Climate Change, Water Resources and Irrigated Crop Yields: A Modeling Framework for Integrated Assessment of the U.S.

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Abstract

While the impact of climate change on rainfed crop yields has been extensively studied, the study of the effect on irrigated crop yields has been more challenging due to competing water uses. By combining a water model and a crop model within the MIT Integrated Global System Model (IGSM) framework (Sokolov et al., 2005), an integrated assessment of the effects of alternative climate policy scenarios on irrigated crop yields is applied to the United States (US). In this analysis, we consider the effect of water shortage for irrigation on the three most important crops for the U.S.: maize, soybean and spring wheat. We find that water shortage for irrigation is expected to reduce irrigated crop yields especially for maize.

1. Introduction

Growing population and diet changes will require increases in food production. Currently, irrigated land, which consists of only 20% of total cultivated land, produces 40% of global food production thanks to crop yields on average 2.7 times larger than their rainfed counterparts (UNESCO, 2012). Expansion of irrigation can contribute to global production increase but can be costly and have serious environmental impacts (Reilly and Schimmelpfennig, 1999). The main constraint, however, is freshwater availability. Food production is already the largest user of freshwater with 70% of global freshwater withdrawal (UNESCO, 2012) and many areas are already water stressed (Wada et al., 2011). Climate change is likely to exert further pressure on irrigation capabilities by altering water resources and water uses. Climate change is expected to impact water availability by altering the geographic pattern of water resources (Arnell, 1999; Arnell, 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). The combined impact of changing water resources and requirements will have an impact in terms of crop yields.

While the impact of climate change on crops has been extensively studied, at the regional level (e.g. Auffhammer et al., 2012; Blanc, 2012; Lobell et al., 2011; Tao et al., 2012) or at the global level (e.g. Arnell et al., 2013; Deryng et al., 2014; Teixeira et al., 2013), the study of 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 future crop yields under different weather conditions but assume that there is no restriction on irrigation water availability. Water resource systems 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. (2013) assess the impact of future water availability for irrigation on crop productivity at the global level. As part of the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP), they use projections of water demand from ten global hydrological models and six global gridded crop models and water supply from the global hydrological models. They consider adaptation by allowing land use change between irrigated cropland depending on irrigation capabilities or constraints. They also account for domestic and industrial water use estimated using the WaterGAP model (Flörke et al., 2013). They find that by the end-of-century the change in production of maize, soybean, wheat, and rice at will decrease in the western part of the U.S., although the projections are contradicting for the Northern and Southern plains depending on the type of model (hydrological or crop model) used to calculate present-day irrigation demand. The major drawback of this analysis is that water stress impact on crop yields are estimated assuming future crop irrigation needs equivalent to present-day irrigation needs, while irrigated land and yields would change.

In this study, we propose an integrated assessment framework allowing the evaluation of the direct and indirect impacts of climate change on water resources and crop production by combining a water model and a crop model within the MIT Integrated Global System Model (IGSM) framework (Sokolov et al., 2005). We propose a spatially detailed analysis of the U.S. (99 river basins) to consider the effect of water shortage for irrigation on the three most important crops for the U.S.: maize, soybean and spring wheat.[1]

In a first section, we present the methods employed to model water and irrigation within an integrated assessment framework. The following section presents projections of climate change impact on irrigated crop yields through 2050. The last section concludes.

2. Method

To investigate the issue of water stress and irrigated crop yields for the U.S., we use the Water Resource System for the US (WRS-US) framework combining a water resource model and a crop model within an integrated assessment framework (IGSM), which models the global geophysical earth system and economic activity.

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[1] Water uses for all crops grown in the U.S. are accounted for in the analysis to determine water stress.

2.1. Integrated assessment framework

In the IGSM-WRS-US framework, the interaction of water resources and anthropogenic water requirements are analyzed using an integrated set of economic and earth system models. A schematic of the framework is provided in Figure 1 with the economic, climatic and hydrologic drivers on the left hand side and the water system on the right hand side.

Within the integrated assessment framework, IGSM (Sokolov et al., 2005), the global economy is represented by the Emissions Prediction and Policy Analysis (EPPA) model (Paltsev et al., 2005). This general equilibrium model simulates GHG emissions associated with the economic activity at the global level every five years. Interpolated hourly, global GHG concentrations are inputs into the MIT Earth System Model (MESM) (Sokolov et al., 2009), which encompasses both climate and land surface models. Latitudinally resolved climate variables are distributed longitudinally using precipitation patterns from archived global circulation models (GCM) using a Hybridized Frequency Distribution (HFD) approach (Schlosser et al., 2012), to provide hourly climate variables needed to simulate hydro-climatic conditions. Runoff is simulated as an output of CLM (version 3.5).

Daily accumulated precipitation and average temperature are used to drive the biophysical crop model, CliCrop (Fant et al., 2012), are also simulated using the HFD approach, and are thus consistent with the climate conditions used to simulate runoff. With these climate inputs, CliCrop simulates daily crop water requirements to maximize crop yields.

The EPPA model, in addition to simulating global GHG emissions contributing to simulated changes in climate, provides projections of U.S. economic activity resulting from different global policies. To obtain region-specific economic activity, EPPA provides boundary conditions to the U.S. Regional Economic and Environmental Policy (USREP) model coupled with the Regional Energy Deployment System (ReEDS) model (Rausch and Mowers, 2012). The USREP model (Rausch et al., 2010) provides economic projections driving water requirements. The ReEDS model (Short et al., 2009) integrated with USREP provides highly resolved (region and technology) projections of electricity production. Thermal power generation by region from USREP-ReEDS is used by the Withdrawal and Consumption for Thermo-electric Systems (WiCTS) model (Strzepek et al., 2012) to compute monthly water withdrawal and consumption (see Section 5.1.1). Also, GDP and population outputs from USREP are inputs to the calculation of water requirements for the other sectors, which are based on econometric estimated relationships.

The right hand side of Figure 1 describes the water system components of the framework, WRS-US (Blanc et al., 2014). Water requirements are composed of anthropogenic water needs for five sectors and environmental requirements. More details on these model components are provided in Section 5. Water resources simulations are provided in Section 4. The estimated resources and requirements are inputs to a Water System Management (WSM) module. As detailed in Section 3, WSM computes water balance and water stress for each basin. In this application, there is no feedback effect between sectoral water stress and national economic activity or agricultural production. 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 U.S.

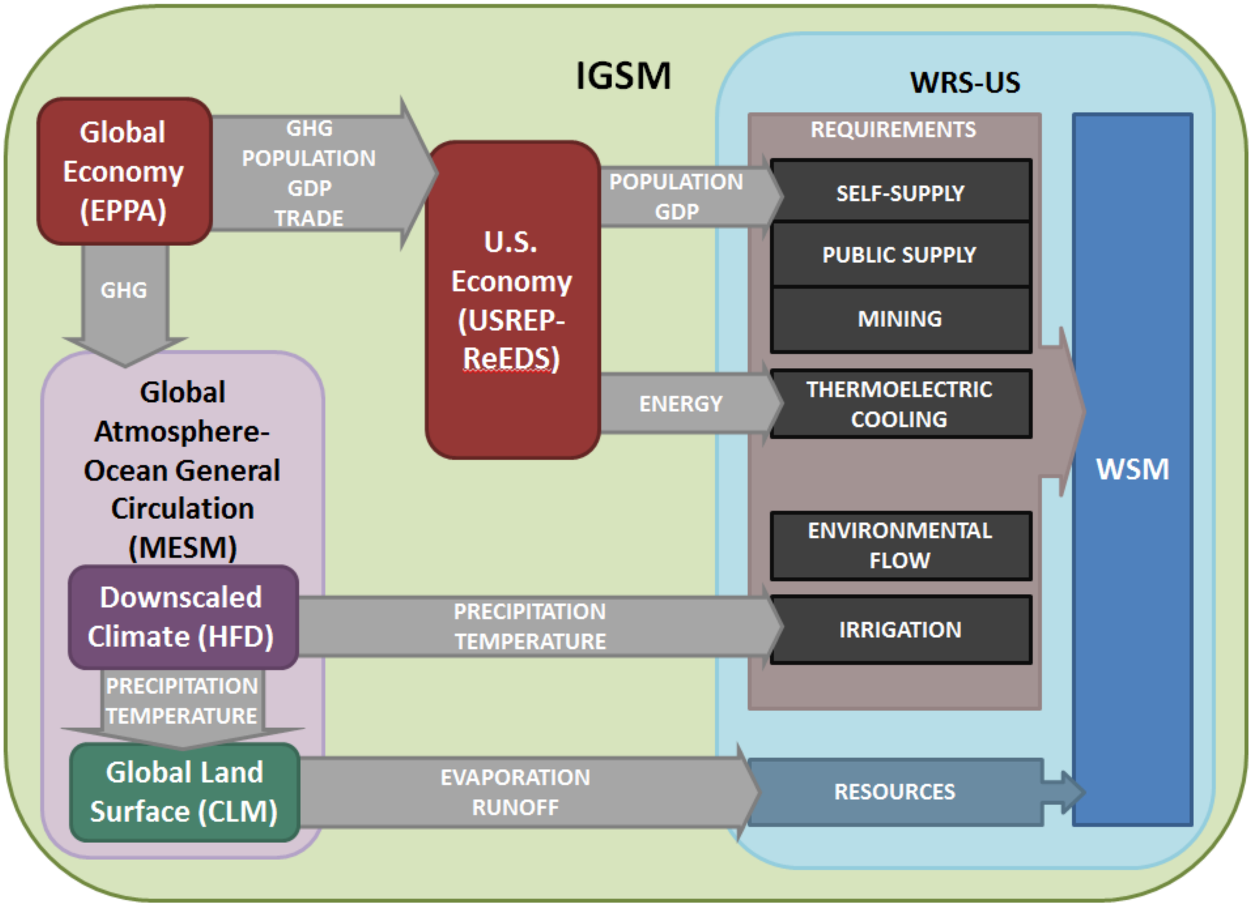


Figure 1. Schematic of the IGSM-WRS-US framework illustrating the connections between the different components of the IGSM framework and the WRS-US components

2.2. Water allocation modeling

Taking advantage of detailed data available for the U.S., the WRS-US model simulates water resources and requirements for 99 river basins following the Assessment Sub-Regions (ASR) delineation set out by the U.S. Water Resources Council (USWRC, 1978).

Water resources considered in WRS-US are mainly determined by runoff, which is estimated using CLM. Groundwater resources are estimated based on past uses. Water requirements are estimated for five sectors. Thermoelectric cooling water requirements are estimated using the Regional Energy Deployment System (ReEDS) model (Short et al.,

2009) integrated into USREP through fossil fuels as well as capital and labor prices and the demands for these commodities by the electricity sector. Water requirements for the public supply, self-supply and mining 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. Self-supply and mining withdrawals are determined by sectoral GDP.

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 smooths deficit across months. To do so, the model solves the allocation of water for each ASR simultaneously for all the months of each year. Upstream basins are solved first, and the calculation proceeds downstream following the structure of river flows. Water spilled from upstream basins becomes the inflow for downstream basins.

2.3. Crop yield and irrigation need modeling

To estimate irrigation needs, we can use two biophysical crop models. These models are used to calculate crop irrigation needs. Based on these needs and outcomes from the water allocation models, we can estimate the impact of water stress on irrigated yields.

2.3.1. Biophysical models

To estimate the water requirement at the crop level, we use the CliCrop model (Fant et al., 2012), which estimates crop water required at the root to eliminate all water stress. CliCrop is a biophysical model developed for use in integrated assessment frameworks (Fant et al., 2012). It is global, fast, and requires a minimal set of inputs. It is based on the Food and Agriculture Organization (FAO)'s CropWat model (Allen et al., 1998) for crop phenology and irrigation requirements, and on the Soil and Water Assessment Tool (SWAT, Neitsch et al., 2005) for soil hydrology. CliCrop runs on a daily timescale, has a 2°×2.5° grid resolution for the globe, and estimates crop water requirements (in mm/crop/month) to obtain maximum yields under given weather conditions for 13 of the most commonly grown crops. The irrigation requirement at the roots of the plant is defined as the difference between the evapotranspiration requirement (as defined by Allen et al., 1998) and the actual evapotranspiration as computed by CliCrop.

2.3.2. Irrigation needs

Daily crop water irrigation at the root required to obtain maximum yields is estimated by CliCrop at the grid cell level, g, (2×2.5 degree resolution) following the methodology of FAO's CropWat model (Allen et al., 1998):

$$IrrCons_{d,crop,g} = ETx_{d,crop,g} - ETa_{d,crop,g}$$

where maximum evapotranspiration (ETx) and actual evapotranspiration (Eta) represent the daily loss of water of a crop under rainfed conditions and a crop under perfect irrigation conditions respectively.

Water requirements at the ASR level (asr), $IrrCons_{m,asr}$, are estimated using the average daily crop water requirements within grid cells and irrigated area for each crop within each county. County level consumptions are aggregated over all counties lying within the ASR:[2]

$$IrrCons_{m,asr} = \sum_{cnt}\sum_{d}\sum_{crop}\frac{\sum_g IrrCons_{d,crop,g}}{G} * IRarea_{crop,cnt}$$

where G is the number of grid cell lying within a county, cnt and $IRarea$ is the irrigated area for each crop at the county level representative of the year 2002.[3]

[2] For counties overlapping several ASRs, the matching is based on the largest share of the county area lying within the ASR.

[3] Irrigated area is estimated using two sources of data: (i) the Farm and Ranch Irrigation Survey (FRIS), which provides detailed information on farm irrigation practices in 2002 (USDA, 2003); and (ii) the U.S.

2.3.3. Water stress impact on irrigated crop yields

Both crop models presented above follow the same crop yield factor method adopted by the CropWat model. The yield factor is calculated as:

$$\left(1-\frac{Ya}{Yx}\right)=Ky\left(1-\frac{ETa}{ETx}\right)$$

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. For crops very sensitive to water shortage, *Ky* >1, the yield reduction is proportionally larger than the reduction in water use. *Ky* <1 apply to crops that are more tolerant to water deficit, for which yield decrease less than proportionally to water use reduction.

The yield factor, *YF*, is then calculated annually as:

$$YF=\left(\frac{Ya}{Yx}\right)=1-Ky\left(1-\frac{ETa}{ETx}\right)$$

Crop water requirements different depending on the growing stage (Brouwer et al., 1989). Out of the four stage usually considered, the third stage, labeled 'mid-season stage', corresponds to the flowering and yield formation. This is the period of greatest water need.

Geological Survey (USGS, 2011), which provides detailed water use information every five years. FRIS provides irrigated area data detailed by crop but at the state level only. USGS (2011) provides information on irrigated area at the county level but does not detail irrigated area by crop. To obtain irrigated area for each crop at the county level, we use county level total irrigated area estimated by USGS for the year 2005 and state level crop specific irrigated areas estimated by FRIS for the year 2002. We allocate state level irrigated areas from FRIS using the ratio of total irrigated area at the county level within each state from USGS following the formula:

$$IRarea_{crop,cnt}=IRareaFRIS_{crop,state}*\frac{IRareaUSGS_{cnt}}{\sum_{cnt}IRareaUSGS_{cnt}}$$

Therefore, a water shortage within this season will have the largest detrimental effect on crop yields. The values of *Ky* will therefore differ by crop and by growing stage (see Table 1) but are common for both CliCrop model.

Table 1. *Ky* values by growing stage and crop type

	1	2	3	4
maize	0.4	0.4	1.3	0.5
soybean	0.4	0.8	1	0.4
spring wheat	0.2	0.6	0.8	0.4

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

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

where crop evapotranspiration under water stress, *ETaS*, is calculated as:

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

IR_SRR represents the irrigation supply requirement ratio, i.e. the ratio of water allocated to irrigation compared to what would be required to obtain maximum irrigated crop yield. The term $(ETx_{crop,cnt,gsc} - ETa_{crop,cnt,gsc})$ represents crop irrigation requirement 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 mean that none of the water necessary for irrigation is available and therefore irrigated crop yields are similar to rainfed crop yields.

3. Projections through 2050

3.1. Scenarios

Water uses and resources are modeled out to 2050 and consider a range of emission scenarios as well as a range of regional shifts in climate patterns. Starting at 2010, two emission scenarios are considered: (i) an unconstrained emissions scenario (UCE) that assumes that no specific effort is made to abate GHG emissions; and (ii) a 'Level 1 stabilization' (L1S) scenario that assumes that GHG emissions are restricted to limit the atmospheric concentration of CO_2 equivalent GHGs to 450 ppm (Clarke et al., 2007). These scenarios serve as inputs into the IGSM climate model (Schlosser et al., 2012) to provide representative 'dry' and 'wet' projections, respectively labeled 'U.S.-DRY' and 'U.S.-WET'.

3.2. Results

3.2.1. Water stress

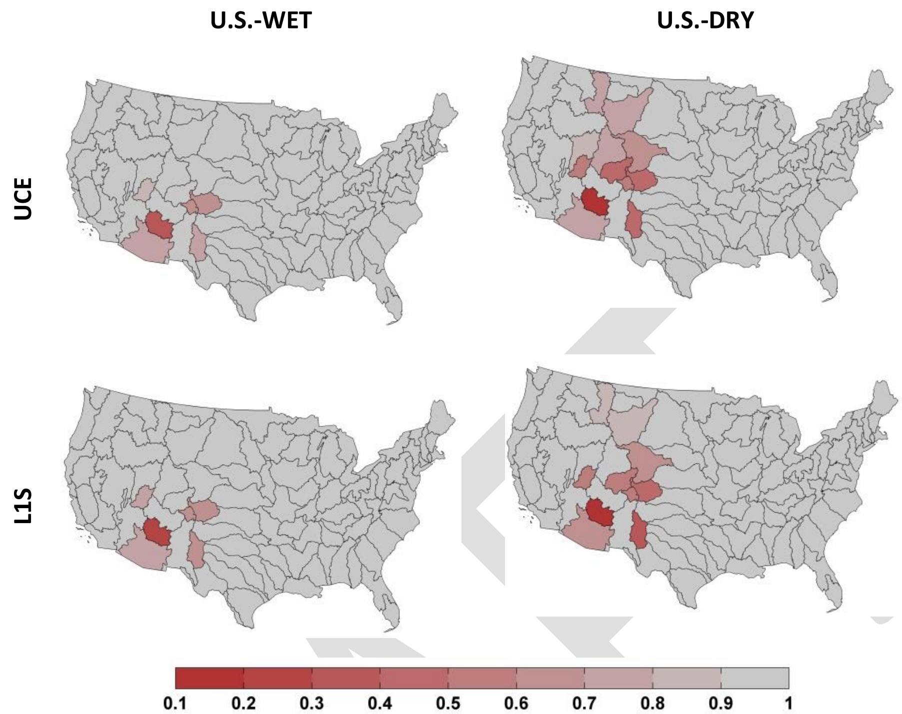
To determine future water stress and allocation, the WRS-US model considers projections of water resources and water uses. Runoff is projected using bias-corrected estimates from CLM under the two policy scenarios and three climate patterns. Total basin natural runoff (not including inflows from upstream basins) is projected to slightly increase toward the mid-century in all cases but to be generally lower under the L1S than under the UCE scenario. For each policy, the projected runoff is very similar for the two climate change patterns (wet vs. dry).

Water requirements for the thermoelectric cooling, public supply, self-supply and mining sectors, are simulated using predictions of population, total GDP and value added of the mining sector. These inputs are predicted by the USREP model under the two emission scenarios. Population is projected to increase steadily over the period 2005 to 2050 with no difference between the UCE and L1S scenarios. U.S. water requirements are projected to increase for all sectors with the largest increases in water requirements being projected under the UCE scenario.

Irrigation water requirements are projected using the CliCrop model. In this study, we assume that there will be no change in the location and amount of irrigated cropland. This condition can be relaxed in subsequent model development as production, area under production, and the location of production may change in the future, with or without climate change. Our goal is to identify currently irrigated areas that may be subject to water limitations. Water requirements for irrigation are driven indirectly through the effect of the different policy scenarios on climate. Some increases in irrigation water requirements are predicted by mid-century, especially under the UCE scenario.

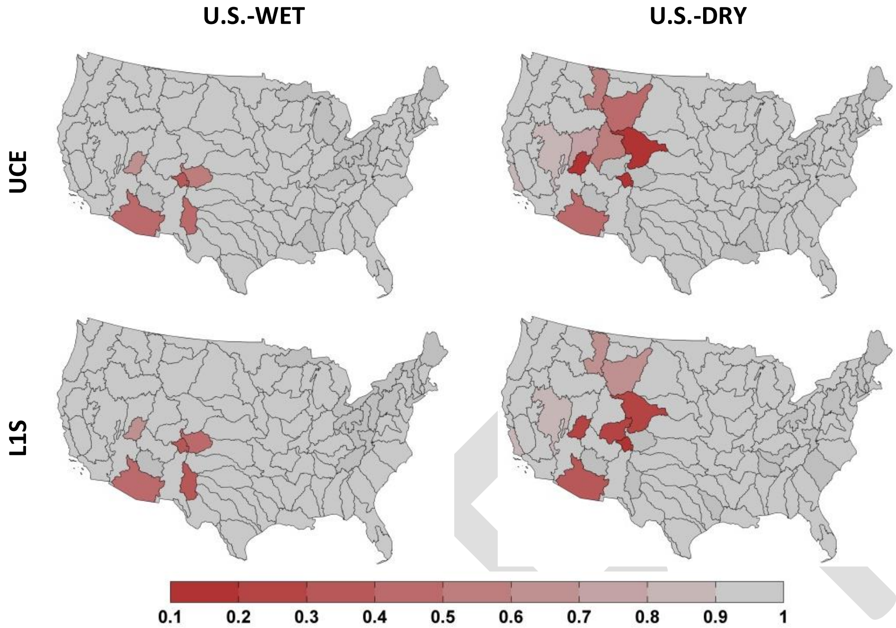
Using the sectoral water requirements and water resources estimates presented above, we evaluate water stress using the water Supply-Requirement Ratio (SRR). SRR is calculated monthly as the ratio of total water supplied over total water required for each sector. This water stress indicator represents physical constraints on anthropogenic water use. Projections of an annual average of SRR for all ASRs weighted by their sectoral water requirements shows that water stress is generally increasing (as the average SRR decreases) under all climate patterns, and especially under the U.S.-DRY climate pattern. The water stress is slightly smaller under stringent GHG controls. As depicted in Figure 2, average annual water stress by mid-century is predicted to increase the most in the South West, with or without climate policy. This water stress is mostly attributable to increases in water requirements, which are mainly driven by irrigation requirements. The choice of climate pattern considered for projections also greatly influences the outcome of the model. On average, larger water stresses are projected under the U.S.-DRY climate pattern, than under the U.S.-WET climate pattern. The impact of a constrained GHG emission policy will generally lessen the increase of mean annual water stress, especially in the U.S.-DRY case. A more detailed analysis of water stress at the monthly level revealed that the variability of monthly water stress is less under the L1S scenario than under the UCE scenario in most basins.

Figure 2. WRS-US total supply requirement ratio averaged over the prediction period (2041-2050)



Irrigation is a residual user, i.e. is allocated water only if the requirements of other sectors are met. Therefore, as the irrigation sector is more affected by a water stress, the irrigation specific SRR is larger than the overall SRR (see Figure 3).

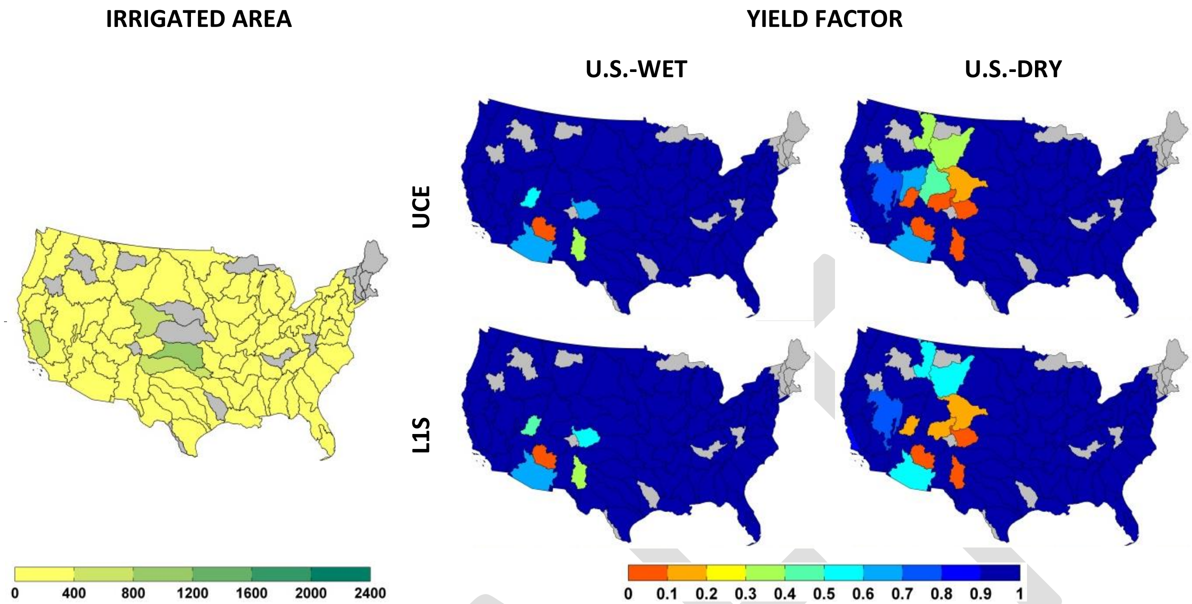
Figure 3. WRS-US Irrigation supply requirement ratio averaged over the prediction period (2041-2050)



3.2.2. Irrigated yields

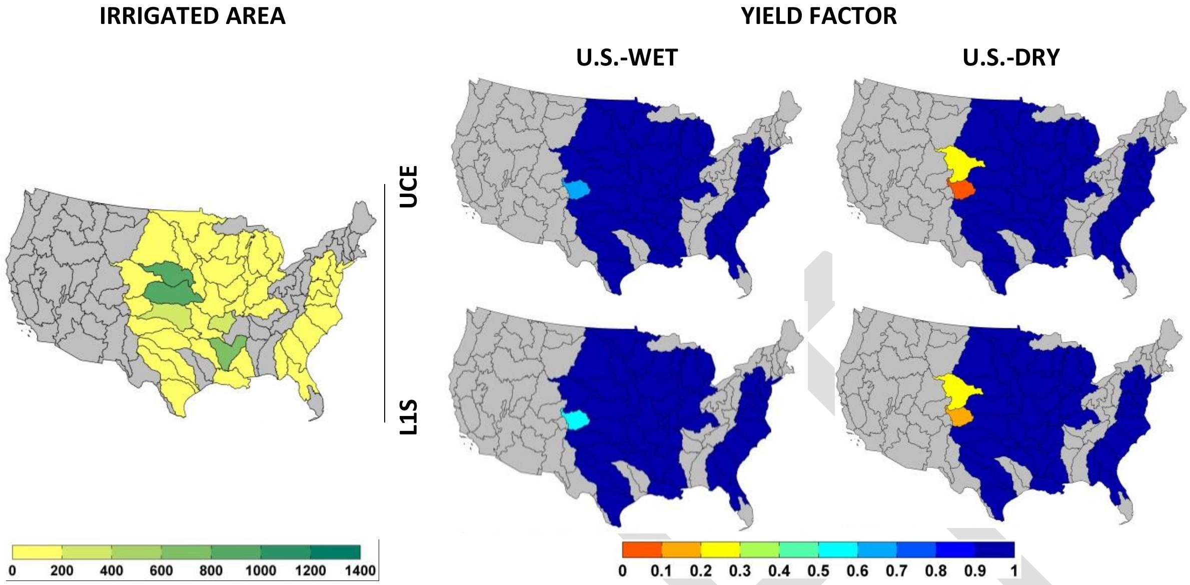
The estimated monthly water stress and its impact on water allocation are then used to determine the impact on irrigated crop yields. Results are provided for maize, soybean and wheat for the prediction period in Figures 4 to 6. Results show that the lack of water available for irrigation in some basins will entail a large reduction in irrigated crop yields in the West. Maize is as expected the crop the most vulnerable to a lack of water. Yield factor for this crop is less than 10% in 5 ASRs (ASR 1402, 1102, 1602, 1501 and 1304) under the UCE-U.S.-DRY scenario. The impact of water stress is somewhat alleviated in two of these basins under a GHG policy. For the North and South Platte basin (ASR 1007), however, the impact is similar under both economic policy under the U.S.-DRY policy which would entail an important reduction in maize production given the extensive area of maize production under irrigation. For this same basin, the effect of a climate policy is beneficial under the U.S.-WET climate scenario, as it will eliminate water stress and the corresponding impact on the yield factor.

Figure 4. CliCrop yield factor for maize (weighted by irrigated area)



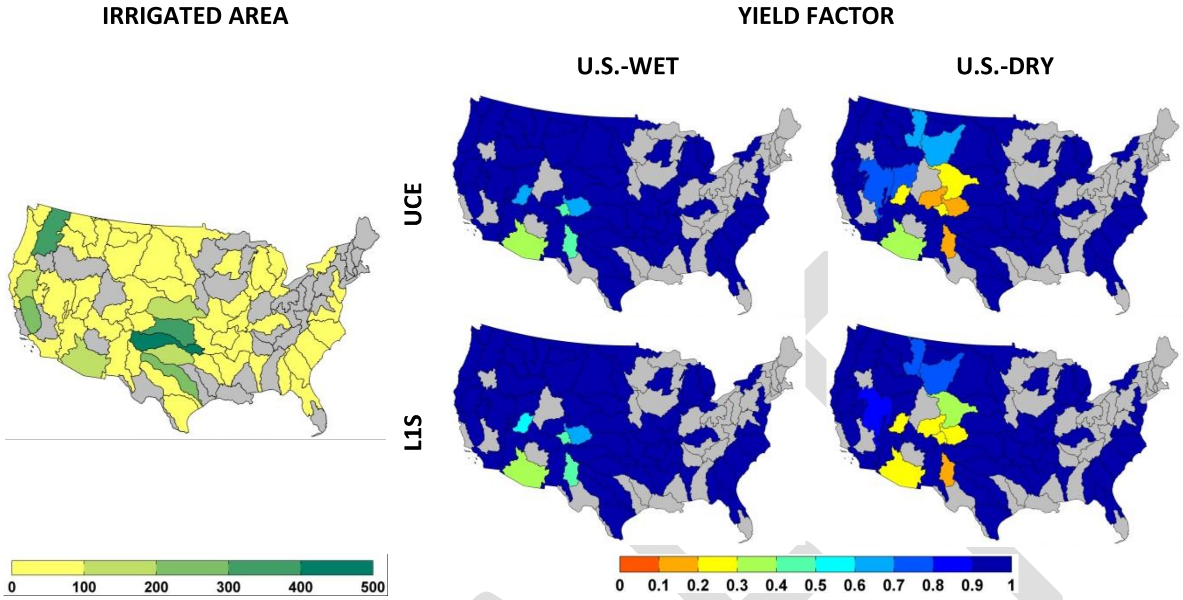
For soybean, which is irrigated only on the Eastern part of the U.S., the effect of water stress is much lower than for maize. As can be seen on Figure 5, the North and South Platte (ASR 1007) and Upper Arkansas (ASR1102) basins are projected to experience the largest reduction in soybean yields in the U.S.-DRY scenario. In the UCE case, where the irrigated area is one of the largest, the Kansas basin (1010) will experience a 14% decrease in soybean yield having important consequences on crop production. An interesting result is observed in the San Joaquin-Tulare, located in the Central Valley of California, which is renowned for its irrigation-intensive agriculture. In this basin, no water stress is predicted and therefore no stress on irrigated maize yields. This result is explained by the assumption of the model that actual water transfer agreement will be respected in the future and that California will receive current inflow of water and therefore will not suffer greater water stress.

Figure 5. CliCrop yield factor for soybean (weighted by irrigated area)



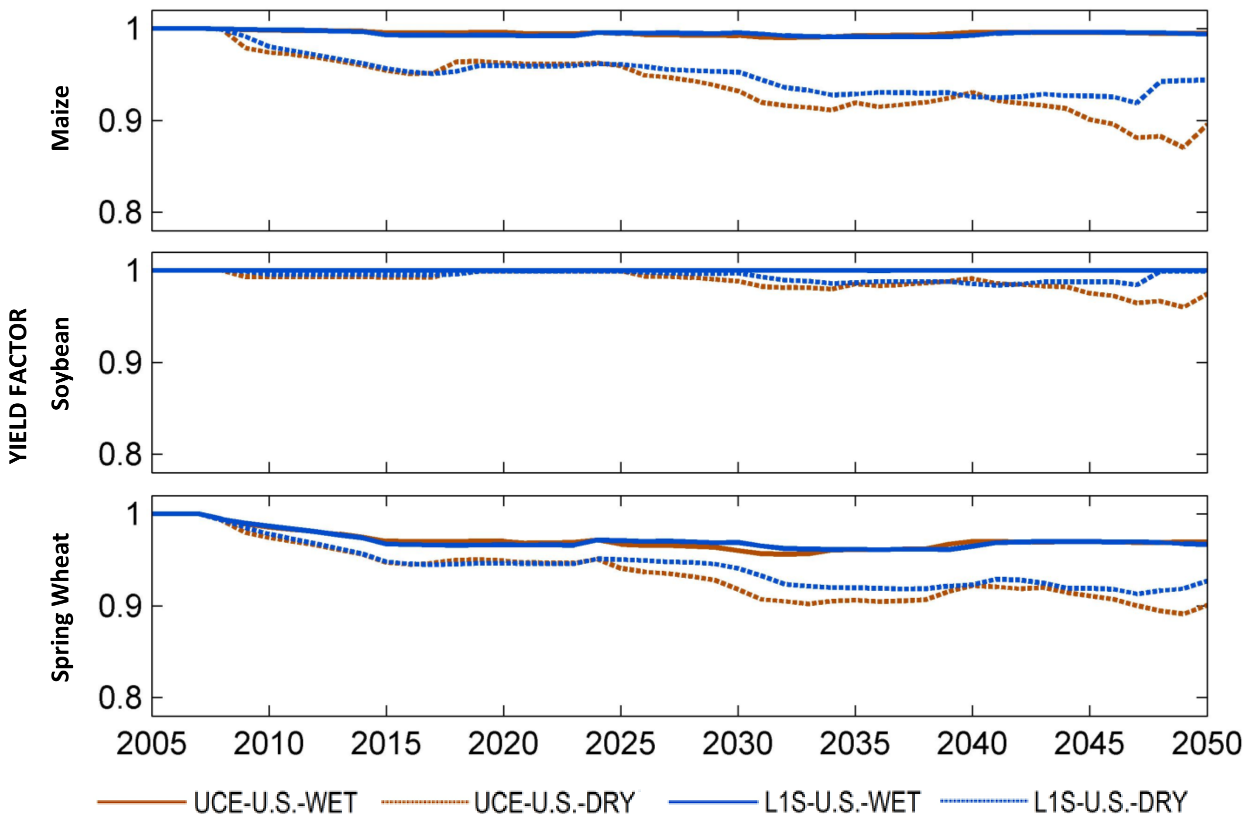
Spring wheat is more affected by water shortages than soybean but less than maize. As for the other crops, the yield factor is smaller under the U.S.-DRY scenario than under the U.S.-WET scenario. Under the U.S.-WET scenario, a GHG reduction policy does not entail significant change in spring wheat yields compared to a business as usual scenario. Under the U.S.-DRY scenario, however, the yield factor is lower, hence the yield reduction is smaller, under the UCE than under the L1S scenario The basin the most reliant on irrigation, Upper/Central Snake (ASR 1703), is not expected to be affected at all in any scenario.

Figure 6. CliCrop yield factor for spring wheat (weighted by irrigated area)



The maps presented above provide crop yield factor as weighted average within each basin. However, as shown in the irrigation maps, irrigated areas are clustered in a limited number of basins. To have a better idea of the U.S. wide impact of water stress taking into the importance of irrigated area, we provide in Figure 7, an average of crop factor over all basins weighted by irrigated area. The graphs show that overall, the yield reduction average between 80 and 100% for the U.S. The largest decrease in yield is expected under the U.S.-DRY case. Maize yields will also be the most affected by water stress under this climate change scenario. However, under the U.S.-WET scenario, spring wheat is expected to experience the largest effect from lack of irrigation water.

Figure 7. CliCrop yield factor (weighted by county level irrigated area) 10 year moving average



4. Conclusion

This study presents an extension of the IGSM-WRS-US, a model of U.S. water resource systems, to consider the effect of water stress on crop productivity. To this end, it links a water resource system model and a crop model. It is unique in its consistent treatment of the complex interactions of climatic, biological, physical and economic elements. It identifies areas of potential stress in the absence of specific adaptation responses at the 99 ASR level for the continental U.S. through 2050 under two climate policies and climate change scenarios. In this analysis, we consider the effect of water shortage for irrigation on the three most important crops for the U.S.: maize, soybean and spring wheat.

We estimate that, with or without climate change, average annual water stress is predicted to increase in the Southwest. The study reveals that the choice of climate pattern considered for projections greatly influences the outcome of the model. On average, larger water stresses are projected under the U.S.-DRY climate pattern, than under the U.S.-WET pattern. The impact of a constrained GHG emission policy (L1S scenario) will generally lessen the increase of mean annual water stress, especially in the U.S.-DRY case. This water stress will translate into water shortage for irrigation. Results show that the lack of water available for irrigation in some basins will entail a large reduction in irrigated crop yields in the West. The water stress impact on crop yield differs by crop with maize being the most sensitive to water shortages.

These results demonstrate the importance of considering the integrated effect of climate change on water resources and crop yields at a detailed river basin level. The water stress analysis shows that is localized and that the disaggregation at the 99 river basin level is necessary to estimate the impact of water shortage on irrigation water use and resulting crop yields. Also, as showed by (Blanc et al., 2014), the increase in water stress is mostly attributable to increases in water requirements, especially irrigation. By not accounting changes in irrigation needs, a large part of the climate change impact on irrigation capabilities and crop yields is ignored.

In this framework, we assumed no change irrigated areas in the future in order to estimate the impact of water shortage in the absence of adaptation. We are therefore able to identify areas already under stress and unlikely to sustain irrigation expansion and intensification. In order to meet increasing food demand, irrigated croplands are likely to expand and therefore irrigation necessary to produce optimum yields increase. Alternatively, the expansion of irrigated area will also have a feedback effect on climate by altering weather patterns. The current assessment framework could be used to estimate this effect.

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