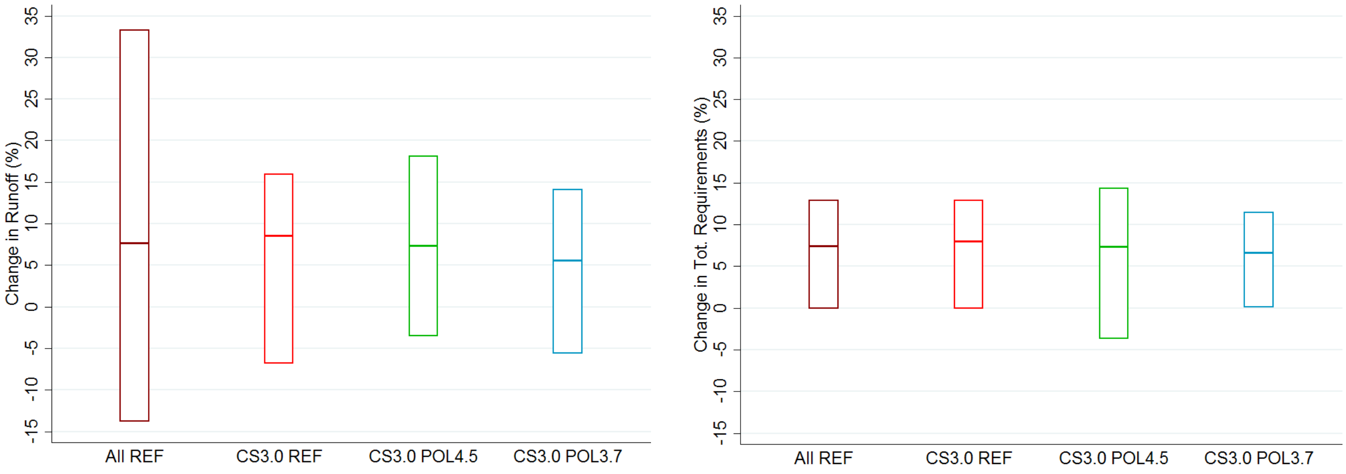


Figure 2. Range of changes in total US runoff and water requirements (calculated as the sum over all ASRs). Change in the future (2041–2050) relative to the present (2005–2010). The range is computed over the five-member ensemble with different representation of natural variability for the CS3.0 REF, CS3.0 POL4.5 and CS3.0 POL3.7, and over the 15-member ensemble that include three different values of climate sensitivity and 5 different representation of natural variability for "All REF". The horizontal line represents the mean over the ensemble considered in each case.

mate. In total over the US, these water requirements are projected to decrease by between 6% and 24% (see Figure A3 in the Appendix). Combining climate-driven and socioeconomic-driven changes, as shown in the second part of Figure 2, results in a projected increase in total US water requirements under all emissions scenarios. Once again, the magnitude of the projection varies strongly from simulation to simulation, highlighting the role of uncertainty in climate change projections, especially the role natural climate variability.

While the GHG emission abatement policies POL3.7 and POL4.5 slightly reduce the increase in total runoff over the US by curtailing the increase in precipitation, they also have a lessening effect on water requirements—due in part to a decrease in thermo-electric power generation and associated cooling water demand—with the smallest increase expected under the most stringent emissions scenario POL3.7 (when considering the ensemble mean).

These changes in water availability and water requirements are not evenly spread across the US. As shown in the top right panel of **Figure 3**, increases in runoff are projected under the reference scenario over most of the US, except in the Western parts of the country where runoff in the present period is large in the North but small in the South. GHG emission abatement policies, and especially POL4.5, are expected to lessen the decrease in runoff in the South West.

Figure 4, on the other hand, reveals large increases in projected total water requirements under the reference scenario in the Northeast of the US, where present requirements are low, and some reductions in the Central Plains and Northwest. Under the GHG emissions abatement policies, reductions in the Central Plains and Northwest are expected to be smaller. In the Southwest, the signals are mixed and differ greatly from basin to basin.

3.2 Water stress

Based on the sectoral water requirements and water resources estimates presented above, WRS-US solves for the water allocation equilibrium by minimizing water deficit (i.e. SRR). To estimate the impact of water stress on irrigation, the residual water user, we calculate the SRR for irrigation for every month, *IR_SRR*. Annual values of *IR_SRR* are calculated as the average *IR_SRR* over each calendar year weighted by irrigation requirements. As shown in the top left map of **Figure 5**, many basins in the Central Plains and the West (particularly the Southwest) currently (2005–2014) experience water shortages for irrigation (as indicated by *IR_SRR* values below 1), while basins in the East are unaffected. The top right part of the figure indicates that under the reference scenario, future (2041–2050) water stress for irrigation will worsen in the West (i.e. decrease in *IR_SRR*) due to a decrease in runoff and increase in requirements, while in the Central Plains an increase in runoff and decrease in requirements are projected. Eastern basins will continue to be unaffected by mid-century.

Emissions abatement scenarios provide some relief for most basins relative to the reference scenario, including in the Mountain area (see positive values in the lower graphs of the figure) and in California's central valley under the most stringent policy (CS3.0 POL3.7). In some basins in the Central Plains, e.g. Arkansas-Cimarron, where higher increases in precipitation are predicted than in the reference scenario, mitigation policies have the op-

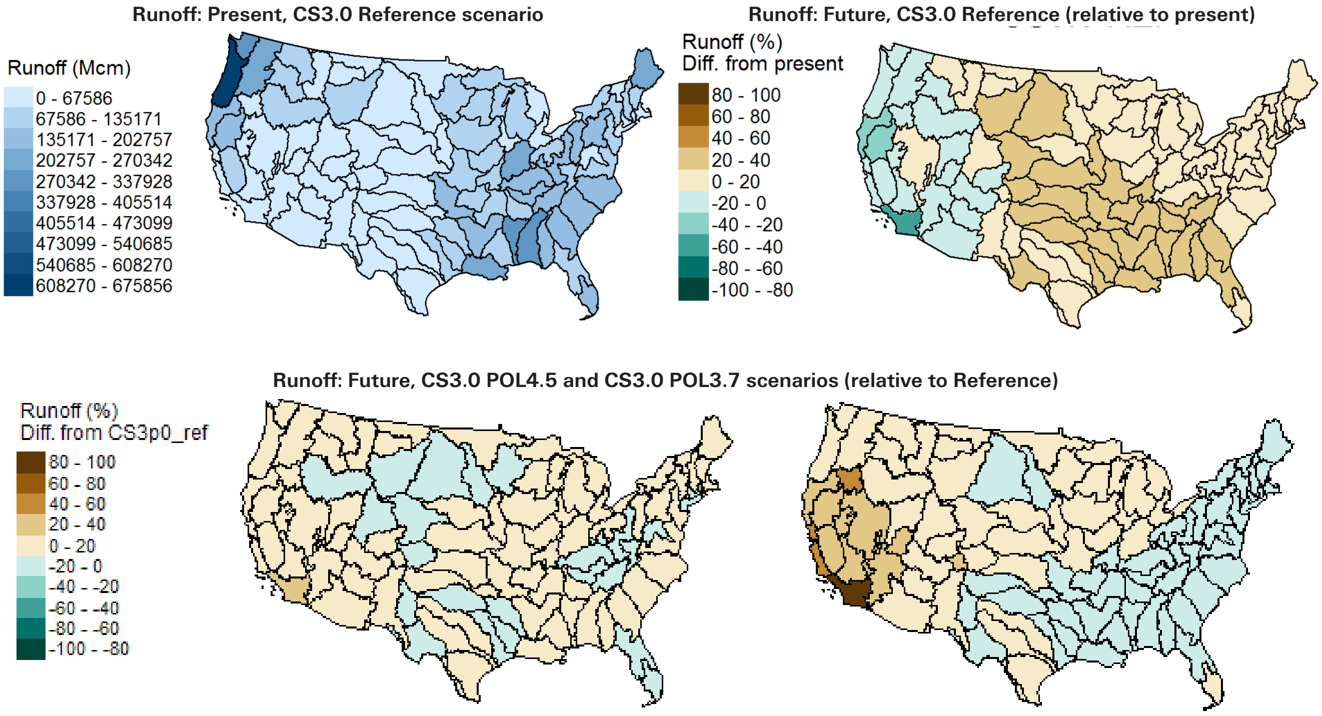


Figure 3. Annual runoff in levels for scenario CS3.0 REF in the present (2005–2014) and in percentage change for the future (2041–2050) relative to the present for the CS3.0 REF, CS3.0 POL4.5 and CS3.0 POL3.7 scenarios.

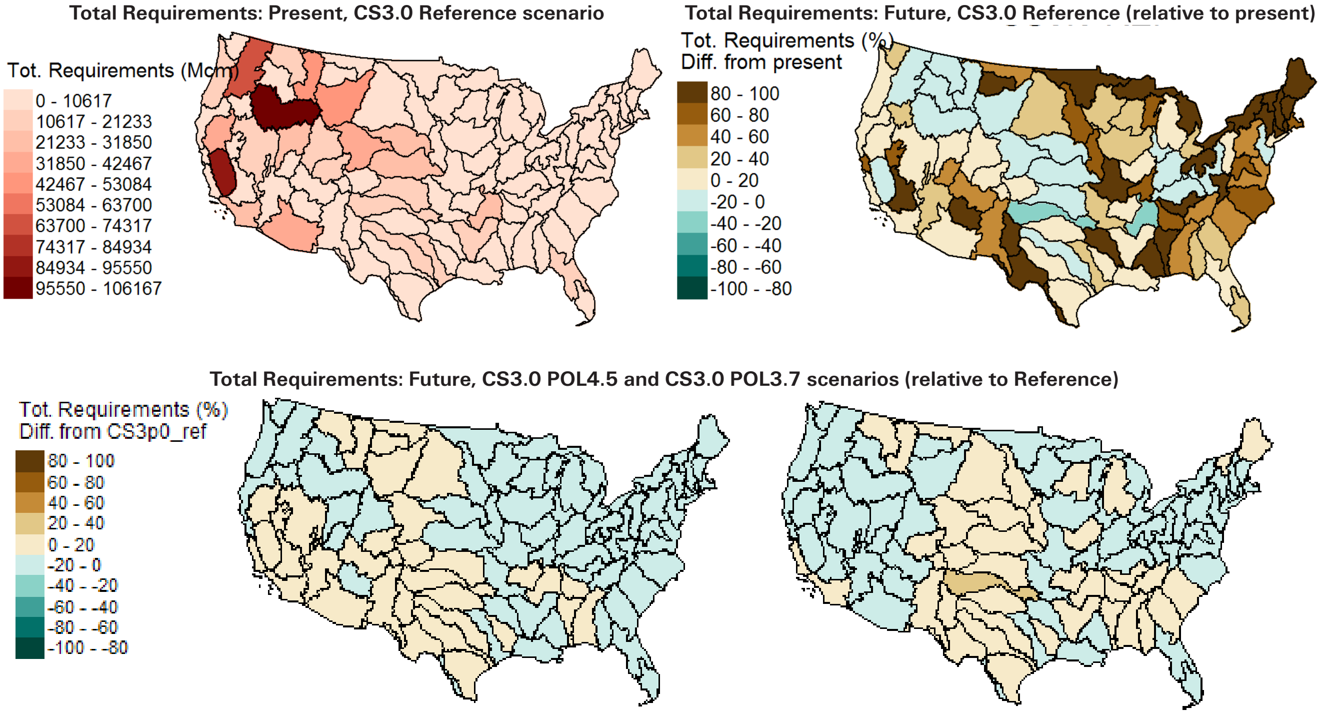


Figure 4. Annual water requirements in levels for scenario CS3.0 REF in the present (2005–2014) and in percentage change for the future (2041–2050) relative to the present for the CS3.0 REF, CS3.0 POL4.5 and CS3.0 POL3.7 scenarios.

posite effect. Note that the results presented in these maps are averaged across representation of natural variability for each scenario so that the anthropogenic signal can be extracted from the noise of internal climate variability.

To account for uncertainties in climate modeling, **Figure 6** plots the kernel density distribution (across ASRs) of the absolute changes in SRR for irrigation in 2041–2050 relative to the present (2005–2010) for the 35 ASRs affected by water stress. Thick lines represent the ensemble mean impact for each climate policy scenario and, in order to assess the uncertainty in projections, thin lines represent the five simulations with different representations of nat-

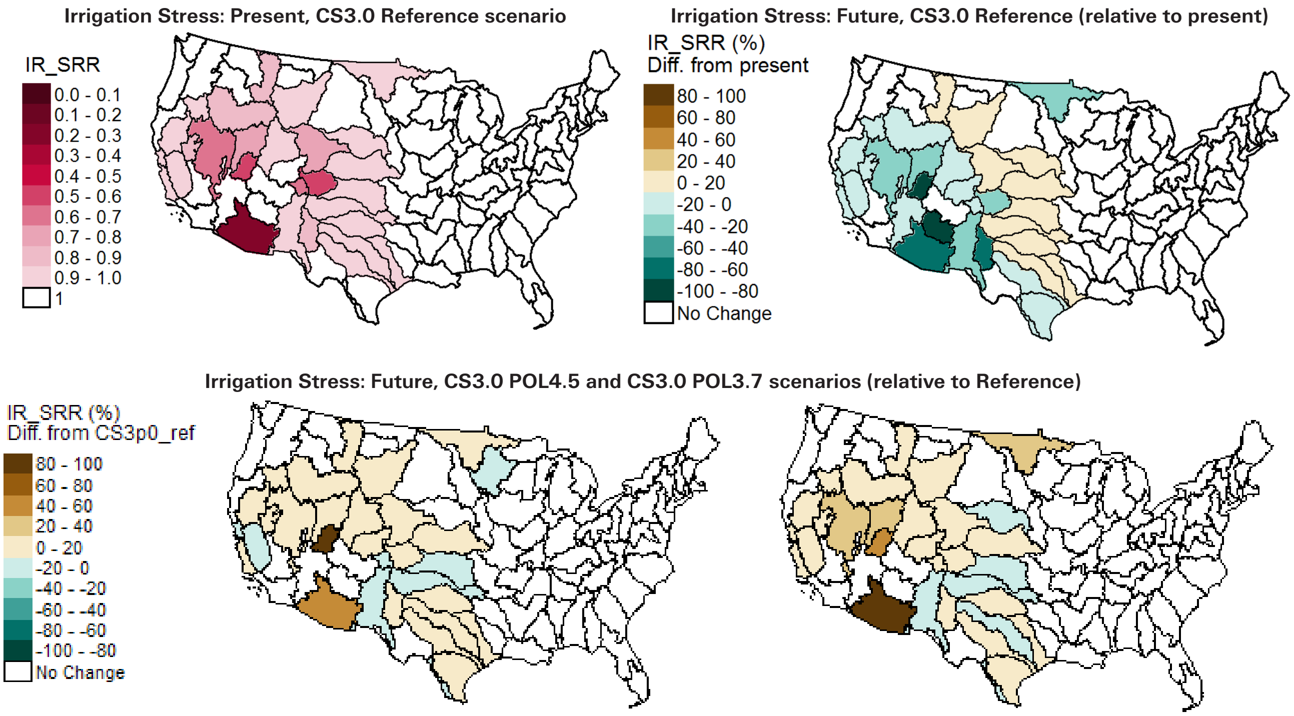


Figure 5. Annual water stress for irrigation (*IR_SRR*) in levels for scenario CS3.0 REF in the present (2005–2014) and in percentage change for the future (2041–2050) relative to the present for the CS3.0 REF, CS3.0 POL4.5 and CS3.0 POL3.7 scenarios.

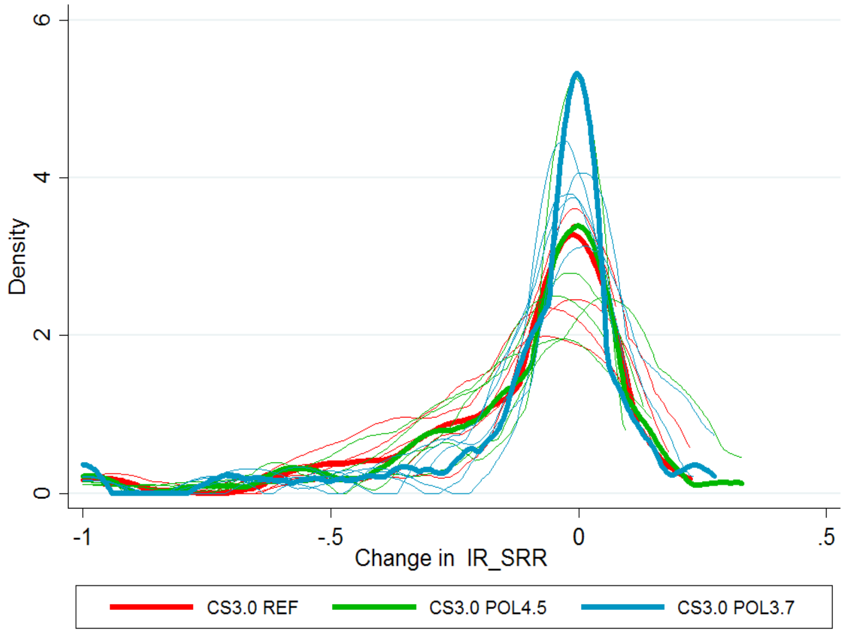


Figure 6. Kernel density distribution of absolute changes in water stress for irrigation (*IR_SRR*) for ASRs affected by water stress for the period 2041–2050 compared to the present (2005–2014). Thin lines represent individual simulations for each natural variability case. Thick lines show the ensemble mean of these simulations for each emissions scenario.

ural variability for each scenario. The graph shows that although the distribution of changes in irrigation water stress relative to the present differs between representations of natural variability for each scenario, in each case the modal ASR has a relatively modest negative impact (i.e. an SSR for irrigation smaller than—but close to—zero). The graph does reveal a relatively long left-tail in impacts: a small number of basins are much more severely affected than average. This varies across scenarios and the overall distributions are flatter and more skewed to the left for the reference and intermediate mitigation scenario (CS3.0 POL4.5) than for the CS3.0 POL3.7 scenario, in which case a smaller number of river basins are expected to experience large changes in irrigation availability. These results highlight the necessity of a very stringent mitigation policy to substantially change the distribution of impacts on irrigation water stress.

3.3 Irrigated yields

Irrigation water shortages, as represented by the *IR_SRR* index plotted in Figure 6, entail reductions in crop yields by limiting transpiration and therefore biomass growth. The timing and severity of water deficit is very important since, as detailed in Section 2.2, plants are particularly vulnerable to water stress during specific stages of the growing season. Using the YFM module, we estimate the impact of monthly water stress on irrigated crop yields. The spatial distribution of results for each crop are presented in **Figure 7 to 12**. The figures' first panels present current growing conditions in terms of irrigated area. The middle panels display yield reduction factors (*IR_SRR*) for each basin for the present (2005–2041) and the change in *IR_SRR* for the future (2041–2050) relative to the present for the reference scenario. Maps in the bottom panel represent future changes in *IR_SRR* for each mitigation policy relative to the reference scenario (in other words, the benefits of greenhouse gas mitigation). Results are shown for the ensemble mean in order to obtain robust estimates of the anthropogenic signal and filter out the noise from natural variability. Yield reductions due to a lack of irrigation are estimated to be very severe in some basins. For instance, in the present period, due to water scarcity irrigated maize yields are only 40% of potential fully irrigated yields in the Sevier Lake basin in Utah (see Table A1 and Figure A1 in Appendix for the geo-localization of basins). Under the CS3.0 REF scenario, future irrigated maize yields in this basin are expected to be on average less than 10% of potential irrigated yields due to water deficits, indicating that the lack of water availability decreases potential yield by 90% (relative to a perfectly irrigated situation). However, maize is only marginally cultivated in this basin, thus this result has few implications for total US irrigated maize production. For the Niobrara-Platte-Loup and Kansas basins, covering most of Nebraska and the northern part of Kansas—where irrigated maize areas are the largest—irrigated yields are expected to increase and represent respectively more than 90 and 70% of the potential irrigated yields. For cotton, however, the Gila basin situated in southern Arizona—which has large irrigated areas and is already severely affected by water scarcity for irrigation in the present period—is expected to be further affected, with a yield factor dropping to less than 10% by mid-century under the CS3.0 REF scenario. Irrigated areas of forage are widely spread across the US with a higher concentration in the Northwest, where basins in the Great Basin region are expected to be greatly impacted by water shortages. Irrigated sorghum and soybean are located mainly in the Southern Plains where moderate effects of water stress are projected. Similar projections are made for wheat, which is also irrigated in the Southern Plains, but also in the Pacific Northwest, where water stress is also expected to be relatively mild.

The lower panels of Figures 7 to 12 show that the differences between the reference scenario and the policy scenarios vary from basin to basin, largely due to differences in climate change patterns between scenarios. Overall, the simulations under the two emissions mitigation policies show a large variety of impacts on irrigated yields across basins, which makes it difficult to identify the role of mitigation on total US production from the maps.

As highlighted by the top map in each of Figures 7–12, irrigated areas are clustered in a limited number of basins. To have a better idea of the US-wide impact of water stress, we calculate an average yield factor over the US weighted by irrigated area for each crop. As we consider irrigated areas fixed at current levels, the projections are representative of what would be expected to occur without adaptation in the agricultural sector. As shown in the left side panel of **Figure 13**, the average crop yield factors in the reference scenario (CS3.0 REF) are expected to increase slightly for four out of six crops by mid-century compared to the present (on average across simulations with different representations of natural variability). Climate and socio-economic changes are therefore expected to reduce the effect of water stress on irrigated yields for all crops, except forage and cotton (for which the basin with the largest irrigated area is also the most water stressed), which are projected to be negatively impacted. In absolute terms, the largest decrease in yield factor is expected for forage (from 0.84 to 0.78), and represents a loss of 6 percentage points. On the one hand, crops benefit from increases in CO_2 concentrations, but on the other hand, this effect can be offset by the impact of water stress. Our results thus suggest that the impact of water stress is stronger (or the effect of CO_2 is weaker) for forage and cotton than for the other four crops.

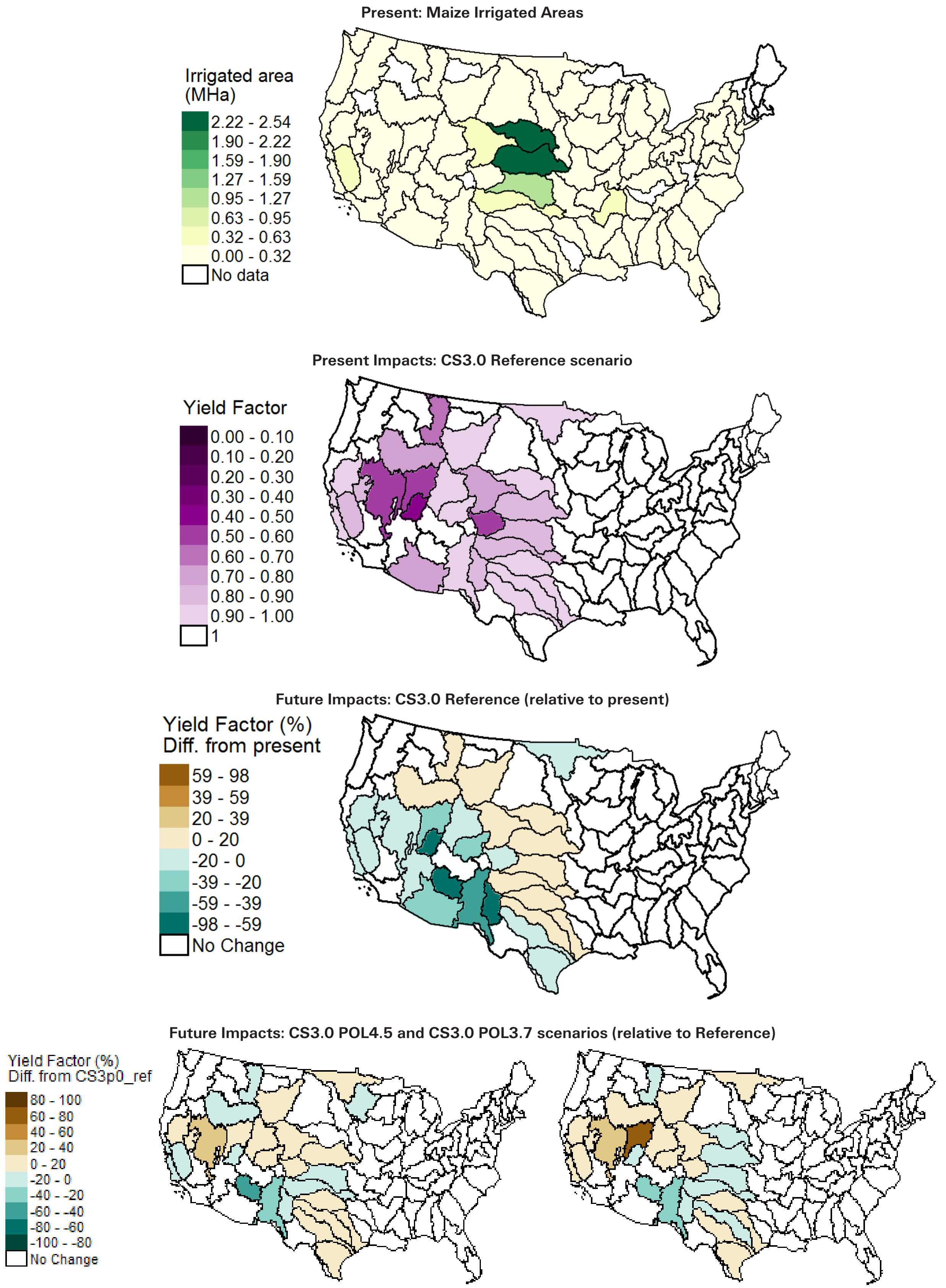
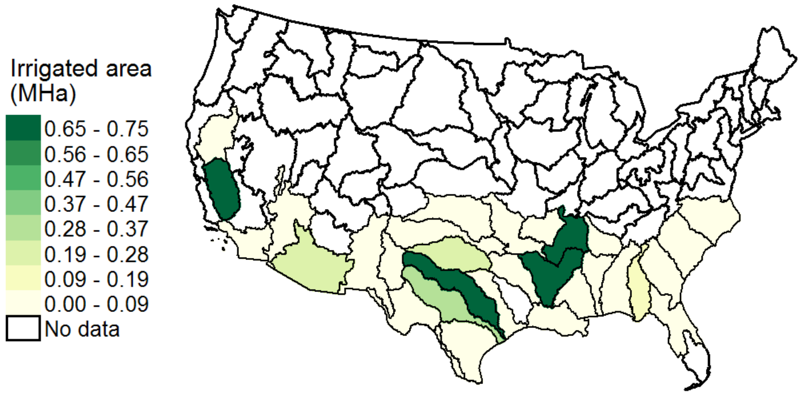
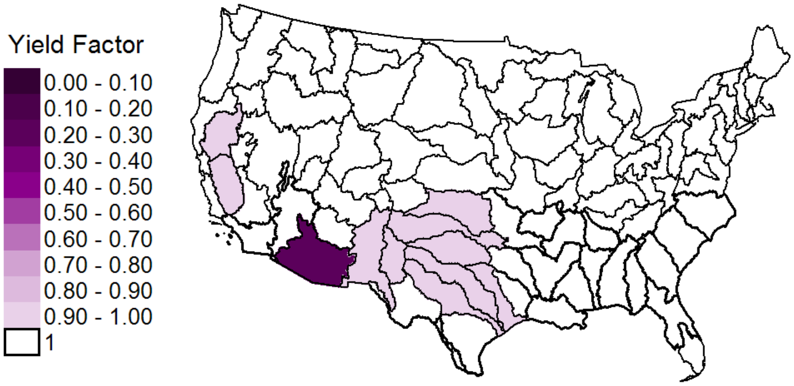


Figure 7. Maize yield factor in levels for scenario CS3.0 REF in the present (2005–2014) and in percentage change for the future (2041–2050) relative to the present for the CS3.0 REF, CS3.0 POL4.5 and CS3.0 POL3.7 scenarios.

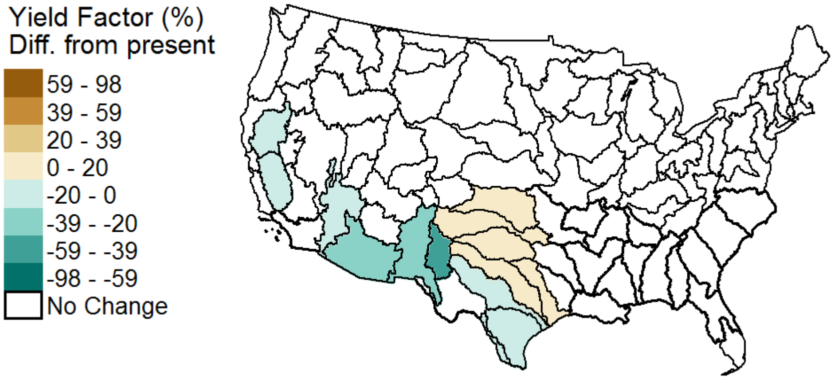
Present: Cotton Irrigated Areas



Present Impacts: CS3.0 Reference scenario



Future Impacts: CS3.0 Reference (relative to present)



Future Impacts: CS3.0 POL4.5 and CS3.0 POL3.7 scenarios (relative to Reference)

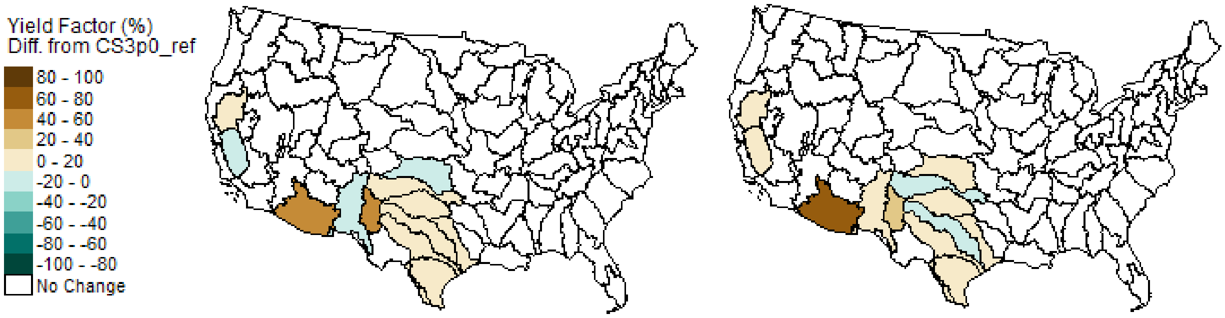
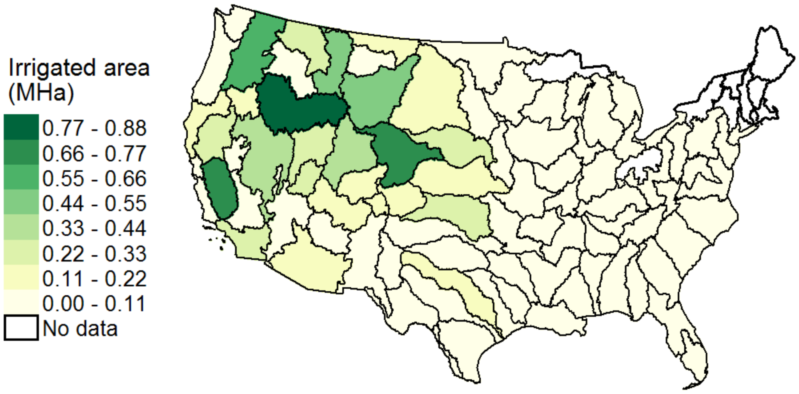
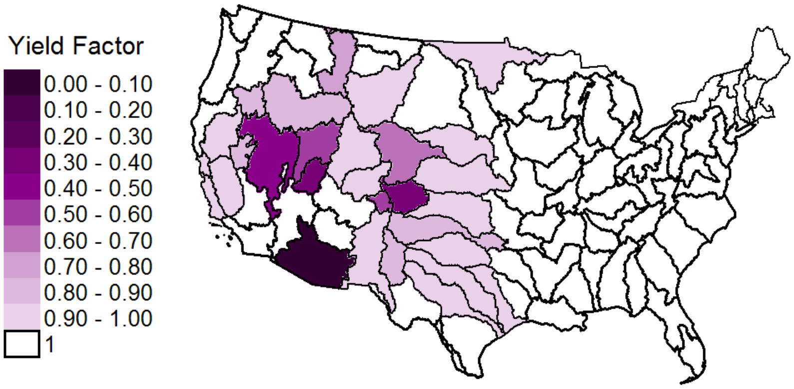


Figure 8. Cotton yield factor in levels for scenario CS3.0 REF in the present (2005–2014) and in percentage change for the future (2041–2050) relative to the present for the CS3.0 REF, CS3.0 POL4.5 and CS3.0 POL3.7 scenarios.

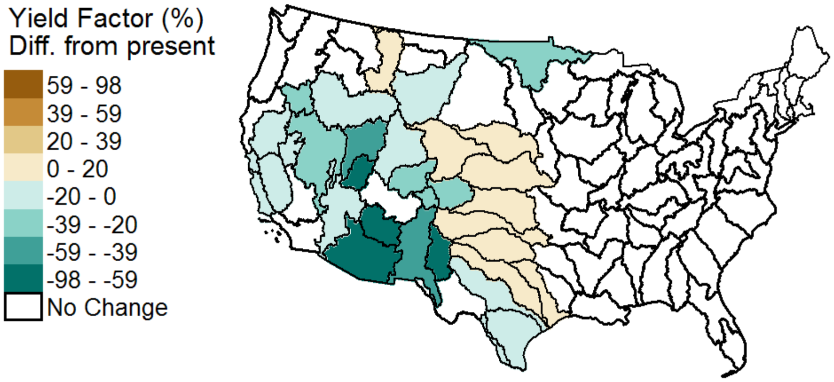
Present: Forage Irrigated Areas



Present Impacts: CS3.0 Reference scenario



Future Impacts: CS3.0 Reference (relative to present)



Future Impacts: CS3.0 POL4.5 and CS3.0 POL3.7 scenarios (relative to Reference)

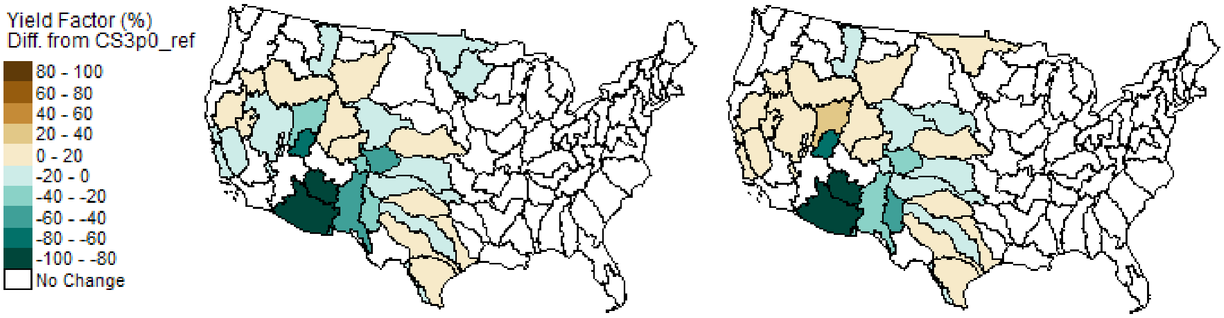
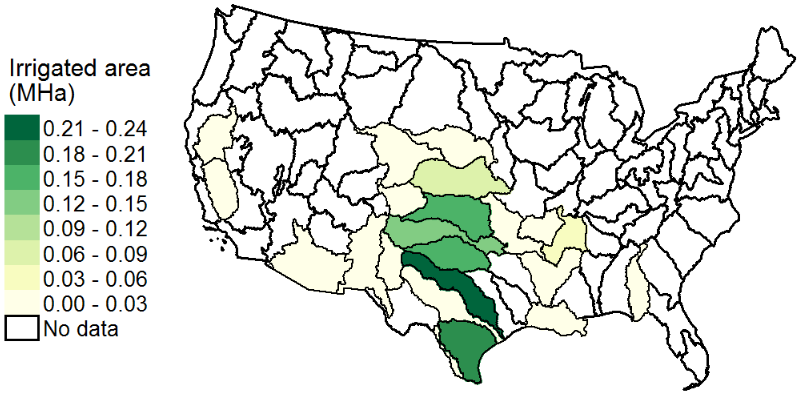
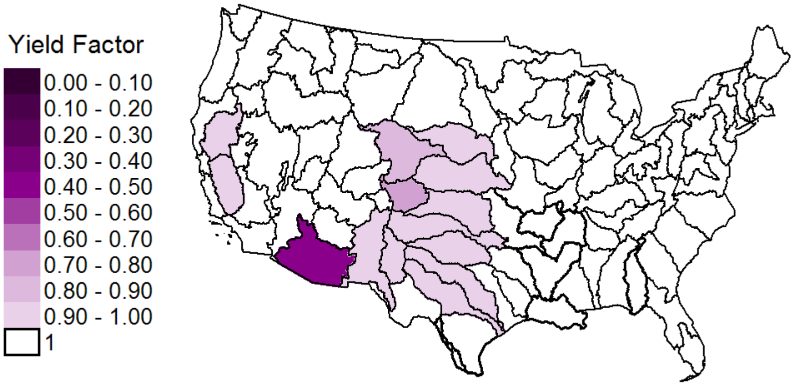


Figure 9. Forage yield factor in levels for scenario CS3.0 REF in the present (2005–2014) and in percentage change for the future (2041–2050) relative to the present for the CS3.0 REF, CS3.0 POL4.5 and CS3.0 POL3.7 scenarios.

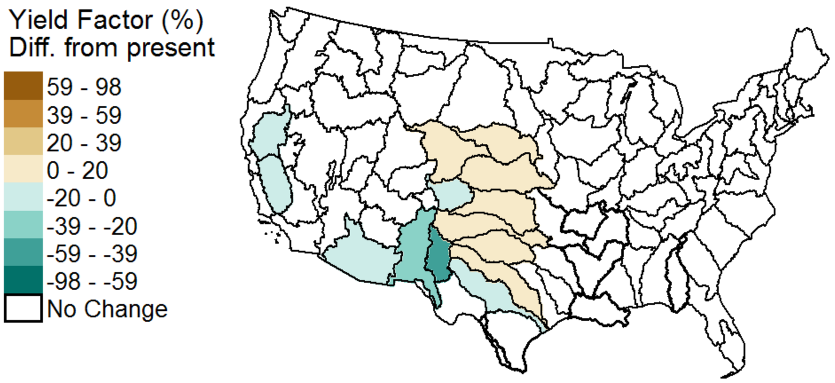
Present: Sorghum Irrigated Areas



Present Impacts: CS3.0 Reference scenario



Future Impacts: CS3.0 Reference (relative to present)



Future Impacts: CS3.0 POL4.5 and CS3.0 POL3.7 scenarios (relative to Reference)

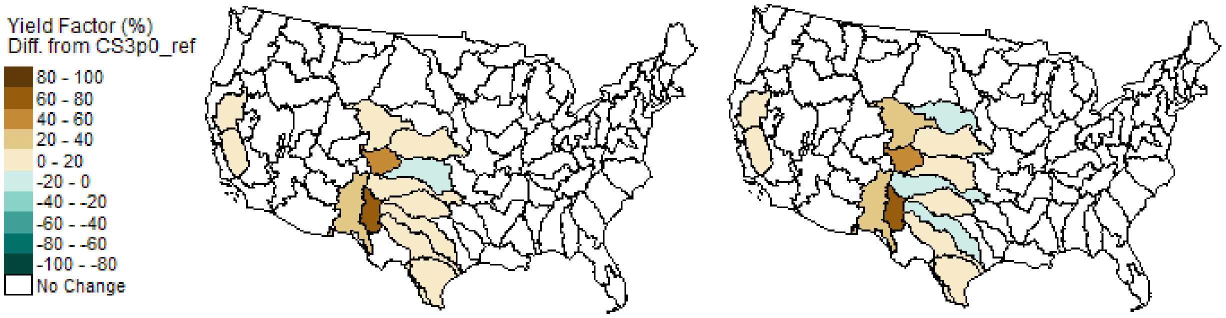


Figure 10. Sorghum yield factor in levels for scenario CS3.0 REF in the present (2005–2014) and in percentage change for the future (2041–2050) relative to the present for the CS3.0 REF, CS3.0 POL4.5 and CS3.0 POL3.7 scenarios.

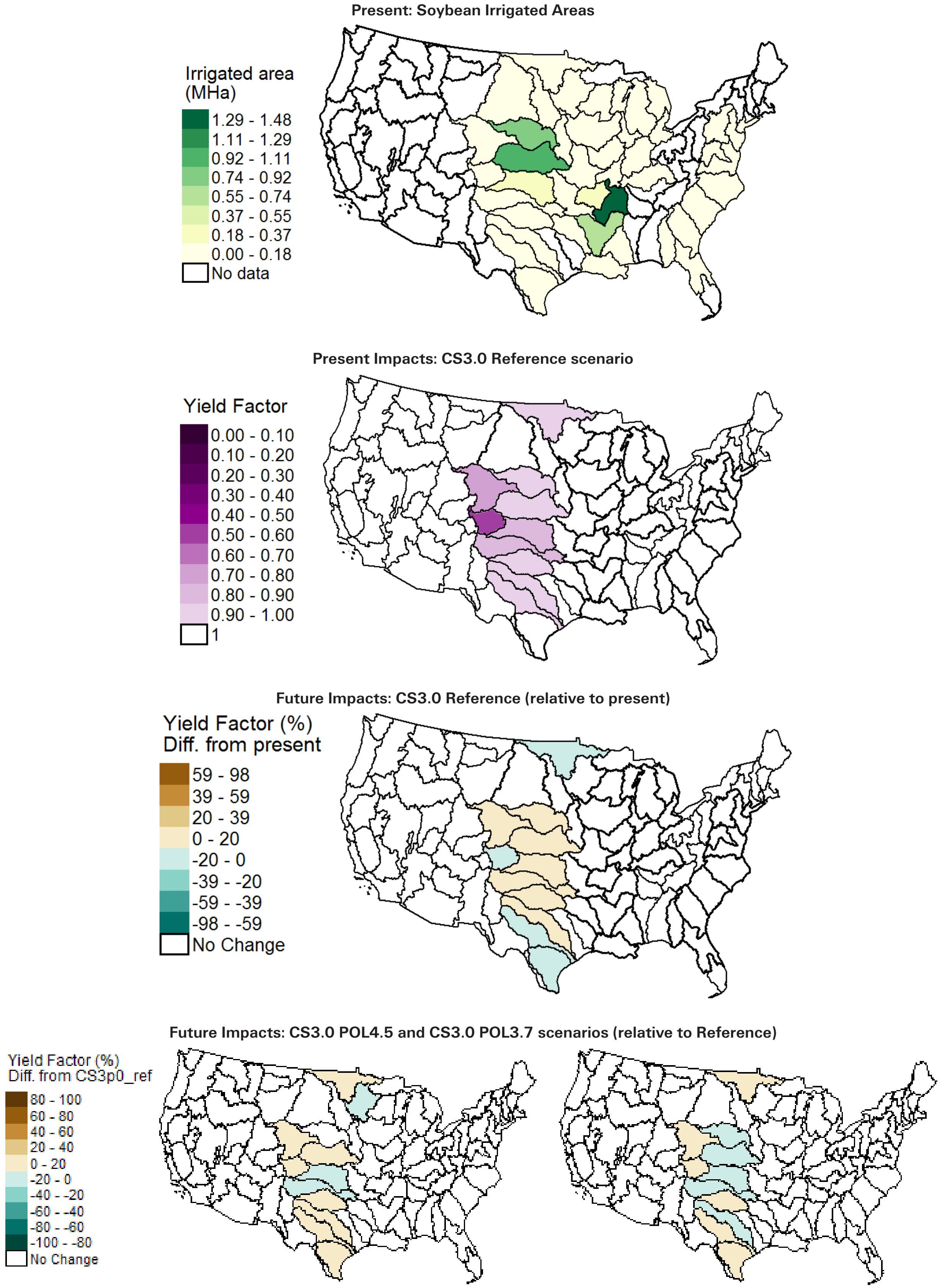
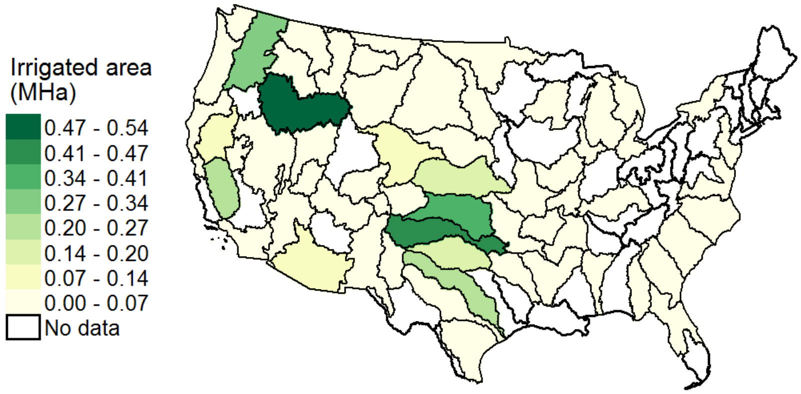
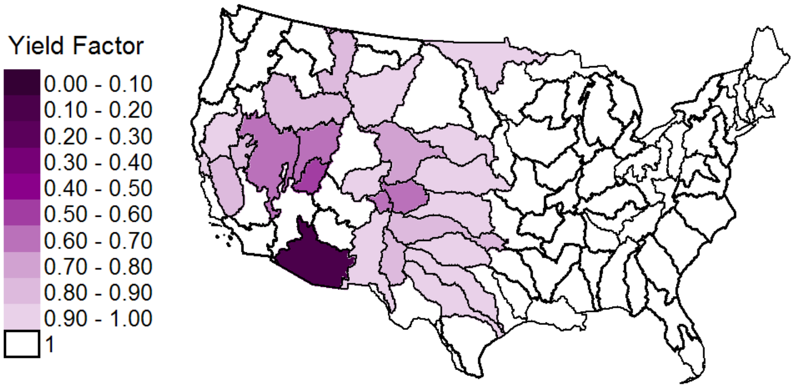


Figure 11. Soybean yield factor in levels for scenario CS3.0 REF in the present (2005–2014) and in percentage change for the future (2041–2050) relative to the present for the CS3.0 REF, CS3.0 POL4.5 and CS3.0 POL3.7 scenarios.

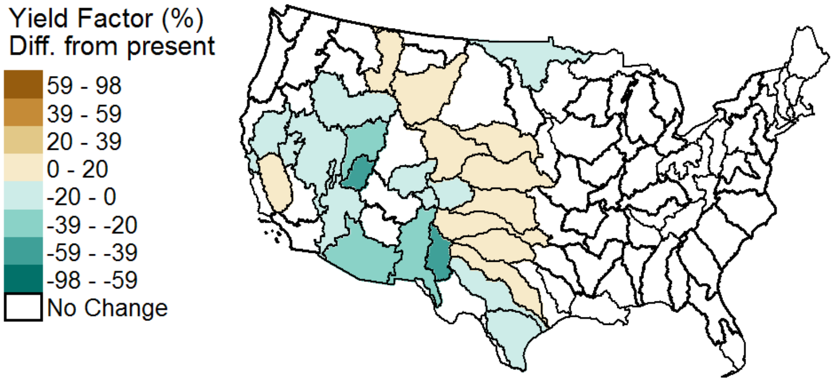
Present: Wheat Irrigated Areas



Present Impacts: CS3.0 Reference scenario



Future Impacts: CS3.0 Reference (relative to present)



Future Impacts: CS3.0 POL4.5 and CS3.0 POL3.7 scenarios (relative to Reference)

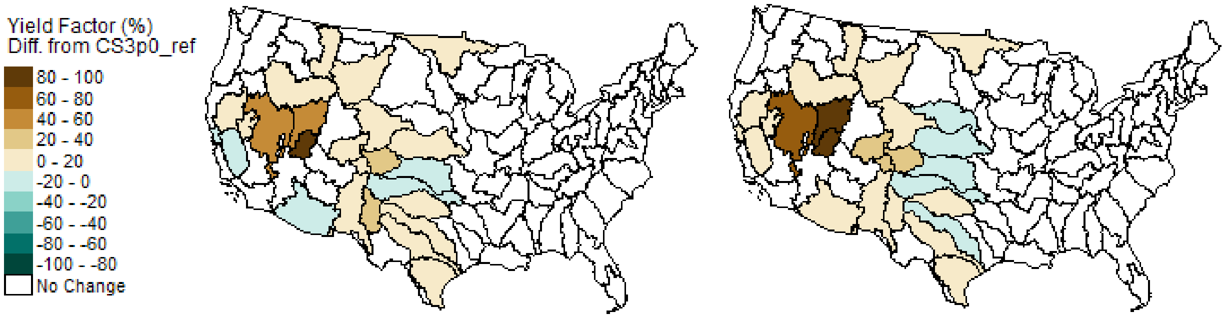


Figure 12. Wheat yield factor in levels for scenario CS3.0 REF in the present (2005–2014) and in percentage change for the future (2041–2050) relative to the present for the CS3.0 REF, CS3.0 POL4.5 and CS3.0 POL3.7 scenarios.

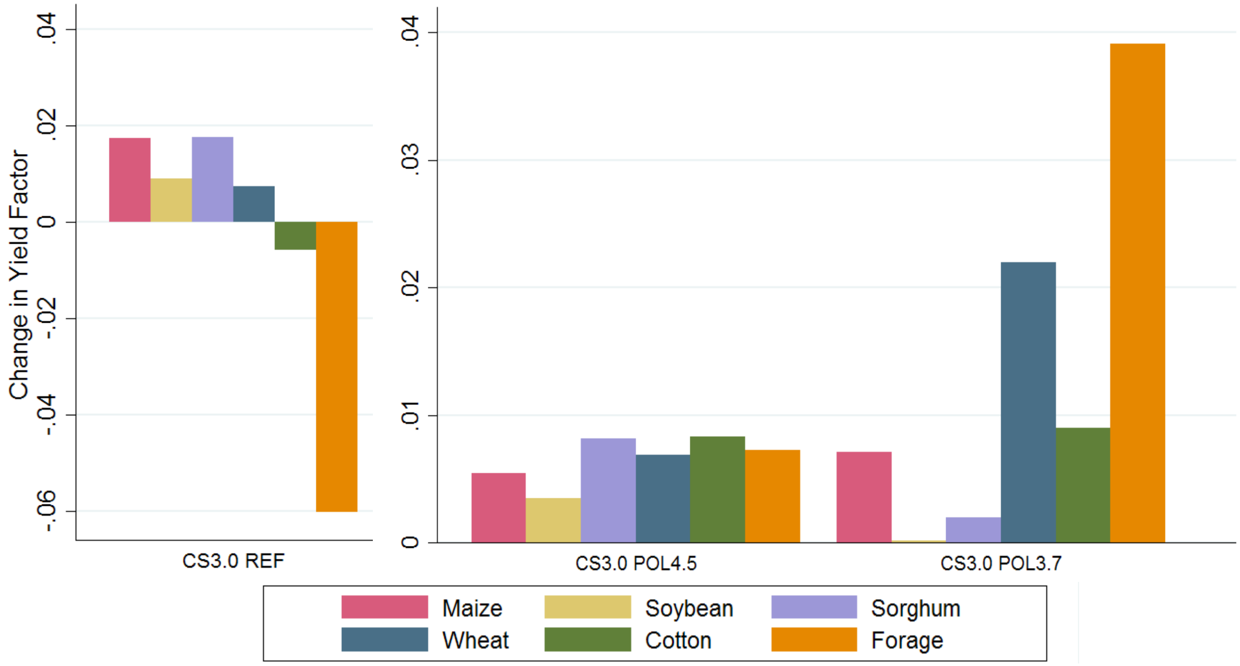


Figure 13. Future (2041–2050) US-wide mean yield factor (weighted by irrigated area) by crop, averaged over natural variability cases for each scenario in absolute change compared to the present (2005–2014) and to the CS3.0 REF scenario.

The right panel of Figure 13 displays the difference in average yield factors under the two abatement policies relative to the reference scenario. These results show that all crops benefit from GHG mitigation, indicating that the reduction in water stress associated with GHG mitigation far offsets the negative impact from reduced CO_2 concentrations compared to the reference scenario (due to less fertilization effect). Under the CS3.0 POL4.5 scenario, yield factors are expected to be higher than under the no-policy scenario (CS3.0 REF). Under the most stringent policy (CS3.0 POL3.7), the increases in yield factors for all crops (except soybean) are expected be even larger than under the CS3.0 POL4.5 scenario. For cotton, both mitigation policies effectively address the detrimental effect of water scarcity for irrigation. For forage, only the harshest mitigation policy is effective at reducing the effect of water stress on irrigated yields compared to the present. Overall, these results show that, in the absence of adaptation, mitigation policies help lessen the effect of water stress on irrigated yields due to climate change, i.e. irrigated crops will on average either experience larger growth or smaller decline in yields compared to a no-policy scenario. However, those results are averaged over the simulations with different initial conditions, and individual simulations can show large variations in these effects.

To further account for the uncertainty in future climate change projections, **Figure 14** presents the average and range (across all crops, weighted by irrigated area and natural variability) of future mean yield factors relative to the present. To account for uncertainty in the global climate system response (e.g., different climate sensitivities), the first boxplot encompasses all climate sensitivities and natural variability for the reference scenario (i.e. CS2.0 REF, CS3.0 REF and CS4.5 REF). As shown by the central line inside the boxes of Figure 14, under the reference scenario, climate change will entail a small reduction in irrigated factor crop yields due to lack of irrigation water. The box's range, however, indicates almost equal possibility of either a positive or negative impact of climate change without mitigation policy. Accounting for different climate sensitivities leads to similar levels and ranges of impacts. Under the policy cases, the likelihood of beneficial impact of climate change is slightly increased, especially under the most stringent policy (CS3.0 POL3.7).

4. Discussion

In this study, we project that some basins will be severely affected by water shortages. As a result, our study suggests that crop modeling studies that assume (perfectly) irrigated crop yields would provide highly misleading results for particular basins. However, most of these basins do not contain large irrigated cropland areas. In the Central Plains, where irrigation is widespread, runoff is projected to increase more than requirements, leading to a decrease in water stress for irrigation. Our analysis thus suggests a large potential for relocation of irrigated

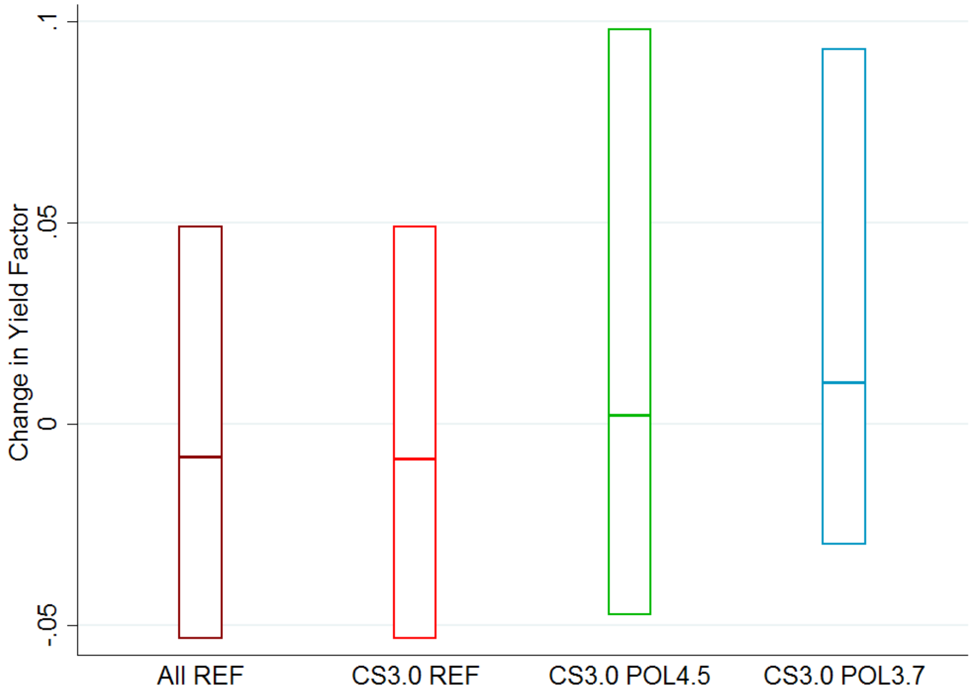


Figure 14. Future (2041–2050) US-wide mean yield factor (weighted by irrigated area), averaged over natural variability cases for each scenario in absolute change compared to the present (2005–2014). The boxes represent the range of predictions across the five cases of natural variability. The lines inside the boxes represent the mean projection.

agriculture from water-stressed regions to regions where irrigated agriculture is more sustainable. Taken together, these results demonstrate the importance of considering the integrated effect of climate change and socio-economic stressors on water resources and crop yields at a detailed river basin level: water stress is highly localized and disaggregation at the 99 river basin level is necessary to estimate the impact of water shortage on irrigation water availability and resulting crop yields.

Furthermore, the results show that under a no-policy scenario, climate and socio-economic changes are expected to reduce the effect of water stress on irrigated yields for most crops, but not for forage and cotton. This increase in irrigated crop yield factors is driven by increased water availability in important growing basins, but also by a reduction in irrigation demand—thanks, in part, to increased crop water use efficiency caused by higher CO_2 concentrations. When considering GHG mitigation policies, results show that, in the absence of adaptation, mitigation policies help lessen the effect of water stress on irrigated yields. The most ambitious GHG mitigation policy has the potential to reduce the number of basins affected by water stress, a finding that resonates with Strzepek *et al.* (2015) and Hejazi *et al.* (2014).

Our analysis provides a unique and comprehensive effort to quantify the impact of water stress on irrigation while accounting for changes in water resources and competing uses from all sectors. This emphasizes the need to rely on integrated modeling frameworks that are capable of establishing better linkages between agriculture and water resources management in the face of climate and socio-economic stressors.

It should be noted that this study only considers a single integrated assessment model and thus does not explore the structural uncertainty associated with different economic, climate and water resources models. Existing studies of the effect of climate policies on water stress generally place little emphasis on uncertainty—e.g. Hejazi *et al.* (2015) only consider two climate simulations from a single climate model. However, we know that the choice of pattern of precipitation change (associated with the climate model employed in this analysis) can greatly influence the outcome of the water model, with larger water stresses projected under a dry climate pattern than under a wet pattern (Blanc *et al.*, 2014; Boehlert *et al.*, 2015). In this study, we attempt to investigate the overall uncertainty in our results by considering multiple socio-economic and GHG mitigation scenarios, different representations of natural variability, and different global climate system responses (via different climate sensitivities). Except for the latter, the results show a large range of impacts on irrigated crop yields when considering such a large ensemble of integrated economic and climate scenarios.

Our modeling framework does not track feedback from sectoral water stress to economic activity. There is also no measure of adaptation taken to prevent water stress and no land use change from areas where water is scarce to locations with greater water availability. International trade is also not taken into account as a response to water-stressed activities in the US. These aspects are intentionally not considered in order to estimate the effect of climate change on irrigated cropping under actual conditions, thereby identifying the areas most vulnerable to irrigation shortages in the future. Also, our analysis focuses on yield factor relative to a potential fully irrigated crop. However, we do not simulate change in irrigated yield caused by changes in temperature. As shown in Sue Wing *et al.* (2015), using the same integrated economic and climate scenarios, climate change and the associated increase in CO_2 concentrations lead to heterogeneous changes to crop yields in the US, which can be either negative or positive depending on the region.

5. Conclusion

This study describes the application of IGSM-WRS-US, a model of US water resource systems, to estimate the effect of climate change and socio-economic drivers on water stress and the resulting impact on crop productivity. To this end, a yield reduction module was integrated into the modeling framework. It is unique in its consistent treatment of the complex interactions of the climatic, biological, physical and economic elements of the system. It identifies areas of potential stress in the absence of specific adaptive responses at the 99 ASR level for the continental US through 2050, under a large ensemble of climate policies and climate modeling uncertainty for the most commonly irrigated crops in the US. On average, irrigation in the Western part of the country will be affected by an increase in water shortages, with particular basins seeing severe increases in water stress. At the national level, however, climate and socio-economic changes will entail an overall reduction in water stress and its effect on irrigated yields for all crops, except for forage and cotton.

GHG mitigation policies are effective at limiting the detrimental effect of climate change on irrigated cotton and forage yields, but results show that a stringent policy (CS3.0 POL3.7) is necessary to considerably reduce the number of strongly affected basins. In addition, adaptation strategies such as improvements in irrigation efficiency to reduce irrigation demand, but also relocation of irrigated crop land to regions less prone to water stress, could further help irrigated agriculture in the next 50 years. While such adaptation measures will be costly, our results show they are possible as irrigated agriculture is sustainable in many river basins.

Acknowledgments

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APPENDIX A

Table A1. ASR names

ASR	Name	ASR	Name	ASR	Name
101	Northern Maine	702	Black-Root-Chippewa-Wisconsin	1501	Little Colorado
102	Saco-Merrimack	703	Rock-Mississippi-Des Moines	1503	Gila
103	Massachusetts-Rhode Island Coastal	704	Salt-Sny-Illinois	1601	Bear-Great Salt Lake
104	Housatonic-Thames	705	Lower Upper Mississippi	1602	Sevier Lake
105	Connecticut River	801	Hatchie-Mississippi-St Francis	1603	Humboldt-Tonopah Desert
106	Richelieu	802	Yazoo-Mississippi-Ouchita	1604	Central Lahontan
201	Upper Hudson	803	Mississippi Delta	1701	Clark Fork-Koontenai
202	Lower Hudson-Long Island-North New Jersey	901	Souris-Red-Rainy	1702	Upper/Middle Columbia
203	Delaware	1001	Missouri-Milk-Saskatchewan	1703	Upper/Central Snake
204	Susquehanna	1002	Missouri-Marias	1704	Lower Snake
205	Upper and Lower Chesapeake	1003	Missouri-Musselshell	1705	Coast-Lower Columbia
206	Potomac	1004	Yellowstone	1706	Puget Sound
301	Roanoke-Cape Fear	1005	Western Dakotas	1707	Oregon Closed Basin
302	Pee Dee-Edisto	1006	Eastern Dakotas	1801	Klamath-North Coastal
303	Savannah-St Marys	1007	North and South Platte	1802	Sacramento-Lahontan
304	St Johns-Suwannee	1008	Niobrara-Platte-Loup	1803	San Joaquin-Tulare
305	Southern Florida	1009	Middle Missouri	1804	San Francisco Bay
306	Apalachicola	1010	Kansas	1805	Central California Coast
307	Alabama-Choctawhatchee	1011	Lower Missouri	1806	Southern California
308	Mobile-Tombigdee	1101	Upper White	1807	Lahontan-South
309	Pascagoula-Pearl	1102	Upper Arkansas	1601	Bear-Great Salt Lake
401	Lake Superior	1103	Arkansas-Cimarron	1602	Sevier Lake
402	NW Lake Michigan	1104	Lower Arkansas	1603	Humboldt-Tonopah Desert
403	SW Lake Michigan	1105	Canadian	1604	Central Lahontan
404	Eastern Lake Michigan	1106	Red-Washita	1701	Clark Fork-Koontenai
405	Lake Huron	1107	Red-Sulphur	1702	Upper/Middle Columbia
406	St Clair-Western Lake Erie	1201	Sabine-Neches	1703	Upper/Central Snake
407	Eastern Lake Erie	1202	Trinity-Galveston Bay	1704	Lower Snake
408	Lake Ontario	1203	Brazos	1705	Coast-Lower Columbia
501	Ohio Headwaters	1204	Colorado (Texas)	1706	Puget Sound
502	Upper Ohio-Big Sandy	1205	Nueces-Texas Coastal	1707	Oregon Closed Basin
503	Muckingum-Scioto-Miami	1301	Rio Grande Headwaters	1801	Klamath-North Coastal
504	Kanawha	1302	Middle Rio Grande	1802	Sacramento-Lahontan
505	Kentucky-Licking-Green-Ohio	1303	Rio Grande-Pecos	1803	San Joaquin-Tulare
506	Wabash	1304	Upper Pecos	1804	San Francisco Bay
507	Cumberland	1305	Lower Rio Grande	1805	Central California Coast
601	Upper Tennessee	1401	Green-White-Yampa	1806	Southern California
602	Lower Tennessee	1402	Colorado-Gunnison	1807	Lahontan-South
701	Mississippi Headwaters	1403	Colorado-San Juan		

Table A2. Ky values for each crop by growing stage

Crops	Growing stages (gsc)			
	1	**2**	**3**	**4**
Cotton	0.4	0.4	0.5	0.4
Forage	1	1	1	1
Maize	0.4	0.4	1.3	0.5
Sorghum	0.2	0.4	0.55	0.2
Soybean	0.4	0.8	1	0.4
Wheat	0.2	0.6	0.8	0.4

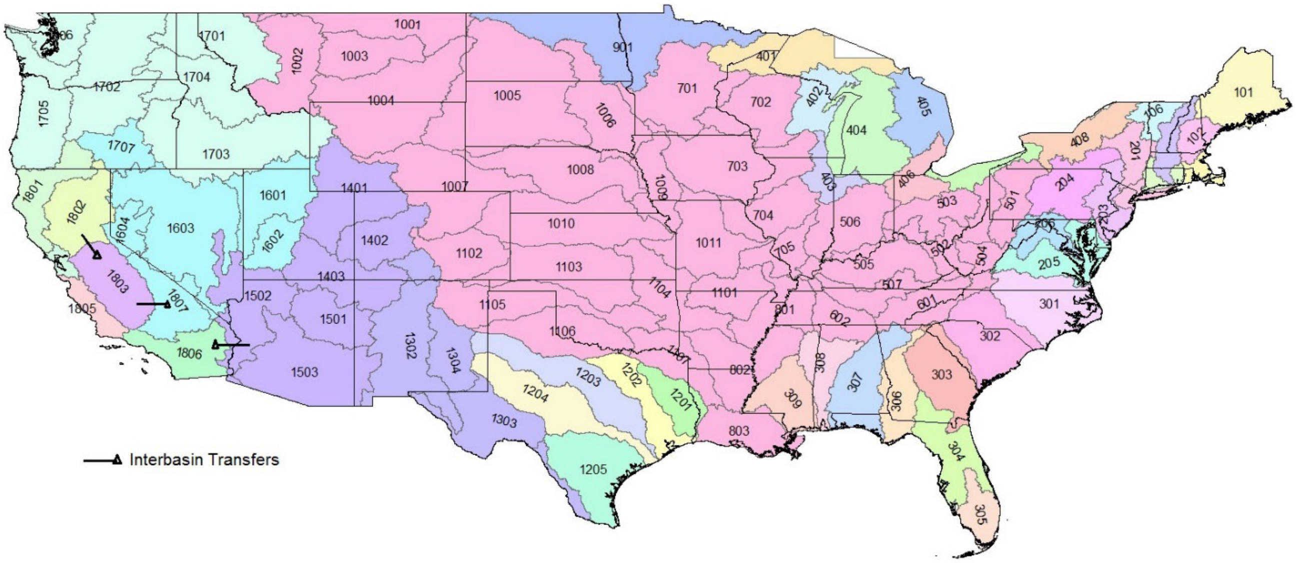

Figure A1. River basins delineation. Each color represent an ensemble of river basins linked by an upstream–downstream relationship.

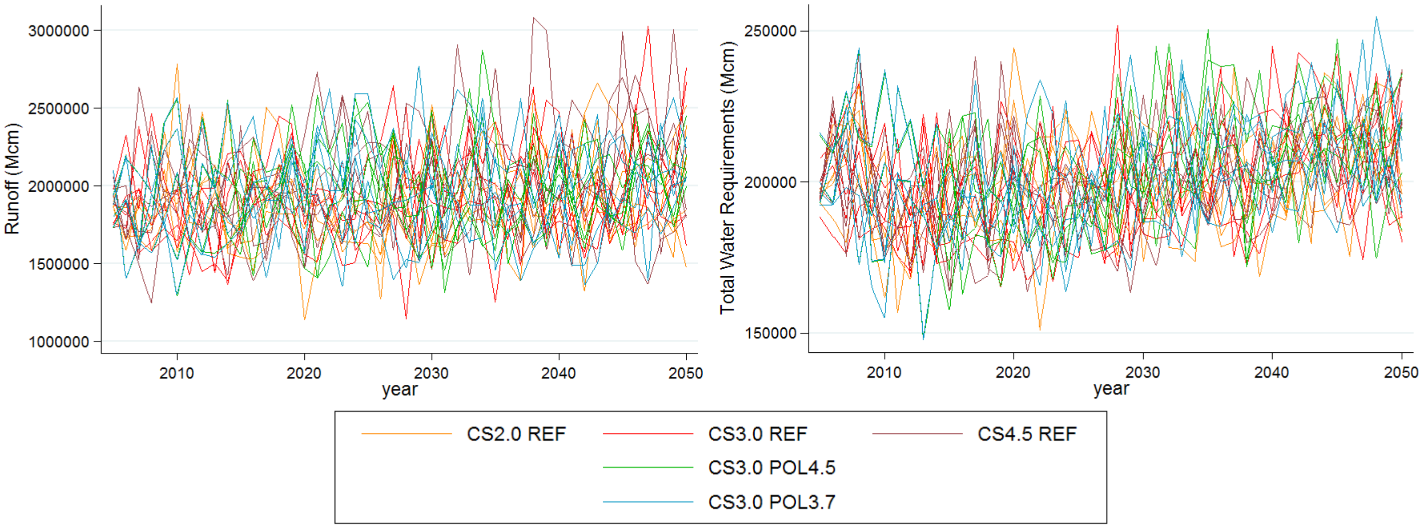

Figure A2. Total runoff and water requirements over all ASRs for each scenario and natural variability case. The lines' colors of simulations for each natural variability case are associated with each scenario's color depicted in Figure 2.

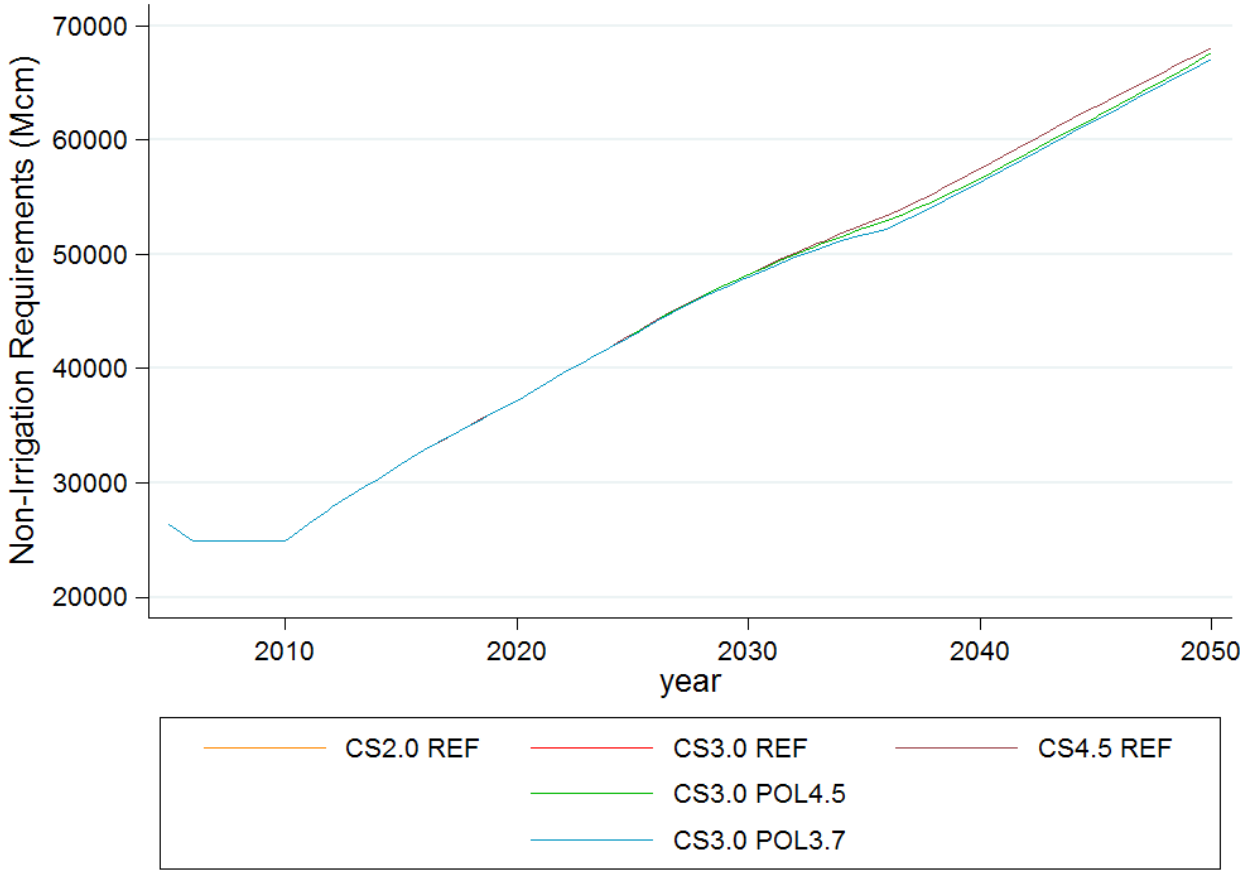

Figure A3. Total irrigation and non-irrigation requirements over all ASRs for each scenario and natural variability case. The lines' colors of simulations for each natural variability case are associated with each scenario's color depicted in Figure 2.