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IIASA www.iiasa.ac.at

Address: IIASA, Schlossplatz 1, A-2361 Laxenburg, Austria

Email: cmwade2@ncsu.edu

Young Scientists Summer Program

Irrigation Response to Climate Change in the US

Christopher M. Wade
cmwade2@ncsu.edu

Approved by:

Mentors: Tamás Kriszten, Stefan Frank
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Mentor signature:

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Abstract

The net impacts of climate change on global agriculture are uncertain, due to confounding effects such as elevated levels of atmospheric carbon, increased temperatures resulting in higher evapotranspiration demands, increased variability in precipitation, and increasing events of severe weather[1]. Increasing the amount of irrigation being applied to crops can compensate for increased evapotranspiration demand, reduce heat stress, and accelerate phenological processes[2,3], possibly reducing the negative impacts from a warming climate. In the United States, irrigated area has remained relatively constant over the past two decades, while irrigation intensity has declined as irrigation technology has improved, crop mixes have changed, and shifts in where irrigation is applied has occured[4]. Overall, it is projected that irrigation may be an adaptation strategy to limit the impacts of climate change on agricultural production. This study utilizes a global biophysical model of the agriculture, forestry, and other land use sectors (GLOBIOM) to assess the potential for intensive and extensive expansion of irrigation applications in the Unites States under a range of projected climate futures. It is shown that irrigated area is expected to expand across most climate change scenarios, while irrigation water consumption increases but at a smaller rate resulting in reduced irrigation intensity on average. Additionally, the location of irrigated cropland shifts with an intensification of irrigation usage in the southern corn belt on acres producing corn; and an extensive expansion of irrigated cropland to produce wheat in the northwest US.

About the author

Christopher Wade is a Ph.D. student in Forestry and Environmental Resources at NC State University minoring in Economics. He currently works as an applied natural resource economist at RTI international while pursuing his doctoral degree. His research focuses on applying dynamic, spatially explicit modeling frameworks to assess tradeoffs in coupled human-environmental systems. His research covers an array of topics including forestry, land use, climate change mitigation, interactions between water and land use management, and coastal resources. (Contact: cmwade2@ncsu.edu)

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Introduction

Climate change and increasing carbon dioxide (CO_2) is expected to increase variability of precipitation patterns and increase average temperatures globally [5–7]. Extreme events such as droughts, floods, heat and cold waves can all impact agricultural productivity [8], while increased CO_2 levels have the potential to shorten crop growing stages and reduce accumulated biomass which may decrease yields [2]. Overall, the productivity of cropping systems are expected to be greatly impacted by a changing climate and increased variability in weather patterns [2,9,10]. While the overall net effects of climate change on agriculture is uncertain, it has been suggested that irrigation has the potential to compensate for increased evapotranspiration demand, reduce heat stress, and accelerate phenological processes [1–3].

Globally, about one-quarter of cropland is irrigated with about 70% of total water withdrawals being used for irrigation [11,12]. Overall, about 35% of agricultural production is from irrigated cropland, with expected declines in yield of global cereal production of about 20% if irrigation was not utilized [12,13]. In the United States, irrigated area has remained relatively constant over the past two decades, while irrigation intensity has declined as irrigation technology has improved, crop mixes have changed, and changes in the location where irrigation is occurring [4]. In 2017, it was estimated that irrigated farms produced more than 54% of total crops by value in the US. The USDA acknowledges that irrigation practices are expected to be impacted under climate change with the sector undergoing shifts in crop mixes, changes in regional cropping patterns, and technological improvements leading to increasing irrigation efficiency [4].

Due to the global impacts of climate change and the connected nature of agricultural markets through international trade, it is vital when assessing the impacts of climate change even at a national or subnational scale to utilize a global modeling approach [14,15]. Here we use a global biophysical model of the agriculture, forestry and other land uses sectors to try to answer three specific questions. First, we hope to further shed light on how US agriculture may respond to a changing climate. Second, subnational cropping patterns are reviewed to see how crop mixes, and agricultural activities may move within the US under climate change, and third, the potential for intensive and extensive expansion of irrigation use under climate change is assessed. Finally, we present areas for further expansion of this work and begin to assess how the US may increase or decrease its competitiveness in production of specific crops under climate change.

Methods

The Global Biosphere Management Model (GLOBIOM) is used to assess the impacts of climate change and the potential for irrigation expansion to be utilized as an adaptation strategy to these impacts. GLOBIOM is a partial equilibrium model representative of the global land use sector [16–18]. The model is recursive dynamic, solving in decadal timesteps from 2000 – 2100 by maximizing net welfare (the sum of consumer and producer welfare). GLOBIOM represents bilateral trade with representative trade costs with 37 demand regions (including the US as a single region). The model also includes endogenous land use change based on relative profitability, with full greenhouse gas accounting of the agriculture, forestry, and other land uses (AFOLU) sector [19]. Previously, GLOBIOM has been used to assess climate change induced shifts to agriculture [20], how trade may be used to lessen the impacts of climate change [14], mitigation potential from agricultural non-CO_2 emissions to reach 1.5° C targets [21], and the potential for healthier diets to mitigate greenhouse gas emissions [22].

Recent efforts have concluded in an updated scenario design within the GLOBIOM framework that encompasses climate change impact projections to crops and forestry production through shifts in precipitation, temperature, and carbon fertilization based on the World Climate Research Programme's global climate modelling effort CMIP Phase 6 [23]. Globally gridded yield, input requirements, and cost impacts (to both irrigated and rainfed cropping systems) from shifts in weather and climate patterns were estimated using the Environmental Policy Integrated Climate model (EPIC) across a range of global circulation models to account for uncertainty [24,25]. Irrigation water availability across a range of climate and socioeconomic futures was projected using the Community Water Model (CWatM) [26,27].

For this analysis, projections from three different earth systems models (IPSL-CM6 [28], MRI-ESM1 [29], and UKESM1 [30]) and three different representative concentration pathways (RCPs) (2.6, 7.0, 8.5) [31] were implemented into GLOBIOM. These three earth systems models represent two of the more pessimistic (UKESM1 and IPSL-CM6) and one of the more optimistic (MRI-ESM1) futures with respect to global crop yield impacts and may provide upper and lower bounds of the net impact from climate change on global agriculture [32]. In the following section, projections from each climate change scenario and a baseline-no climate change impacts scenario are presented.

In order to assess the potential for irrigation to be used as an adaptation measure to climate change, the irrigation area in the United States was updated in GLOBIOM to better align with recently updated data from the United States Department of Agriculture's Irrigation Yearbook [33]. Previous inputs in the GLOBIOM model overestimated irrigation usage in the United States, which has remained relatively constant over the past 15 years. State level, crop specific irrigated areas from 2017 were collected for corn, wheat, soybeans, rice, cotton, and potatoes. This represents about 30.8 million acres out of 32.2 million acres included in the USDA dataset. To account for spatial heterogeneity in irrigation practices, each land unit (SIMU) in the United States was spatially weighted to the states which it overlaid. Then, state totals of irrigated area for each crop were proportionally assigned to the overlaying spatial unit. Figure 1 presents the revised total irrigated area by SIMU based on the USDA Irrigation Yearbook [33]. The revised input data results in better alignment in projected irrigated area from GLOBIOM and the historical data, with irrigated corn area dropping from about 48 million acres to 18 million acres (Figure 2).

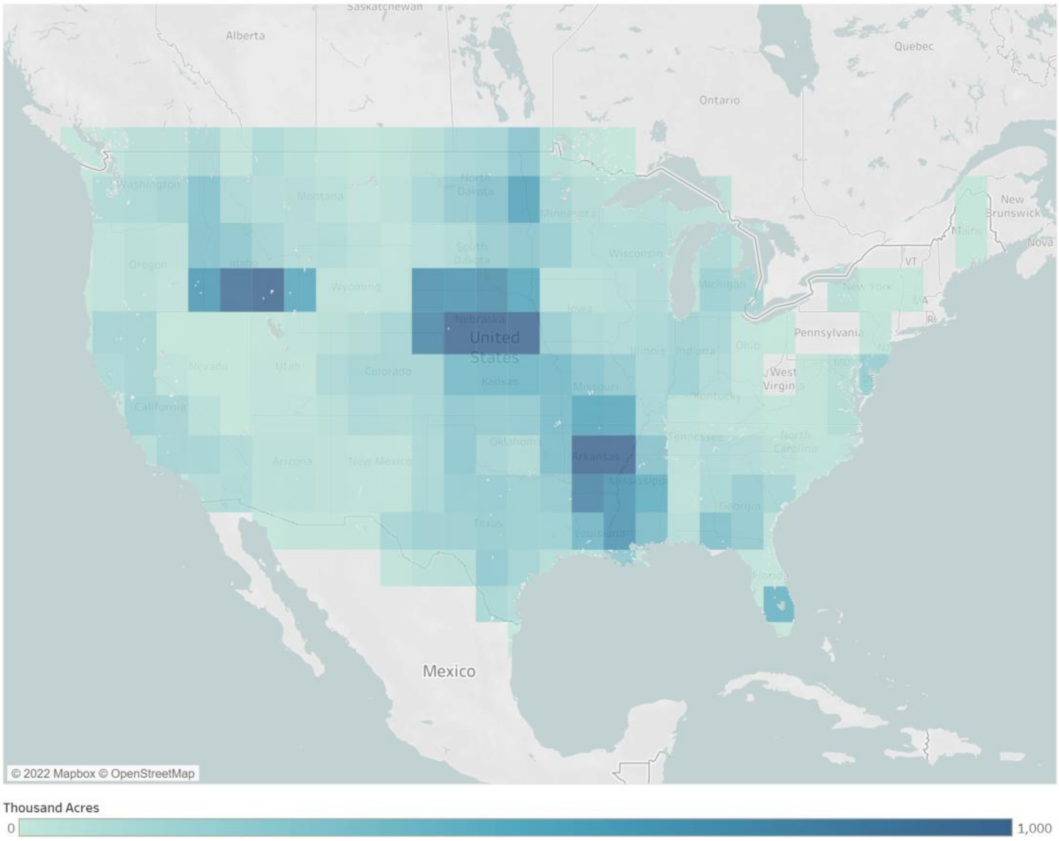

Figure 1: Total irrigated area by GLOBIOM simulation unit (SIMU) in revised input data for the year 2000.

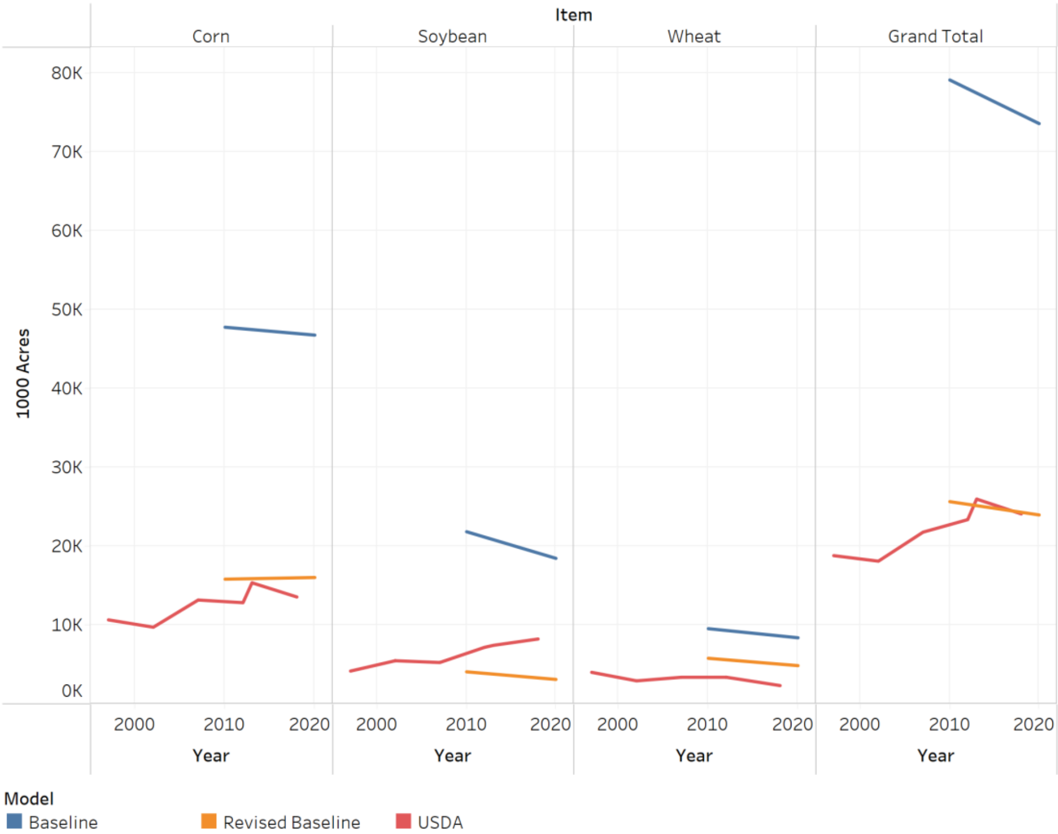

Figure 2: Projected irrigation area for corn, soybeans, wheat, and the total of these three crops from the original GLOBIOM baseline, the revised baseline, and historical measures from USDA.

Results

Global impacts to agriculture due to climate change

Overall, climate change is expected to negatively impact global agricultural productivity due to rising temperatures and increased variability of precipitation. Global production in 2050 is projected to decrease by 1.9% on average across each climate scenario (with a range of +0.3% to -4.8%), which results in a decline of nearly 300 million tons of agricultural production (Figure 3). Major grains used for both food and feed, including corn and soybeans, are expected to be the largest hit commodities with an average decline in production of 4.6% (-0.6% to -7.8%) and 5.6% (-0.7% to – 9.1%) respectively. Reduced productivity of major crop feeds leads to a decline in meat production as well, with an average decline of 3.0% (+0.3% to -6.4%) in 2050 of all meat production. This can be considered conservative since climate impacts on pastures were not considered in the assessment. Global producer prices are negatively impacted by climate change (resulting in higher prices), with most crop and meat prices increasing significantly on average. This leads to a reduction in demand and thus a reduction in land area used for agriculture production. Climate change impacts also shift the average global diet and result in an overall decline in average caloric intake of about

0.5% (+1.0% to -2.6%), mostly driven by a decline in meat consumption (average decline of 3.2%, with a range of +0.4% to -6.5%).

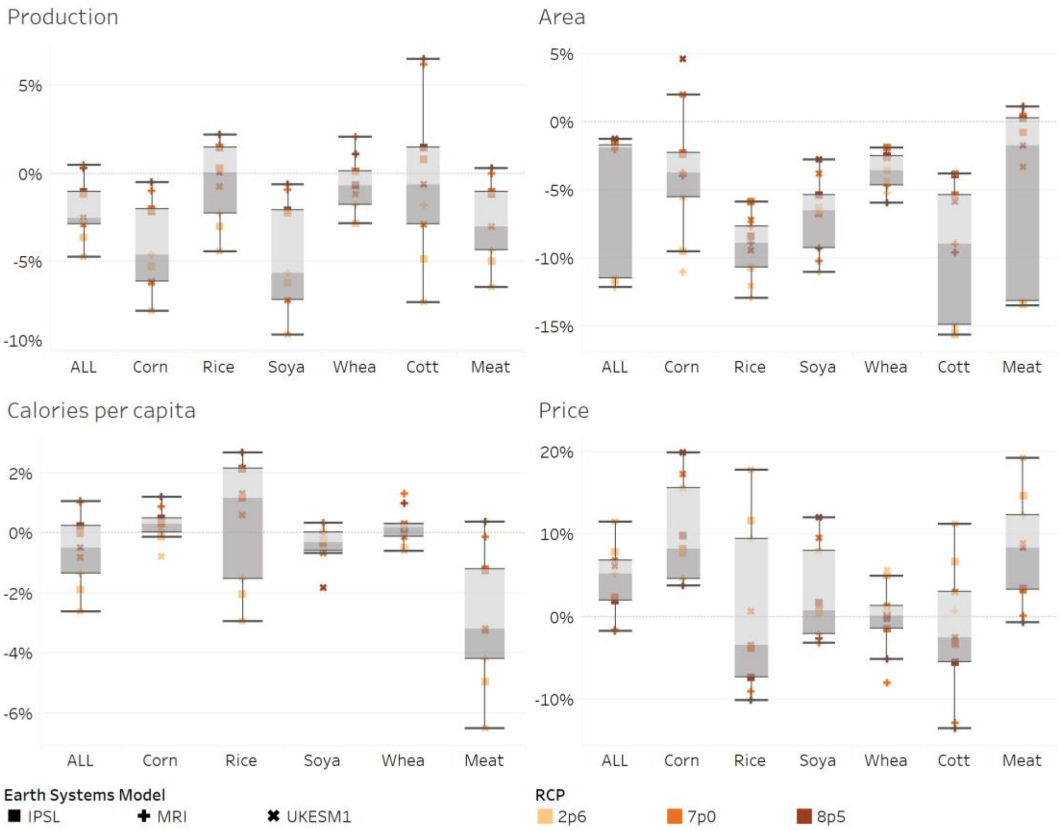

Figure 3: Global impacts from climate change to the agricultural sector in 2050 relative to a stable climate future.

United States impacts to agriculture due to climate change

Compared to global impacts, the impacts of climate change on US agriculture are more varied (Figure 4). Some crops, such as wheat and rice, benefit from increasing temperatures resulting in increased yields. This allows cropland area to decline slightly on average (-1.7% on average, with a range of -0.8% to -3.8%). Despite an overall decline in crop area relative to a stable climate, our results suggest that planted areas of both rice and wheat could increase due to shifts in relative productivity in the US compared to other regions. On average, wheat area is projected to increase by about 2.1 million acres. Production across all agricultural commodities remains relatively constant across all scenarios, with rice and wheat increasing in production, and soybean and cotton production declining as the US' competitive advantage in production of these crops declines when climate change impacts are included. Despite a stable level of production (or even increasing for some crops), the US is projected to have increasing producer prices under climate change, as regions that have historically been highly productive see declining yields due to higher temperatures and reduced precipitation. This results in a spatial shift in where crops are being produced in the US.

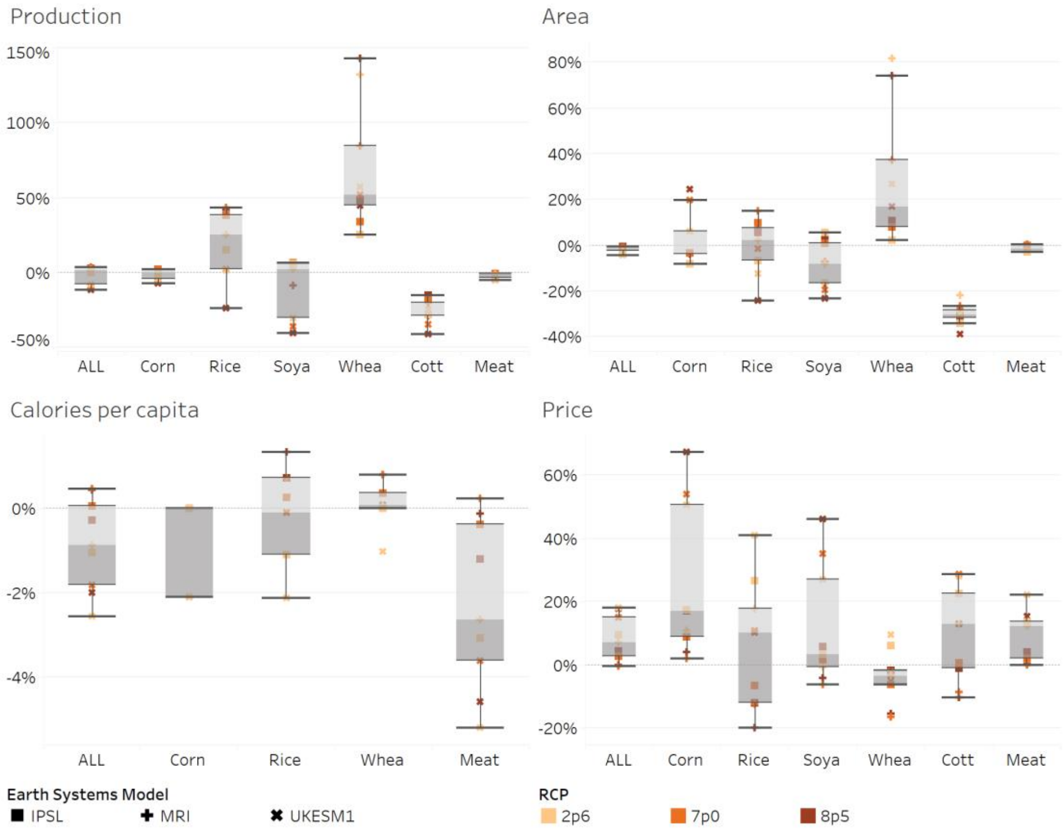

Figure 4: United States impacts from climate change to the agricultural sector in 2050 relative to a stable climate future.

Climate change is projected to have heterogeneous impacts across the United States, which results in a spatial redistribution of where crops are grown. Across most climate change scenarios, a decline in harvested crop area is occurring in the central US (Figure 5), a major production area of wheat and soybeans historically. This is being replaced by an extensive expansion in harvested area in the south central, northwest, and southeast, each of which is projected to have increased water availability for irrigation across most climate change scenarios. Wheat production is projected to expand in the northwestern US as temperature increases result in a more favourable climate. Corn production continues in the central US, but also expands into the southeast as precipitation is expected to increase, lessoning the negative impacts of potential temperature increases. Soybean area decreases in total, but in the northern US and near the Canadian border we project an increase in soybean production as increasing temperatures make this region more favourable. Finally, area dedicated to cotton production is expected to decline across most of the southern US, with little northern movement projected due to the low relative value of cotton compared to major commodities such as corn, wheat, and soybeans.

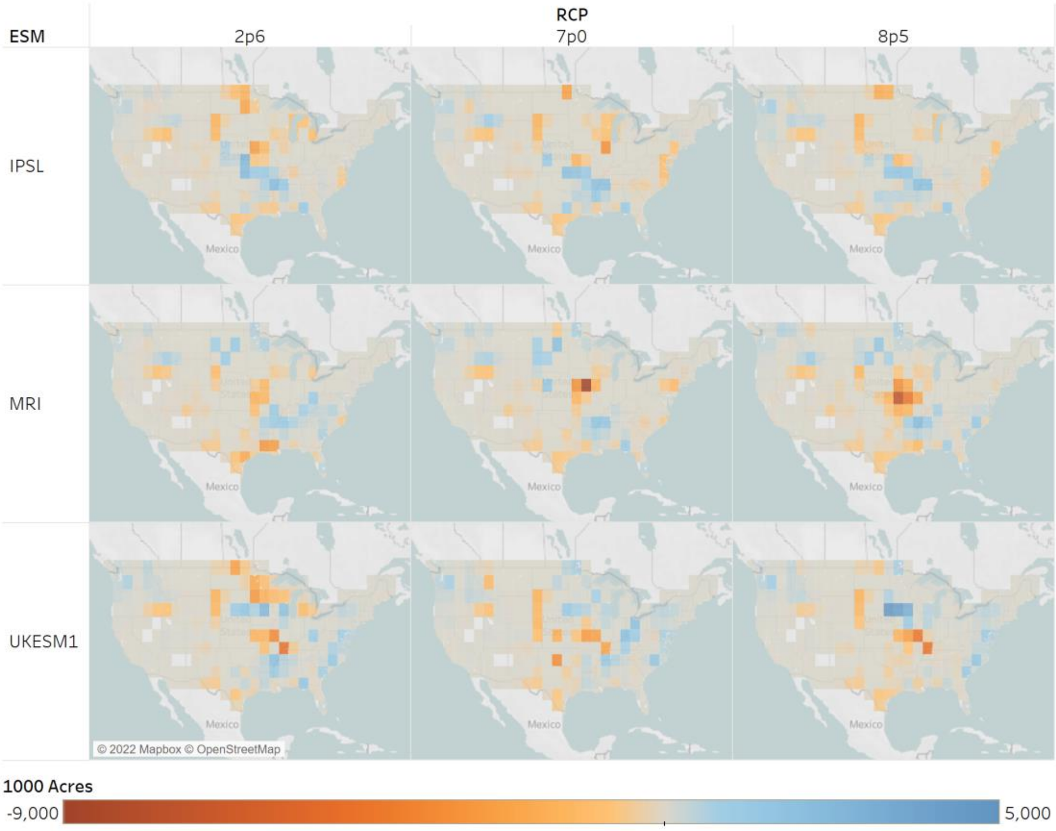

Figure 5: Projected difference from baseline in harvested area from 2020-2050 in the United States.

Irrigation response to climate change in the United States

Overall, it is shown that irrigation intensity is expected to decline in the US when climate change impacts are accounted for. At mid-century, each scenario projects an increase in irrigated area of between 1.6 and 13.5 million acres (or an increase of between 4.6% and 39.0%) (Figure 6), while irrigation water consumed changes from between a decrease of 20.7 km^3 to an increase of 24.1 km^3. This relatively larger shift in irrigated area compared to irrigation water usage results in irrigation intensity decreasing by between 5.2% to 21.7% or by an average reduction of between 0.3 to 1.1 acre foot of water applied per acre.

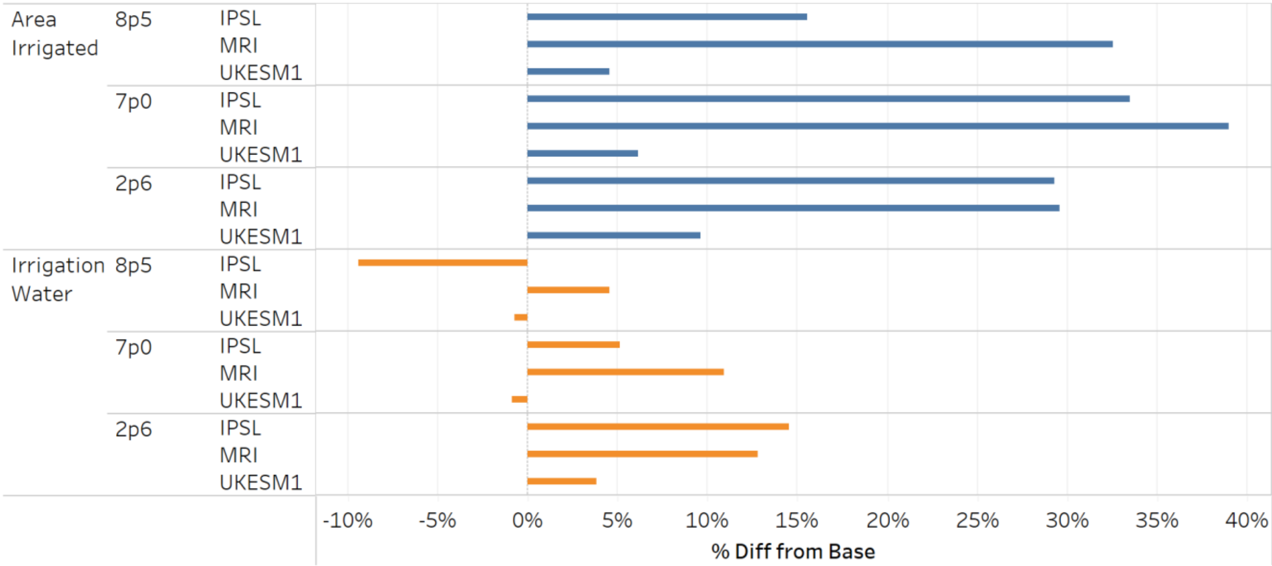

Figure 6: Percent difference in area irrigated (top) and irrigation water consumption (bottom) across each ESM and RCP in 2050 relative to baseline.

This reduction in irrigation intensity is occurring due to two main factors. The first is that most climate change scenarios project an increase in total precipitation in the United States under climate change scenarios. And more specifically, these increases are occurring in major crop growing regions such as the southeast and southern corn belt which allows some areas to shift from high cost irrigated systems to lower cost non-irrigated systems and still achieve profitable yield levels, while other regions continue to irrigate, but apply less water on average to reach optimal yield levels. Overall, this results in irrigated area of corn to increase in the southern corn belt, while overall water usage in the region declines. The second factor is a response from the land use sector where crop production is moving to regions in the north (Additionally, we find reductions in irrigation usage for rice production along the Mississippi River, as precipitation is expected to increase in this region under climate change.

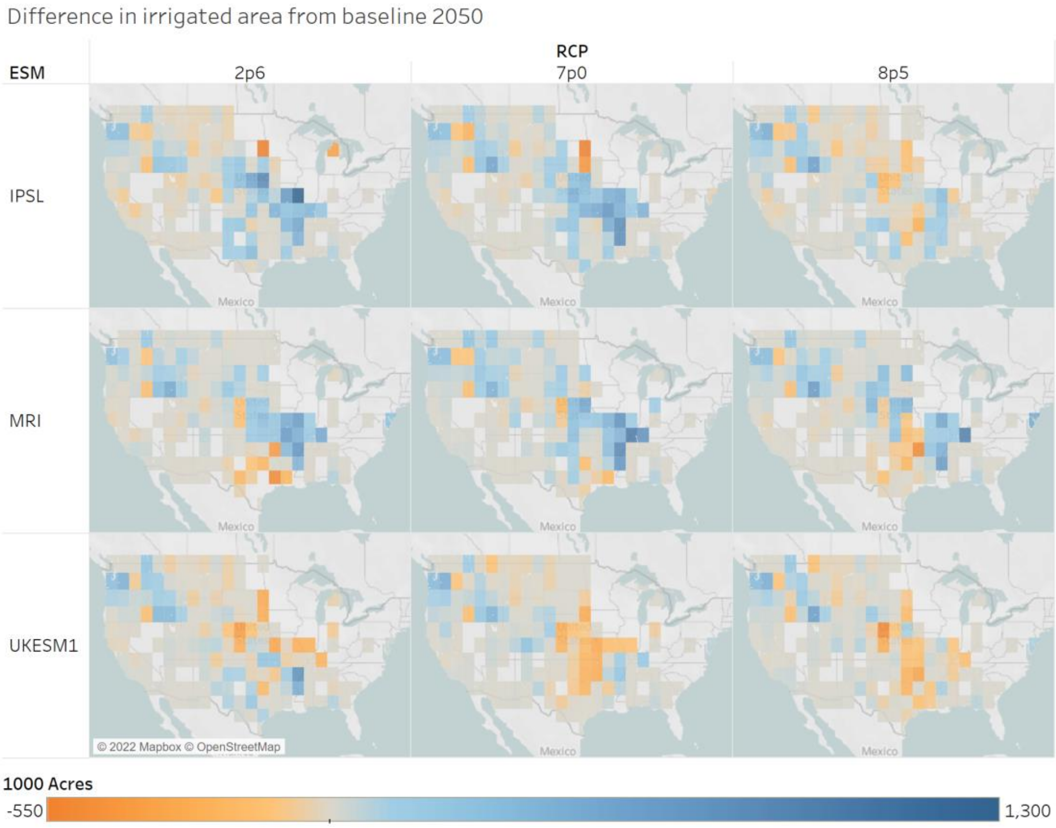

Figure 7) where temperature increases promote higher yields relative to historical amounts and precipitation is expected to increase. Specifically, irrigated wheat area increases in the pacific northwest as climatic conditions in this region become more conducive to wheat production. Additionally, we find reductions in irrigation usage for rice production along the Mississippi River, as precipitation is expected to increase in this region under climate change.

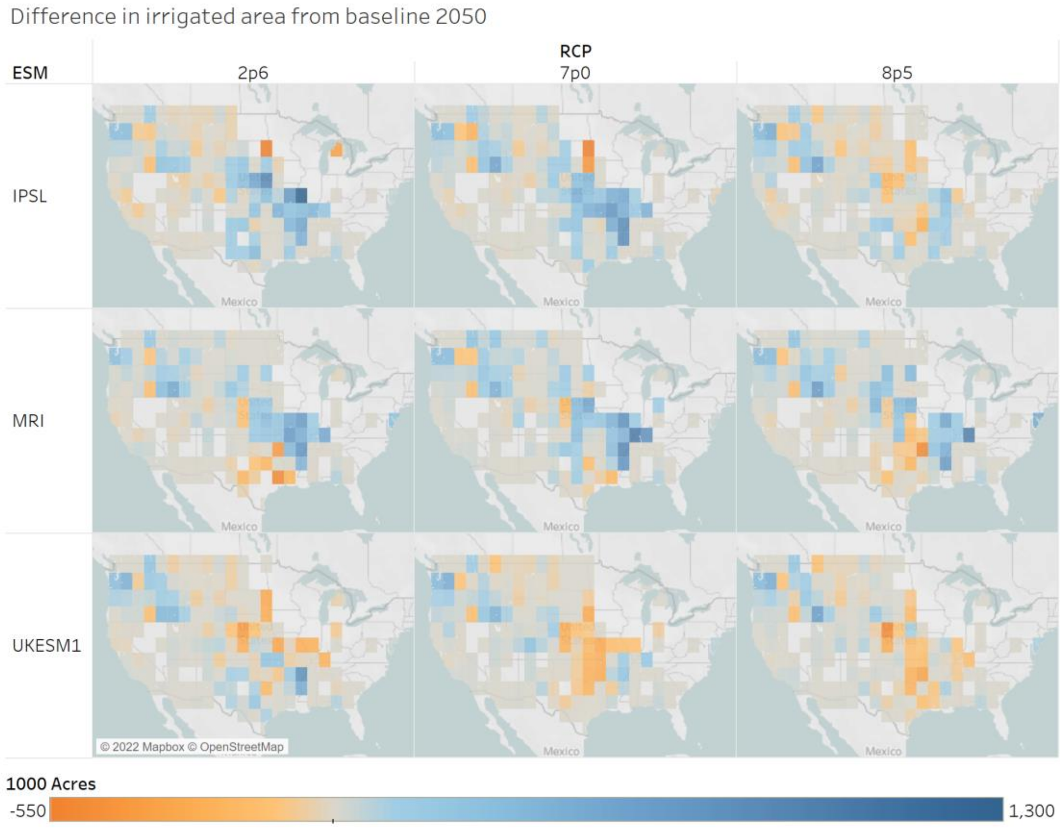

Figure 7: Difference in irrigation area from baseline in 2050.

With falling crop water requirements due to increased precipitation and a spatial reallocation of planting crops, many crops within the US increase irrigated area under climate change scenarios relative to a stable climate. Corn, wheat, soybeans, sorghum, barley, and cotton all increase on average, while rice, potatoes and sweet potatoes either decrease or remain relatively constant in irrigated area across climate change scenarios (Figure 8). With decreasing irrigation requirements in certain regions of the US, the agricultural sector is able to reduce production in regions where climate change impacts are having negative impacts on productivity, and intensive in regions where irrigation water becomes more abundant. This allows the sector to remain a robust producer of agricultural commodities globally while other, mostly tropical, regions are more negatively impacted under climate change.

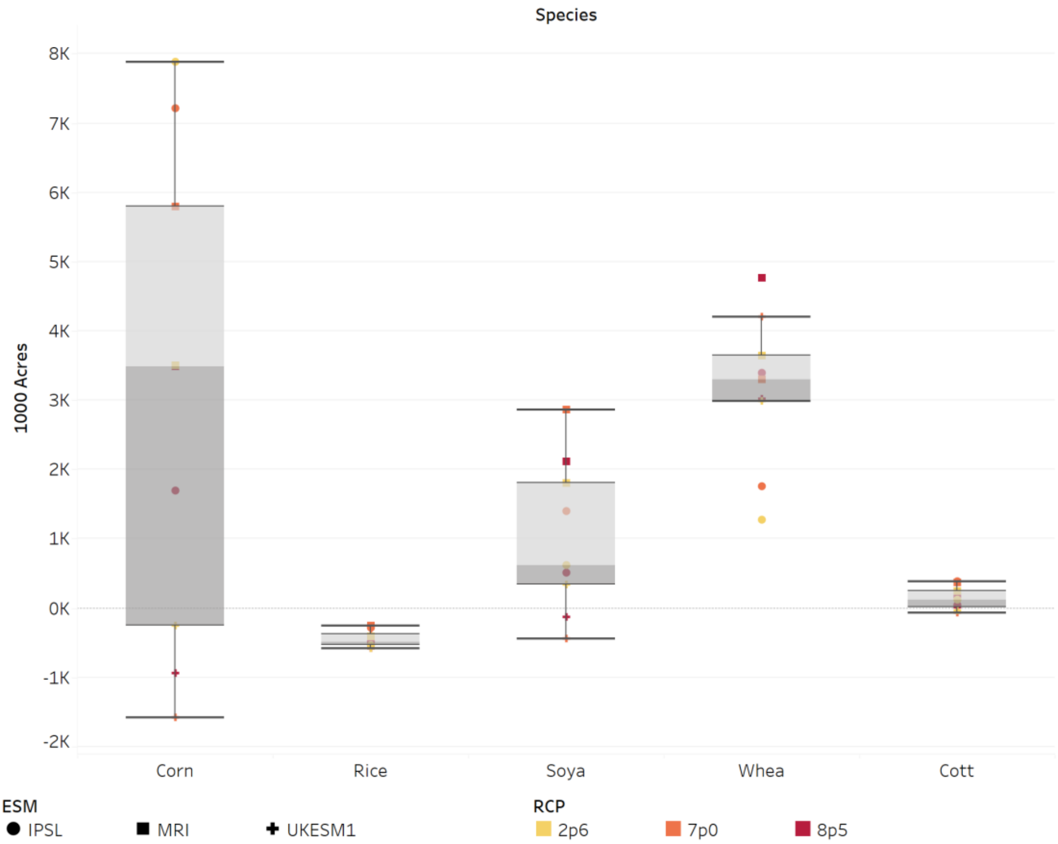

Figure 8: Difference in irrigated area by crop relative to baseline stable climate scenario.

Conclusions and Next Steps

Under climate change, it is projected that irrigated agriculture will increase in the United States relative to a stable climate future. This is driven by a confluence of factors including increased evapotranspiration requirements from increased temperatures, the potential for increased precipitation in certain regions to decrease the irrigation water requirements to achieve optimal yields, and global commodity market shifts as other regions become less productive under climate change (such as soybean production in Brazil falling by as much as 21% in 2050 in these scenarios). Overall, we find that irrigated area is expected to increase, while irrigation intensity falls. This is driven by both a spatial redistribution of where crops are grown due to impacts from temperature changes and water availability, and by a reduction in the additional water needed from irrigation to fully meet evapotranspiration requirements. While this study does not explicitly look at the most extreme events from climate change such as drought, floods, or major storms like hurricanes, we still find evidence that irrigation may be an adaptation measure in response to a changing climate. We find that existing cropping regions like the southern corn belt could see a net decline in total area harvested at mid-century, but also an increase in irrigation input usage to continue high production levels of commodities such as corn under climate change. It is also shown that regions that historically have been less involved in crop production such as the northwest could see agricultural land rents increase as temperatures increase to more favourable levels for crop production and from a potential increase in average precipitation.

These results begin to highlight regions where irrigation infrastructure investment may be needed in order to overcome climate change impacts, as well as where potential water supply and storage systems may be needed to address interannual variability in water supply.

Future efforts on this work will continue to decompose the impacts of climate change to US agriculture from those impacts caused by market forces. Specifically, US bilateral trade levels will be held at levels consistent with the baseline stable climate scenario, which will allow us to disentangle the drivers of irrigation expansion. Figure 9 presents the decomposition of both climate change and market driven impacts for corn, soybean, wheat, and cotton in the US in 2050. Here we begin to see how climate change can have heterogeneous impacts across different crops. For example, both corn and soybean see domestic production increase, exports increase at a rate larger than production increase, domestic consumption in both food and feed markets is decreasing due to global prices increasing. This would suggest that the US has an increasing competitive advantage in production of these products where the price differential between domestic and international markets is large enough to cause domestic demand destruction. Wheat is a similar situation except where the US is a net exporter of corn and soybeans, the US is a net importer of wheat. So instead of seeing increased exports, we see a reduction in imports which is being replaced by an increase in domestic production. Finally, with cotton we find evidence that the US may become less competitive in production relative to other regions. We see a decrease in domestic production, and a heavier reliance on imports to meet a declining domestic demand. Further efforts will aim at breaking down these impacts across domestic impacts from climate change, and market impacts driven by changes to international trade. Additionally, we plan to include more climate change impact projections from additional ESMs to hopefully shift from providing upper and lower bounds on the agricultural sectors response, to having higher confidence in which outcomes are more likely to occur.

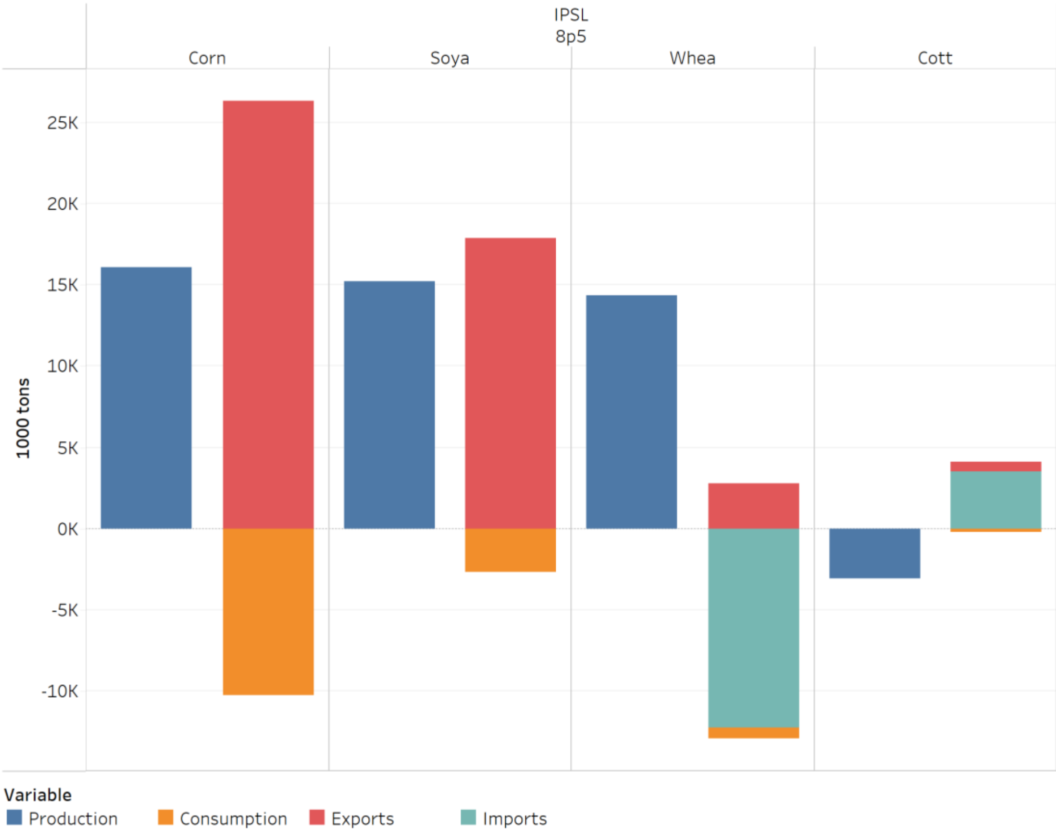

Figure 9: Decomposition of climate change impacts and market impacts on US commodities in 2050 under a single climate change scenario.

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