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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, Justin Caron, Charles Fant and Erwan Monier

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—***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

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Key Points:
- Climate and socioeconomic changes will increase water shortages and strongly reduce irrigated crop yields in specific regions or crops
- GHG mitigation has the potential to alleviate the effect of water stress on irrigated crop yields

Supporting Information:
- Supporting Information S1

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Abstract While climate change impacts on crop yields has been extensively studied, estimating the impact of water shortages on irrigated crop yields is challenging because the water resources management system is complex. To investigate this issue, we integrate a crop yield reduction module and a water resources model into the MIT Integrated Global System Modeling framework, an integrated assessment model linking a global economic model to an Earth system model. We assess the effects of climate and socioeconomic changes on water availability for irrigation in the U.S. as well as subsequent impacts on crop yields by 2050, while accounting for climate change projection uncertainty. We find that climate and socioeconomic changes will increase water shortages and strongly reduce irrigated yields for specific crops (i.e., cotton and forage), or in specific regions (i.e., the Southwest) where irrigation is not sustainable. Crop modeling studies that do not represent changes in irrigation availability can thus be misleading. Yet, since the most water-stressed basins represent a relatively small share of U.S. irrigated areas, the overall reduction in U.S. crop yields is small. The response of crop yields to climate change and water stress also suggests that some level of adaptation will be feasible, like relocating croplands to regions with sustainable irrigation or switching to less irrigation intensive crops. Finally, additional simulations show that greenhouse gas (GHG) mitigation can 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.

1. Introduction

Climate change poses a real threat to global food security [*Schmidhuber and Tubiello,* 2007; *Lang and Heasman,* 2015] with some regions being more at risk than others [*Lobell et al.,* 2008; *Wheeler and von Braun,* 2013]. One of the most beneficial adaptation measures to tackle the detrimental impacts of climate change is irrigation [*Rosenzweig and Parry,* 1994], which, thanks to crop yields on average 2.7 times larger than their rainfed counterparts, supports 40% of global food production on only 20% of total cultivated land [*UNESCO,* 2012]. Expanding irrigation can contribute to increasing global production but can be costly and have serious environmental impacts [*Reilly and Schimmelpfennig,* 1999], including contributing to increased greenhouse gas (GHG) emissions [*Carlson et al.,* 2017]. Another essential constraint to irrigated cropland expansion 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]. Future climate change could exert further pressure on irrigation capabilities by altering water resources and water uses. More specifically, climate change is expected to affect water availability by altering the geographic distribution of water resources [*Arnell,* 1999, 2004], its temporal distribution [*Middelkoop et al.,* 2001], and 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? Are current modeling frameworks, which generally do not account for changes in irrigation water availability, appropriate?

While the impact of climate change on crops has been extensively studied, both at the regional level [e.g., *Lobell et al.,* 2011; *Auffhammer et al.,* 2012; *Blanc,* 2012; *Tao et al.,* 2012] and at the global level [e.g., *Arnell et al.,* 2013; *Teixeira et al.,* 2013; *Deryng et al.,* 2014], 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 consider only two irrigation scenarios [*Rosenzweig et al.,* 2014]: no irrigation (rainfed yield) or perfect irrigation with no water stress experienced by the crops (optimal irrigated yield). Water resources 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 projections of 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 practices. Focusing on the U.S., *Hejazi et al.* [2015] do include a river routing and reservoir operations models in an integrated assessment framework but do not account for any uncertainty in projections of climate change other than two GHG emissions scenarios.

In this U.S.-focused study, we evaluate the impacts of climate change and socioeconomic 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) model version 2.0 [*Blanc et al.,* 2014; *Blanc,* 2015] 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 crop yield reduction 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 U.S. Environmental Protection Agency's Climate Change Impacts and risk analysis (CIRA) project [*Waldhoff et al*., 2015], which includes three different GHG mitigation scenarios, different global climate responses and initial conditions to account for the large uncertainty in climate change projections [*Monier et al.,* 2015].

While our modeling framework allows us to track the impact of climate change and socioeconomic 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 rainfed crops or where agricultural production will decrease or disappear.

2. Methods

2.1. Integrated Assessment Framework

In this study, the interaction between water resources and anthropogenic water requirements is analyzed using the IGSM-WRS-US integrated assessment framework. This section provides an overview of the framework schematized in Figure 1 (further details can be found in *Blanc et al.* [2014] and *Blanc* [2015]).

Within the integrated assessment framework, the global economy is represented by the Economic Projection and Policy Analysis (EPPA) model [*Paltsev et al.,* 2005]. U.S. national-level economic projections from EPPA are used to provide boundary conditions to the U.S. Regional Energy Policy (USREP) model [*Rausch et al.,* 2010], a general equilibrium model of the U.S. economy with subnational detail. USREP's projections of economic activity in different regions of the U.S. are then used to determine water requirements, as detailed below. The USREP model is also coupled with the National Renewable Energy Lab Regional Energy Deployment System (ReEDS) model [*Short et al.,* 2009; *Rausch and Mowers,* 2012] to provide highly resolved 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 input into the WRS-US model presented on the right-hand side of Figure 1.

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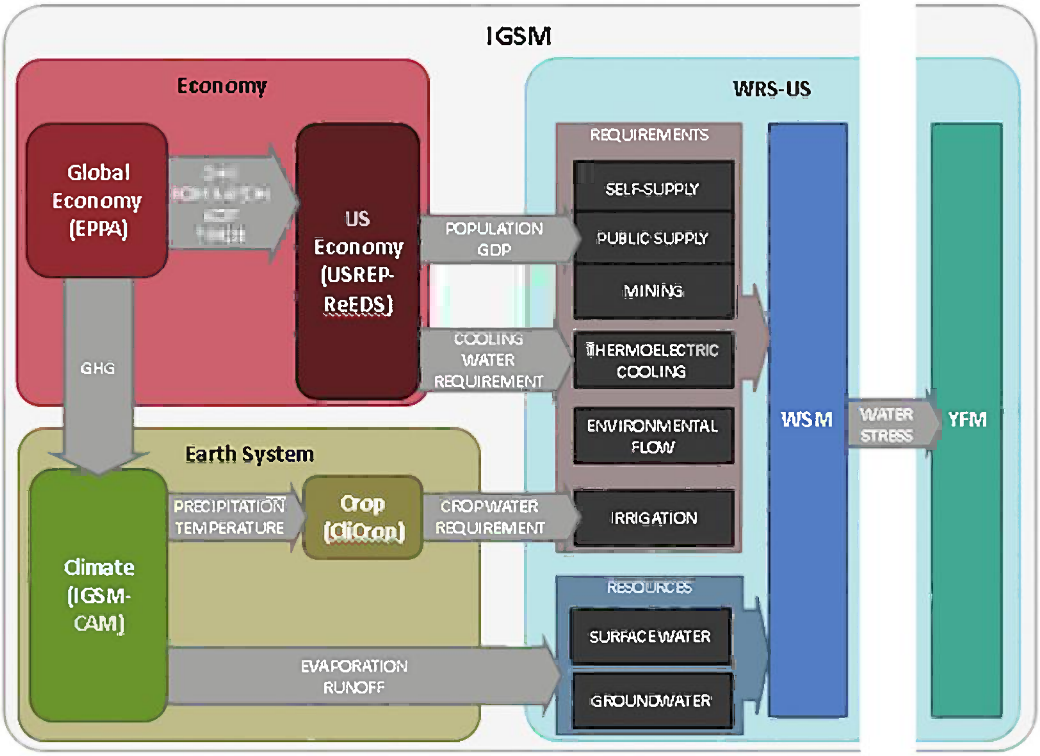

Figure 1. Schematic of the IGSM-WRS-US framework illustrating the connections between the different components of the IGSM framework and the WRS-US components.

The water resources considered in WRS-US are composed of runoff (estimated using the IGSM-CAM) and groundwater resources (see *Blanc* [2015] for more details). Anthropogenic water requirements are estimated for five sectors: irrigation, thermoelectric cooling (estimated directly by the ReEDS model), public supply (drinking water and other domestic uses by public utilities), self-supply (mostly industrial) and the mining sector. Changes in requirements from the last three sectors are estimated as a function of population and gross domestic product per capita projections from USREP. Water withdrawals for irrigation are estimated with the CliCrop model [*Fant et al.,* 2012], which simulates daily crop water requirements driven by daily accumulated precipitation, mean temperature, and temperature range from the IGSM-CAM. These crop water requirements account for the effect of CO_2 concentrations on crop water use (via stomatal closure and biomass development), management practices as well as conveyance and field efficiency. 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 the calculations of irrigation requirements.

The estimated water resources and requirements are inputs to a Water System Management (WSM) module. For each of the 99 river basins (see Figure S1 and Table S1, Supporting Information, for a spatial representation of the river basin structure), 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 basins 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 [*Molle and Berkoff,* 2007] 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 the 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 the agriculture sector. This stress indicator is used to calculate irrigated yield reductions due to insufficient of irrigation caused by water shortages.

2.2. Crop Yield Factor Module

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

$$\mathrm{YF}_{\mathrm{crop,gsc}} = \left(\frac{\mathrm{Y}a_{\mathrm{crop}}}{\mathrm{Y}x_{\mathrm{crop}}}\right) = 1 - \mathrm{Ky}_{\mathrm{crop,gsc}}\left(1 - \frac{\mathrm{ET}a_{\mathrm{crop}}}{\mathrm{ET}x_{\mathrm{crop}}}\right) \tag{1}$$

where the ratio of actual yield, Ya, and maximum yields, Yx, representing the crop yield factor are a function of actual and maximum crop evapotranspiration (ETa and ETx, respectively). *Ky* is a crop yield response factor that represents the sensitivity of crop yields to a reduction in evapotranspiration due to water shortage. Values for this parameter are also sourced from the CropWat model and reported in Table S2. For crops that are very sensitive to water shortage have $Ky > 1$ 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 (initial, development, mid-season, and late season) 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 which provides growing stages and water requirements to the crop YFM .

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

$$\mathrm{YF}_{\mathrm{crop,asr,year}} = \frac{\sum_{\mathrm{cnt}}\left(\prod_{\mathrm{gsc}=1,\dots,4}\left(1 - \mathrm{Ky}_{\mathrm{crop,gsc}}\left(1 - \frac{\mathrm{ET}aS_{\mathrm{crop,cnt,gsc}}}{\mathrm{ET}x_{\mathrm{crop,cnt,gsc}}}\right)\right)\mathrm{IRarea}_{\mathrm{crop,cnt}}\right)}{IRarea_{crop,asr}} \tag{2}$$

where IRarea at the county level, cnt, is the crop-specific irrigated area [*USDA,* 2003; *USGS,* 2011]; see *Blanc et al.* [2014] and *Blanc* [2015] for further details. Crop evapotranspiration under water stress, ETaS, is calculated as:

$$\mathrm{ET}aS_{\mathrm{crop,cnt,gsc}} = \mathrm{ET}a_{\mathrm{crop,cnt,gsc}} + \left(\mathrm{ET}x_{\mathrm{crop,cnt,gsc}} - \mathrm{ET}a_{\mathrm{crop,cnt,gsc}}\right)^{*} IR\_SRR_{\mathrm{cnt,gsc}} \tag{3}$$

where *IR_SRR* is calculated for each growing stage using the monthly *IR_SRR* estimated with the WSM module prorated by the share of each month within each growing stage. The term ($\mathrm{ET}x_{\mathrm{crop,cnt,gsc}} - \mathrm{ET}a_{\mathrm{crop,cnt,gsc}}$) represents the 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.

2.3. Major Assumptions

A set of major assumptions are made in the modeling framework regarding: (1) Conveyance and field efficiencies: they 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; (2) Groundwater resources: they are estimated to remain constant at 2005 levels unless groundwater extraction is greater than groundwater recharge; (3) the allocation of irrigation water to the various crop considered: we assume that all crops are affected equally by a shortage of water for irrigation, i.e., no specific crop has priority access to water over

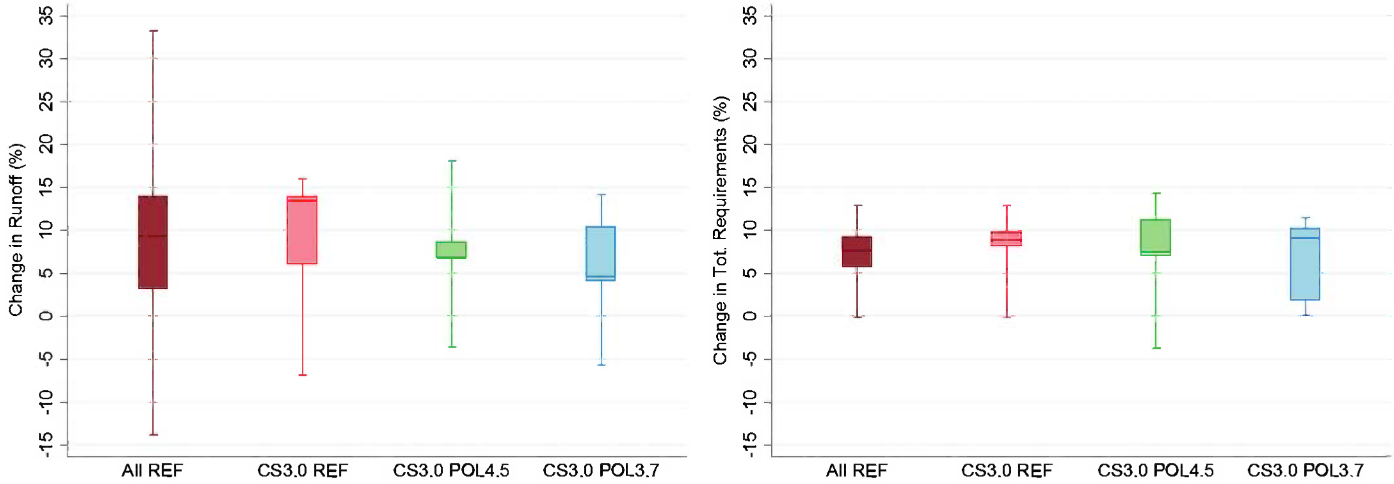

Figure 2. Box plot of changes in total U.S. runoff and water requirements (calculated as the sum over all basins) in the future (2041–2050) relative to the present (2005–2014). The boxes are computed over the five-member ensemble with different representation of natural variability for the CS3.0 REF, CS3.0 POL4.5, and CS3.0 POL3.7, and over the 15-member ensemble that include three different values of climate sensitivity and five different representation of natural variability for "All REF." The boxes represent the range of projections between the 25th and 75th percentiles. The lines inside the boxes represent the median predictions. The whiskers represent upper and lower values.

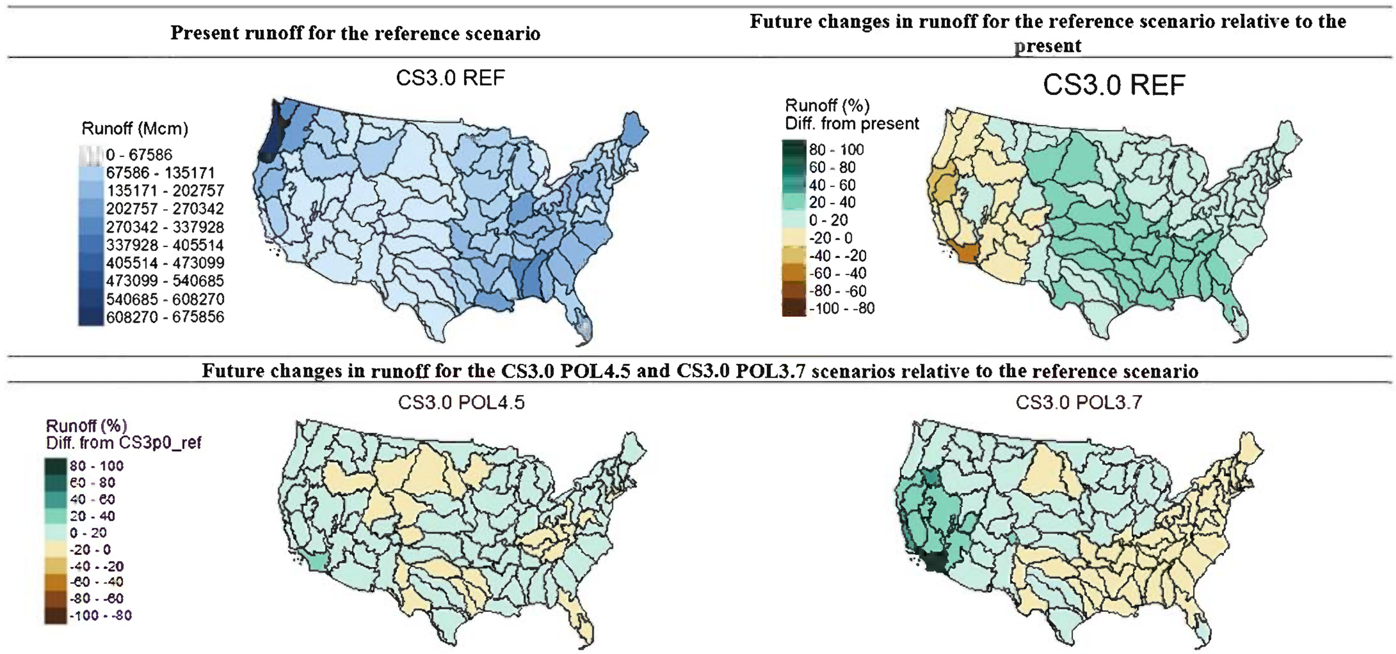

Figure 3. Annual runoff in levels for the present (2005–2014) for the CS3.0 REF scenario and in percentage change for the future (2041–2050) relative to the present for the CS3.0 REF scenario, and relative to the CS3.0 REF for the CS3.0 POL4.5 and CS3.0 POL3.7 scenarios.

another crop; and (4) irrigated areas: we assume that they remain fixed at current levels with the explicit aim to estimate the effect of climate change on irrigated crops under actual cropping conditions (i.e., without adaptation) and identify the areas most vulnerable to irrigation shortages in the future.

2.4. 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 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 GHGs mitigation scenarios: POL4.5, a

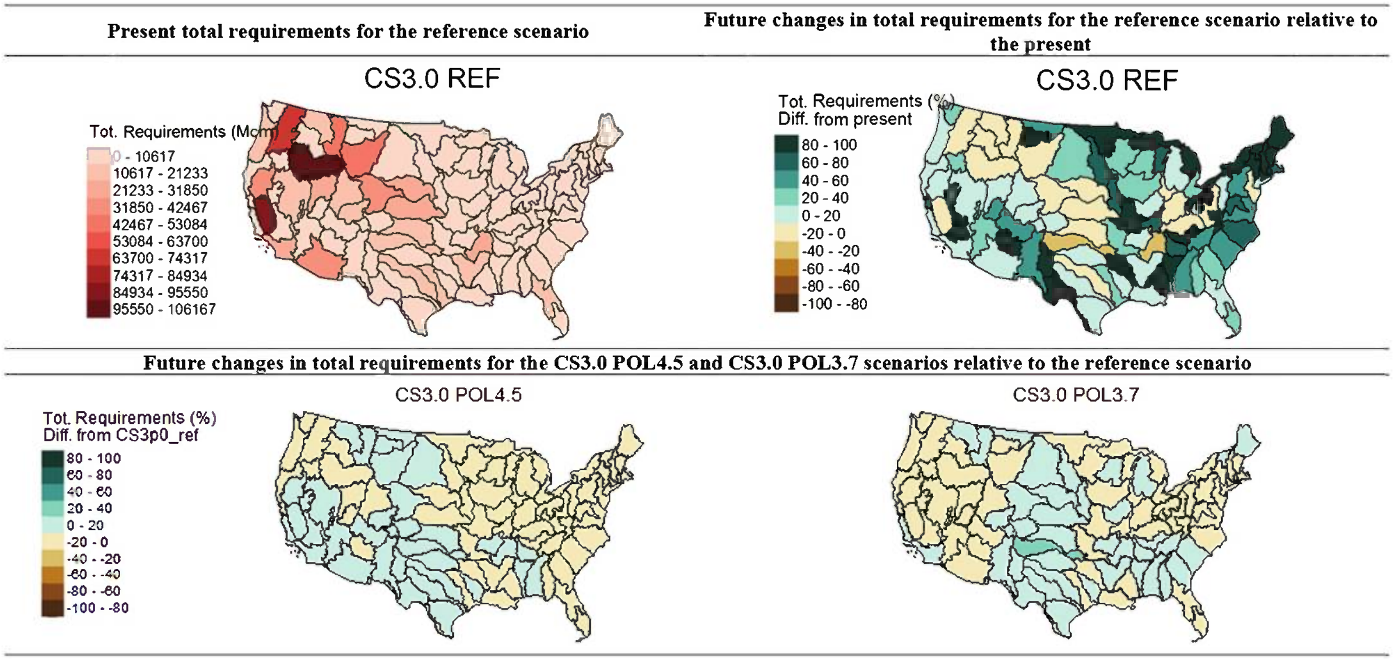

Figure 4. Annual water requirements in levels for the present (2005–2014) for the CS3.0 REF scenario and in percentage change for the future (2041–2050) relative to the present for the CS3.0 REF scenario, and relative to the CS3.0 REF for the CS3.0 POL4.5 and CS3.0 POL3.7 scenarios.

moderate mitigation scenario reaching 4.5 W m^{-2} by 2100, similar to RCP4.5; and POL3.7, a more stringent mitigation scenario reaching 3.7 W m^{-2}, corresponding to an intermediate stabilization scenario between RCP4.5 and RCP2.6. More details on the emissions scenarios and their economic implications are given in *Paltsev et al.* [2015]. 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), which are obtained by changing the strength of the cloud feedback in the climate model using a radiative cloud adjustment method (see *Sokolov and Monier* [2012]. 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. More details on the design of the climate ensemble and the analysis of the projections of temperature and precipitation changes over the U.S. can be found in *Monier et al.* [2015]. 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 Coupled Model Intercomparison Project Phase 5 (CMIP5) multimodel ensemble. That is because the IGSM-CAM ensemble samples key sources of uncertainty, namely emissions levels, 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. While five initial conditions might not be enough to fully filter out natural variability, it is an improvement over current modeling studies and practices, which generally do not run with multiple initial conditions and thus do not filter out the role of natural variability. We further identify the range of projections associated with the uncertainty in natural variability to determine its contribution in our analysis. 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 projects future water resources and uses. The ensemble-mean total runoff is projected to increase on average for all emissions scenarios (see Figure 2 for a box plot of projected changes in total natural runoff by mid-century, not including inflows from upstream basins, for each emissions scenario). Some individual simulations,

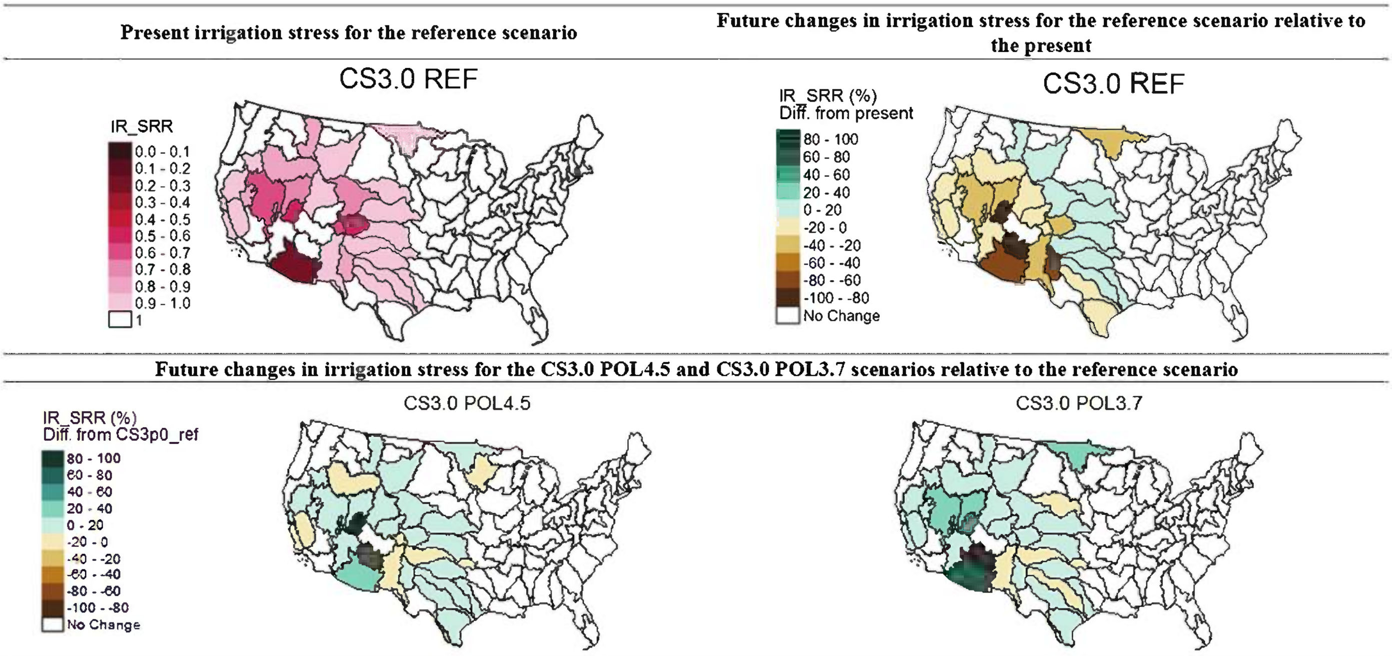

Figure 5. Annual water stress for irrigation (*IR_SRR*) in levels for the present (2005–2014) for the CS3.0 REF scenario and in percentage change for the future (2041–2050) relative to the present for the CS3.0 REF scenario, and relative to the CS3.0 REF for the CS3.0 POL4.5 and CS3.0 POL3.7 scenarios.

however, project a decrease (see Figure S2). 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* [2009], *Deser et al.* [2012], and *Monier et al.* [2015]. This confirms that a wide range of outcomes can be projected by the single model framework used in this study.

Water requirements for the thermoelectric cooling, public supply, self-supply and mining sectors are projected to increase by between 135% and 140% driven by a steady increase in population and economic activity (see Figure S3). Irrigation water requirements are projected to decrease by between 6% and 24% in total over the U.S. (see Figure S3), thanks to changes in the evaporative demand and crop water use efficiency that result from increases in atmospheric CO_2 concentrations and climate change (i.e., increases in precipitation). In the Western part of the Unite States, where irrigation water demand is the largest, the projected decreases are smaller and in the 1% to 13% range (see Figure S4). Combining climate-driven and socioeconomic-driven changes, as shown in the right panel of Figure 2, results in a projected increase in total United States water requirements under all emissions scenarios. Once again, the magnitude of the projected changes varies strongly from simulation to simulation, highlighting the large uncertainty in climate change projections, especially the role of natural climate variability.

While the GHG emission abatement policies POL3.7 and POL4.5 slightly reduce the mean increase in total runoff over the United States 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).

The changes in water availability are not evenly spread across the United States with increases in runoff projected under the reference scenario over most of the country, except in the West where runoff in the present period (2005–2014) is large in the North but small in the South (see Figure 3). GHG emission abatement policies, and especially POL4.5, are expected to lessen the decrease in runoff in the South West.

On the other hand, total water requirements are projected to largely increase under the reference scenario in the North East of the United States, where present requirements are low, and experience some reductions in the central Plains and North West (see Figure 4). Under the GHG emission abatement policies, the reductions in the central Plains and North West are expected to be smaller.

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3.2. Water Stress

Many basins in the Central Plains, West, and particularly the South West, currently (2005–2014) experience water shortages for irrigation (as indicated by values below 1 in the top left map of Figure 5), while basins in the East are unaffected. Under the reference scenario, water stress for irrigation will worsen by mid-century in the West (i.e., decrease the *IR_SRR*) due to a decrease in runoff and increase in requirements, while the opposite is projected to happen in the central Plains where an increase in runoff and a decrease in water requirements are projected (see top right part of Figure 5). Eastern basins will continue to be unaffected.

Emissions abatement scenarios provide some relief for most basins relative to the reference scenario, including in the Mountain area (reflected as positive values in the lower graphs of the Figure 5) and in California's central valley under the most stringent policy (CS3.0 POL3.7). In some basins in the Central Plains, for example, Arkansas-Cimarron, where higher increases in precipitation are predicted than in the reference scenario, mitigation policies have the opposite 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.

The distribution of changes in irrigation water stress relative to the present (see Figure 6) differs between representations of natural variability for each scenario. However, in each case the modal basin 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 a smaller number of river basins are expected to experience large changes in irrigation availability. These results highlight the need for a very stringent mitigation policy to substantially change the distribution of impacts on irrigation water stress.

3.3. Irrigated Yields

Yield reductions for some crops caused by a lack of irrigation are estimated to be very severe in some basins (see Figures 7–12). For instance, in the present period, irrigated maize yields in the Sevier Lake basin in Utah (see Table S1 and Figure S1 for the geo-localization of basins) are only 40% of optimal irrigated yields due to water scarcity. By 2050 and under the CS3.0 REF scenario, future irrigated maize yields in this basin are on average expected to decrease to only 10% of the optimal irrigated yields because of an increase in water deficits. This means that the lack of water results in a yield loss of 90% relative to a perfectly irrigated situation. However, maize is only marginally cultivated in this basin, thus this result has little implications for total U.S. 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 more than 90% and 70% of the potential irrigated yields, respectively. For cotton, however, the Gila basin of 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 crop yield dropping to less than 10% of the optimal irrigated yield by mid-century under the CS3.0 REF scenario. Irrigated areas of forage are widely spread across the United States with a higher

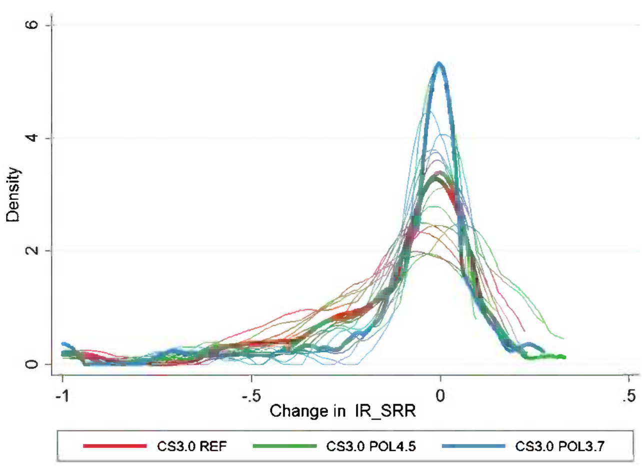

Figure 6. Kernel density distribution of absolute changes in water stress for irrigation (*IR_SRR*) for the 35 basins affected by water stress for the period 2041–2050 compared to the present (2005–2014). Thin lines represent individual simulations for each natural variability case. Thick lines show the ensemble mean of these simulations for each emissions scenario.

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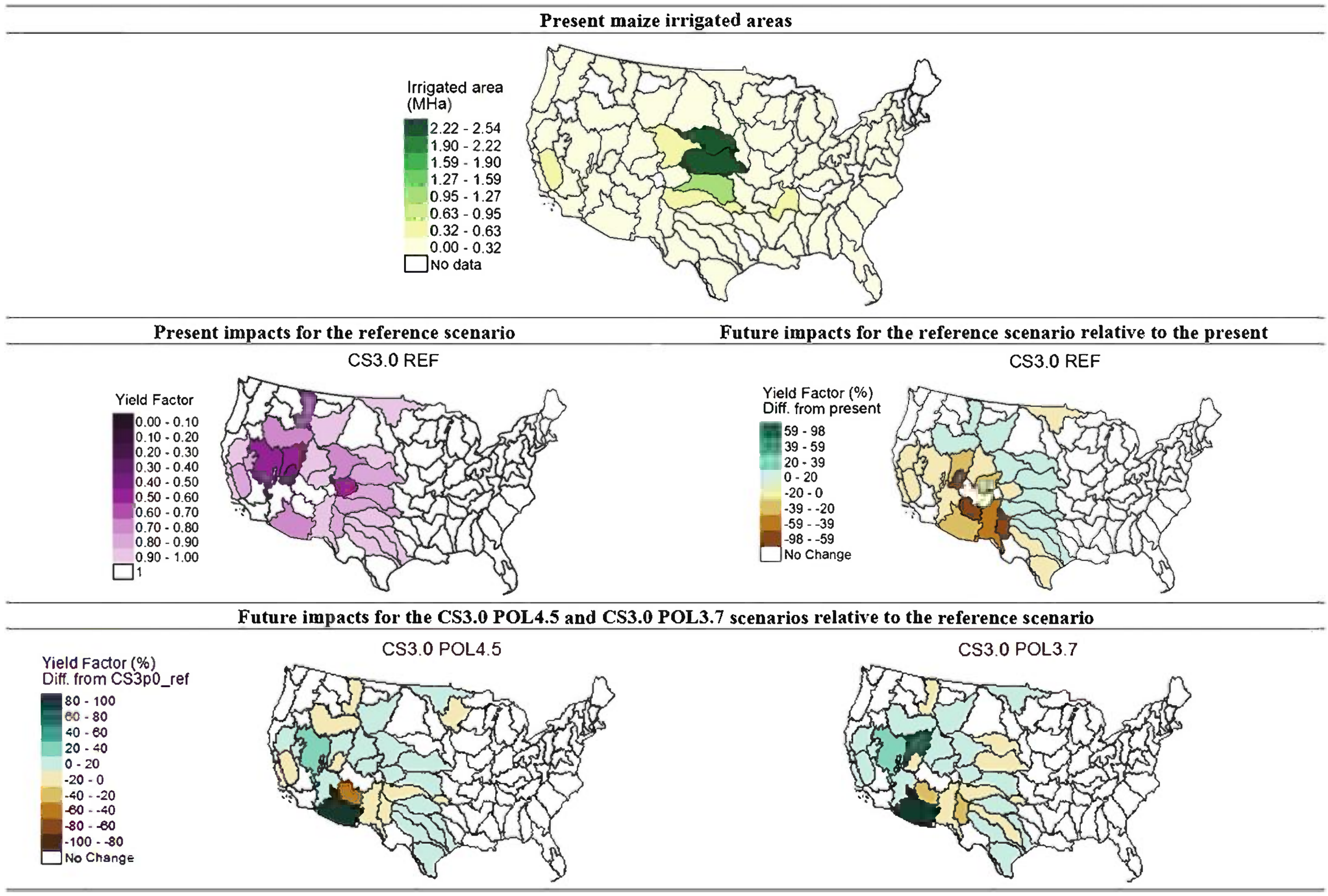

Figure 7. Maize yield factor in levels for the present (2005–2014) for the CS3.0 REF scenario and in percentage change for the future (2041–2050) relative to the present for the CS3.0 REF scenario, and relative to the CS3.0 REF for the CS3.0 POL4.5 and CS3.0 POL3.7 scenarios.

concentration in the North West where basins in the Great Basin region are projected 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 North West, where water stress is also expected to be relatively mild.

The differences in future crop yields impacts between the reference scenario and the policy scenarios (see lower panels of Figures 7–12) vary from basin to basin, largely due to differences in climate change patterns and atmospheric CO_2 concentration (different level of CO_2 fertilization) between scenarios. Overall, the simulations under the two emission 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 U.S. production from the maps.

Over the United States as a whole, 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; see left side panel of Figure 13). Climate and socioeconomic 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 crop 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.

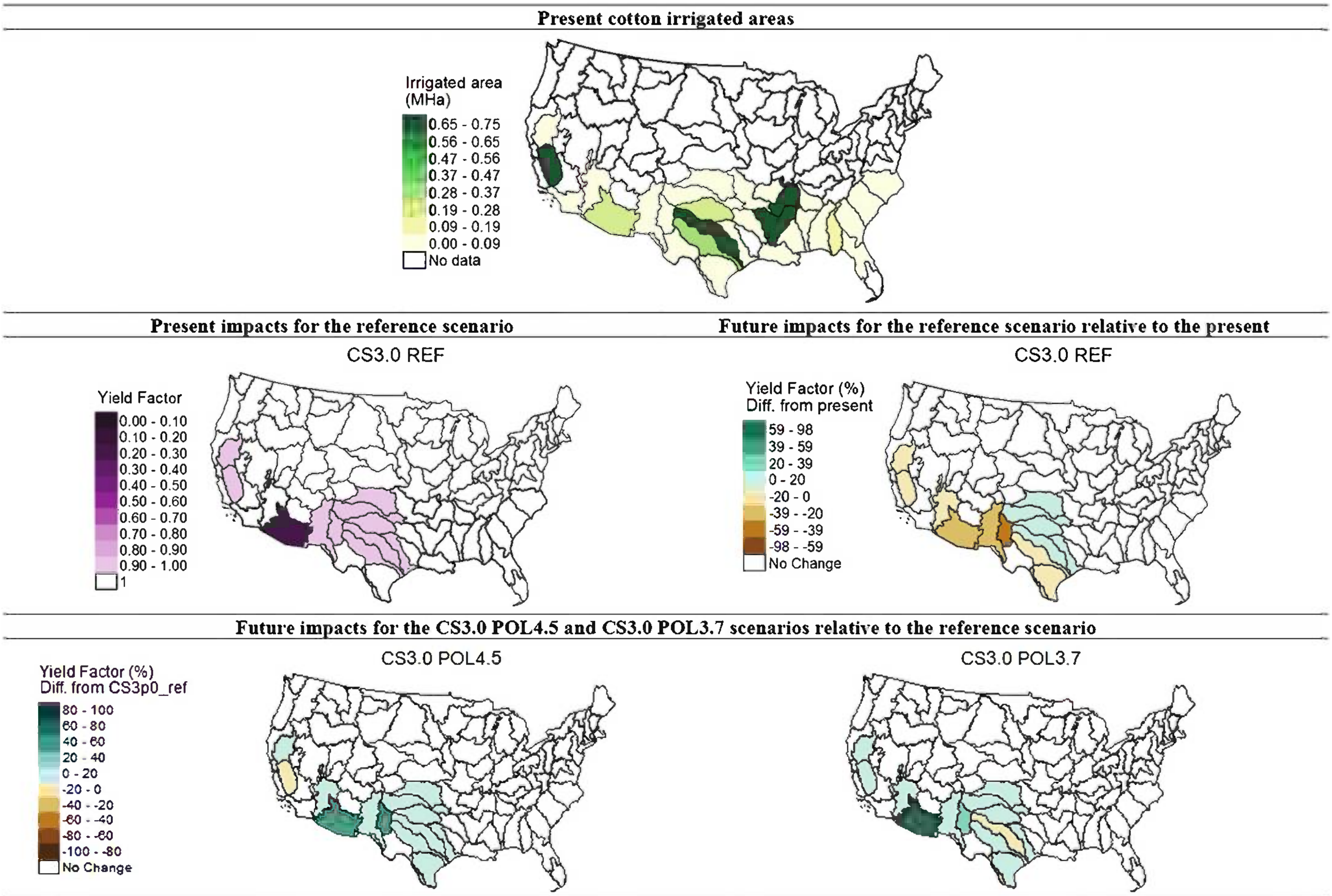

Figure 8. Cotton yield factor in levels for the present (2005–2014) for the CS3.0 REF scenario and in percentage change for the future (2041–2050) relative to the present for the CS3.0 REF scenario, and relative to the CS3.0 REF for the CS3.0 POL4.5 and CS3.0 POL3.7 scenarios.

When considering all U.S. basins, GHG mitigation is beneficial for all crop yields (see right panel of Figure 13). The reduction in water stress associated with GHG mitigation under both policies far offsets the negative impact from reduced CO_2 concentrations compared to the reference scenario (e.g., less CO_2 fertilization effect). Under the CS3.0 POL4.5 scenario, crop 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 crop yield factors for all crops (except soybean) are expected to 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, that is, irrigated crops will on average either experience larger growth or smaller decreases 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.

Over all crops and all basins, climate and socioeconomic changes will entail a small reduction in irrigated crop yields due to a lack of irrigation water availability in the reference scenario (see Figure 14). Accounting for different climate sensitivities leads to a wider range of impacts. Under the mitigation policies, the likelihood of beneficial impact of climate change is slightly increased especially under the most stringent policy (CS3.0 POL3.7).

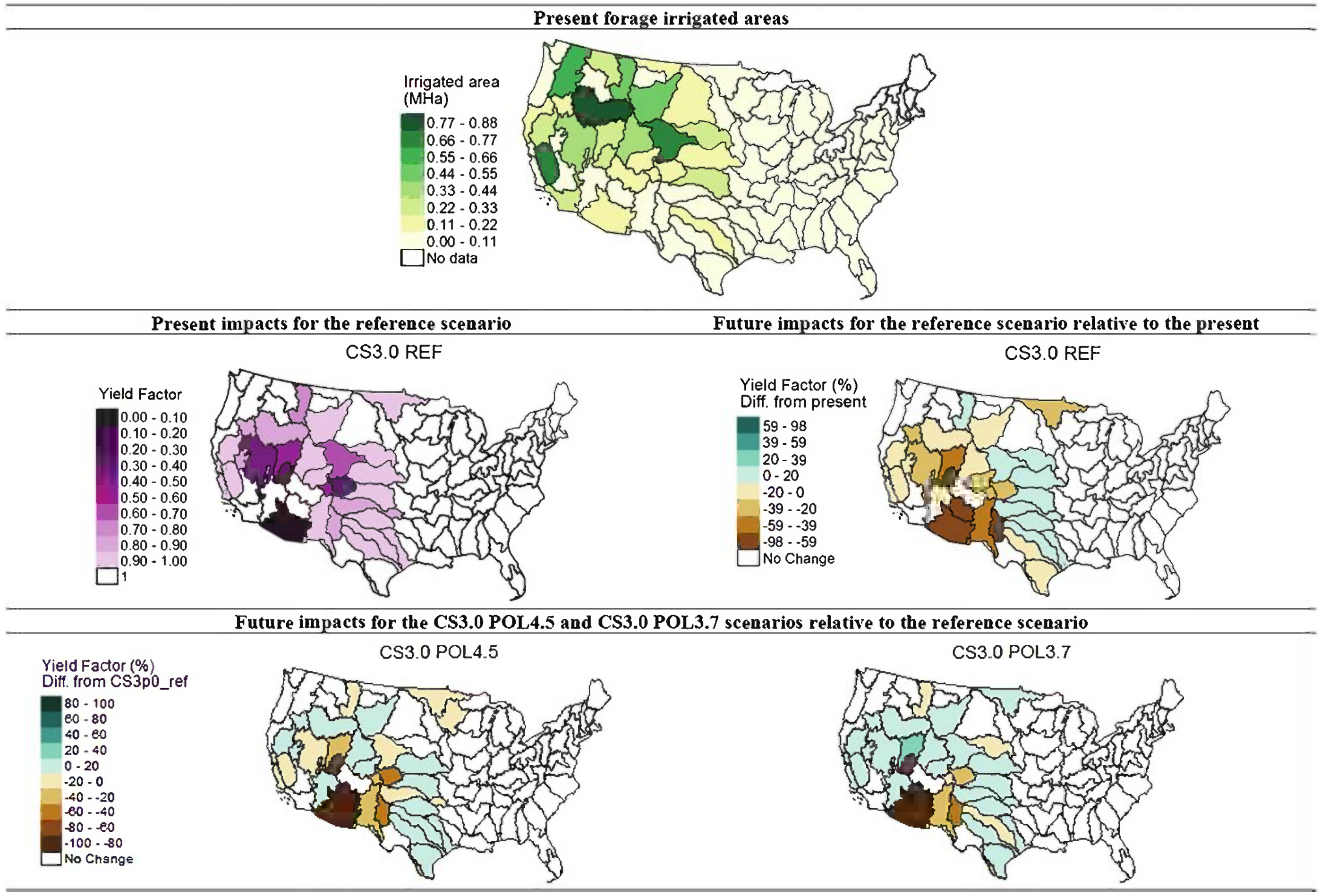

Figure 9. Forage yield factor in levels for the present (2005–2014) for the CS3.0 REF scenario and in percentage change for the future (2041–2050) relative to the present for the CS3.0 REF scenario, and relative to the CS3.0 REF for the CS3.0 POL4.5 and CS3.0 POL3.7 scenarios.

4. Discussion

In this study, we project that by 2050, under a wide range of emissions scenarios and climate change projections, a number of U.S. basins will start experiencing water shortages while several basins will see their existing shortages severely accentuated. As a result, irrigated yields in these basins will be reduced, in extreme cases to levels that are only 10% of optimal irrigated yields. Our findings thus suggest that crop modeling studies that do not account for changes in the availability of irrigation water under varying socioeconomic drivers and climate change, in essence assuming optimal irrigated crop yields, can be misleading. However, the basins affected by water shortages generally do not contain most of the irrigated cropland areas. Therefore, while our analysis suggests that cropland expansion and land-use change decisions can be constrained by water availability for irrigation, it also indicates a large potential for relocation of irrigated 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 socioeconomic 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.

At the U.S.-wide level, our results show that under a no-policy scenario, future irrigated yields factors, for all crops except forage and cotton, are projected to be higher than in the present. 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

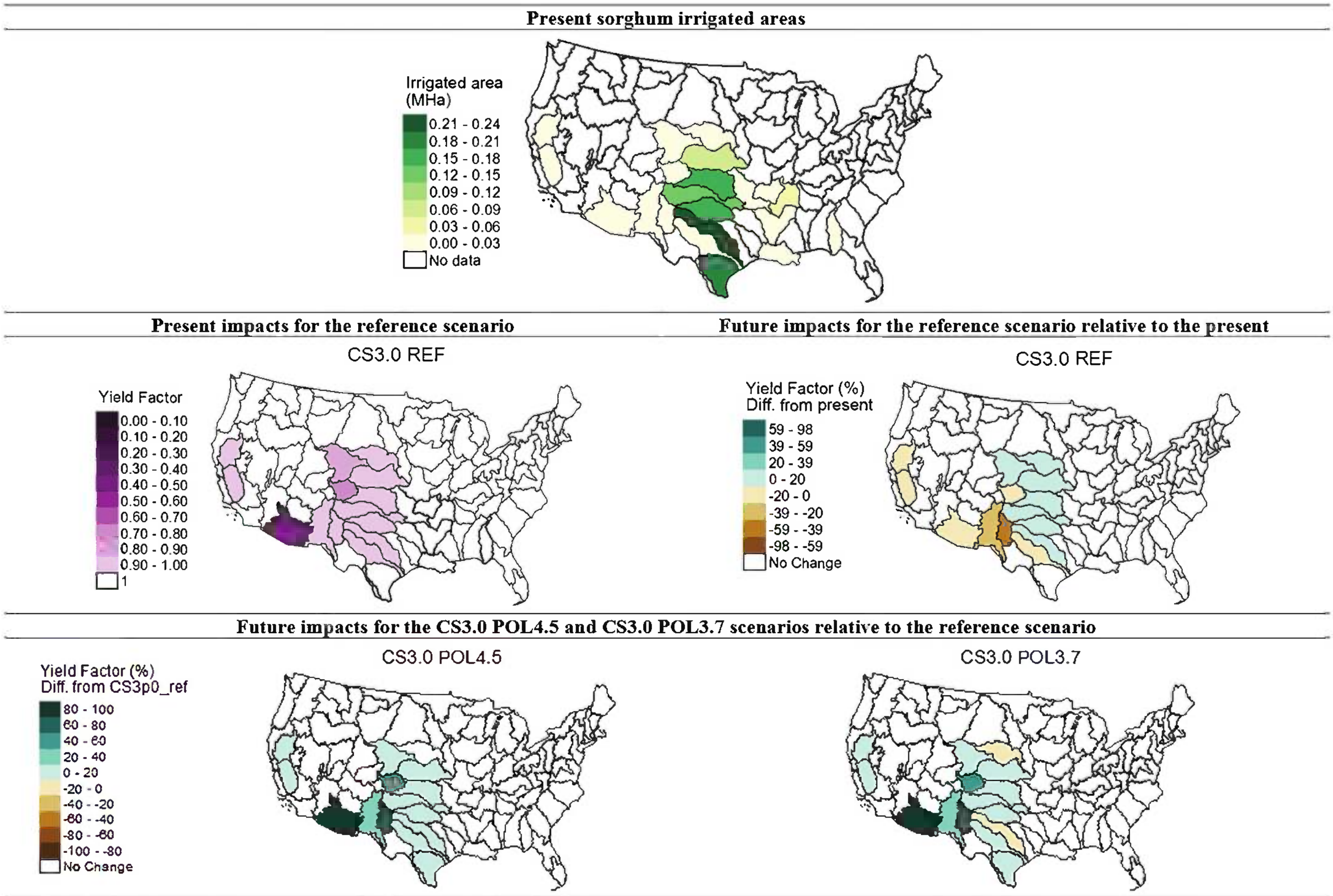

Figure 10. Sorghum yield factor in levels for the present (2005–2014) for the CS3.0 REF scenario and in percentage change for the future (2041–2050) relative to the present for the CS3.0 REF scenario, and relative to the CS3.0 REF for the CS3.0 POL4.5 and CS3.0 POL3.7 scenarios.

policies enhance future yield factors for all crops, and even offset the projected decrease in irrigated cotton yield factor. In particular, we show that reductions in water stress associated with GHG mitigation under both policies far offsets the negative impact from reduced CO_2 concentrations compared to the reference scenario. Furthermore, 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 *Waldhoff et al.* [2015].

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 change and socioeconomic 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—for example, *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 influences 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; *Strzepek, et al.*, 2015]. In this study, we attempt to investigate the overall uncertainty in our results by considering multiple socioeconomic and GHG mitigation scenarios, different representations of natural variability, as well as different global climate system responses (via different climate sensitivities). Our results show a large range of impacts on irrigated crop yields when considering such a large ensemble of integrated economic

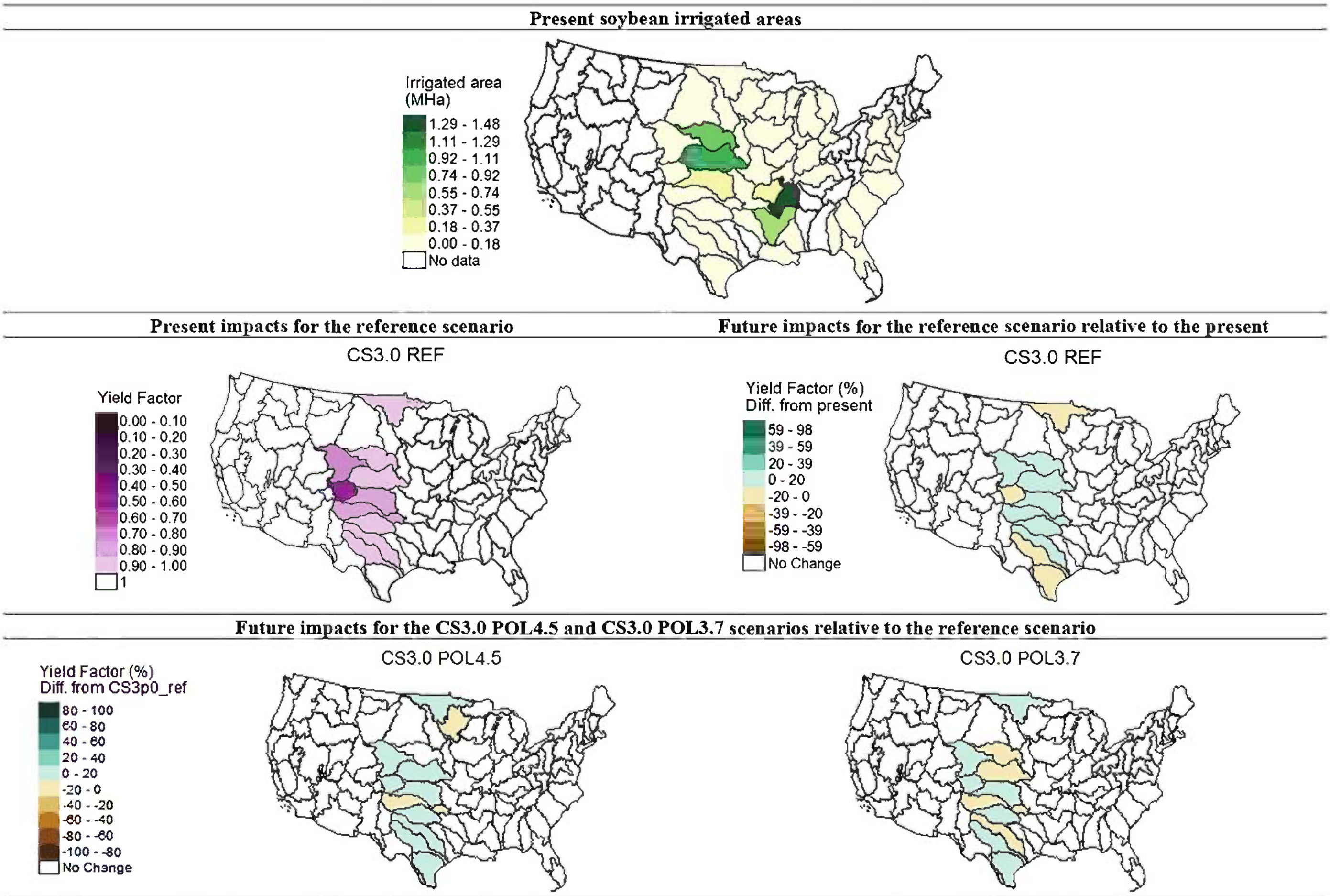

Figure 11. Soybean yield factor in levels for the present (2005–2014) for the CS3.0 REF scenario and in percentage change for the future (2041–2050) relative to the present for the CS3.0 REF scenario, and relative to the CS3.0 REF for the CS3.0 POL4.5 and CS3.0 POL3.7 scenarios.

and climate scenarios, and highlight the considerable uncertainty associated with natural variability in particular.

Our modeling framework does not track feedbacks 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 United States. These aspects are intentionally not considered in order to estimate the effect of climate change on irrigated cropping under actual conditions and therefore identify the areas the most vulnerable to irrigation shortages in the future. Also, our analysis focuses on crop 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 United States, which can be either negative and positive depending on the region.

5. Conclusion

This study describes the application of the IGSM-WRS-US, a model of U.S. water resource systems, to estimate the effect of climate change and socioeconomic 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 between the climatic, biological, physical, and economic elements of the system. It identifies areas of potential stress in the absence of specific adaptive

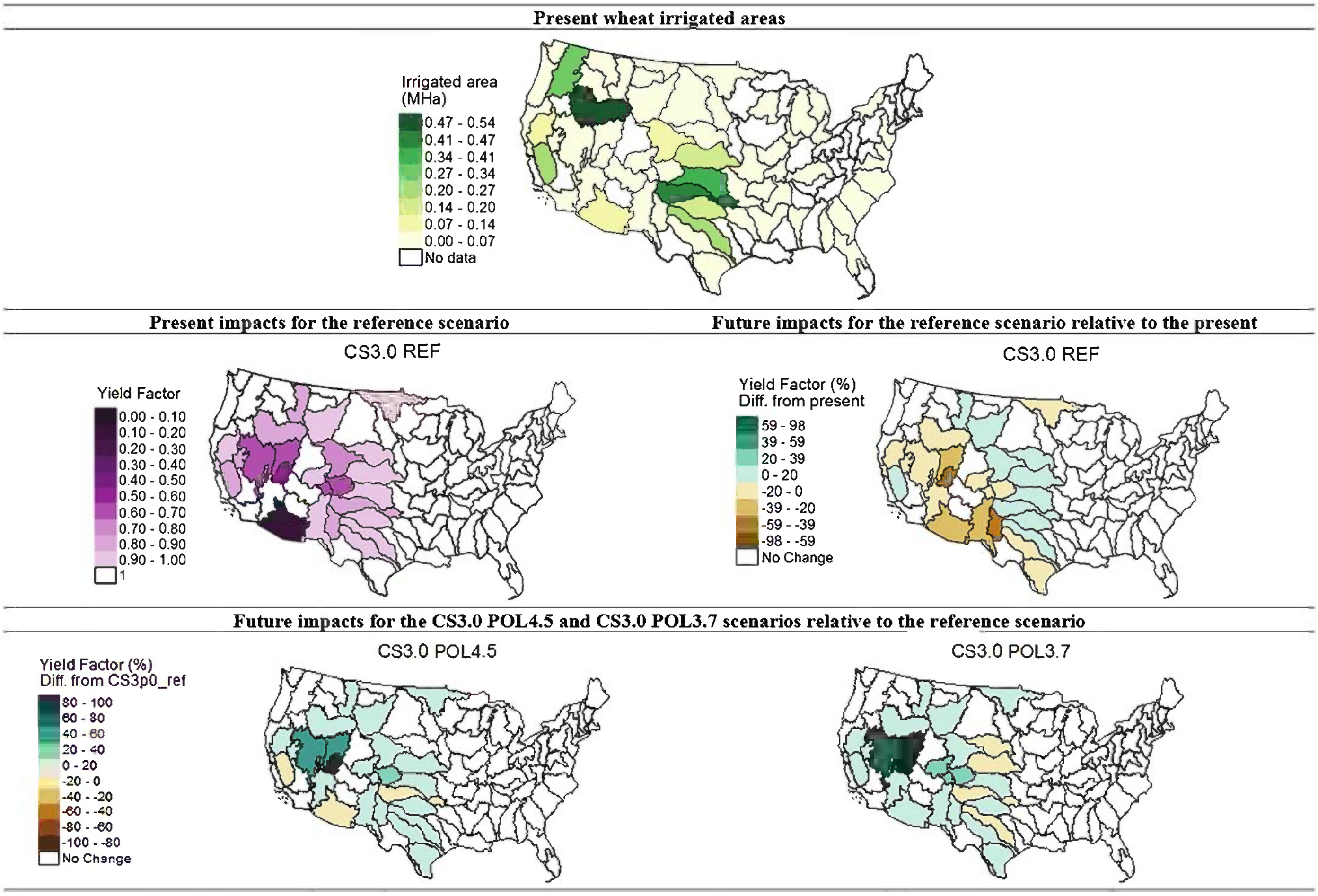

Figure 12. Wheat yield factor in levels for the present (2005–2014) for the CS3.0 REF scenario and in percentage change for the future (2041–2050) relative to the present for the CS3.0 REF scenario, and relative to the CS3.0 REF for the CS3.0 POL4.5 and CS3.0 POL3.7 scenarios.

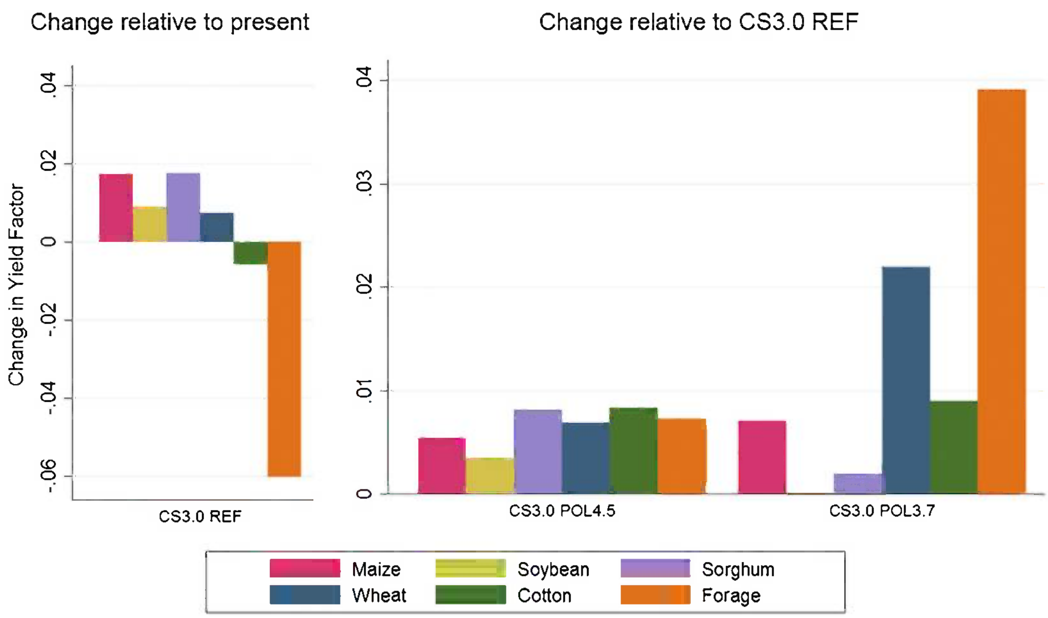

Figure 13. Future (2041–2050) U.S.-wide mean yield factor (weighted by irrigated area) by crop, averaged over natural variability cases for each scenario in absolute change compared to the present (2005–2014) and to the CS3.0 REF scenario.

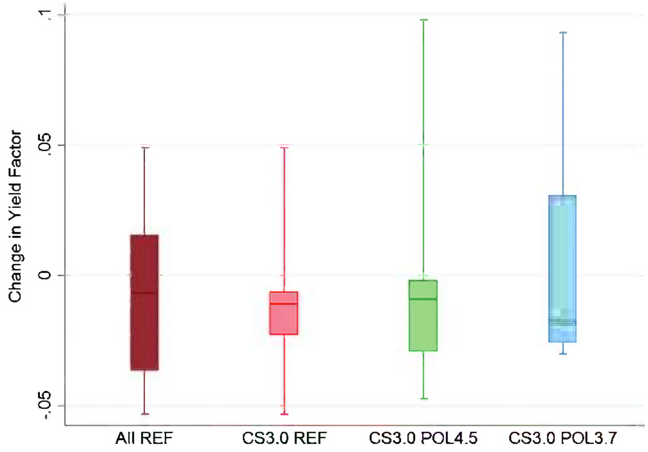

Figure 14. Box plot of changes in U.S.-wide mean crop yield factor (weighted by irrigated area) in the future (2041–2050) relative to the present (2005–2014). The boxes are computed over the five-member ensemble with different representation of natural variability for the CS3.0 REF, CS3.0 POL4.5, and CS3.0 POL3.7, and over the 15-member ensemble that include three different values of climate sensitivity and five different representation of natural variability for "All REF." The boxes represent the range of projections between the 25th and 75th percentiles. The lines inside the boxes represent the median predictions. The whiskers represent upper and lower values.

responses at the 99 river basin level for the continental United States through 2050 under a large ensemble of integrated economic and climate scenarios, including different GHG mitigation policies for the most commonly irrigated crops in the United States. On average, we find that 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. As a result we identify various basins where current irrigation is not sustainable. At the national level, however, climate and socioeconomic 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. Overall, our study shows potential for adaptation strategies, such as improvements in irrigation efficiency to reduce irrigation demand, but also relocation of irrigated cropland to regions less prone to water stress, to further develop irrigated agriculture in the coming decades. At the same time, these adaptation measures will be costly, as they will require relocation of agricultural production and transport capacity. Additionally, regions which are projected to be irrigation-constrained will lose irrigation's implicit value as an insurance mechanism against droughts and other adverse effects of climate change. Our study points to the areas and crops which will bear the burden of these costs.

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