

Shifts in Hydroclimatology of U.S. Croplands

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Research Article

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Abstract

Changes in precipitation, temperature and water availability can significantly affect crop yields and hence food security at local and national scales. Despite the significant foreseen changes in hydroclimatology of croplands across the United States over the last decades, there are still lacking consistent information on how future hydroclimatic conditions of U.S. major croplands may change in response to climate change. This study investigates and quantifies shifts in hydroclimatology of five major crops including cotton, corn, soybean, sorghum, and wheat across the conterminous United States (CONUS). The results indicate that the direction and magnitude of hydroclimatic changes are highly variable across the climate projections. However, on average, hydroclimatic changes have a higher impact on sorghum and cotton, respectively. Understanding how croplands can be affected by climate change in the future can help decision-makers and water planners for the implementation and expansion of adaptive paths such as irrigation and conservation plans.

Irrigation | Agriculture | Hydrology | Climate impacts | Crop yield

2. Introduction

Agriculture is by far one of the largest water use sectors in the United States that can be significantly influenced by future hydroclimatic change [1–3]. Climate change already made a reduction in average yields of most major U.S crops [4]. An increase in temperature and changes in precipitation patterns during the growing season may lead to a decrease in crop productivity [5]. Enhanced understanding of shifts in the hydroclimatology of croplands has gained much attention as a key factor in investigating the climate-water-food nexus [6] which is not sufficiently and quantitatively reported in the previous studies [7].

The main goal of this study is thus to obtain a meaningful and quantitative understanding of how each US major cropping region can be affected in response to climate change. To this end, we evaluated shifts in regional hydroclimatic conditions of U.S. croplands by movements on the Budyko space from current (1986-2015) to future (2070-2099) conditions. The Budyko framework was applied as an effective way to evaluate the integrated effects of hydroclimatic variables [8, 9]. We calculated shifts in the Budyko space for five major crops including cotton, corn, soybean, sorghum, and wheat within the United States.

The analysis is based on the projected Multivariate Adaptive Constructed Analogs (MACA) climate dataset [10] ranging from the driest to wettest projections at the 8-digit hydrologic unit code (HUC8) basin scale [11]. We considered three climate projections including wettest (WET), driest (DRY), and a model located near the middle of these ranges (MID) to account for uncertainties on the spatial pattern and magnitude of changes in precipitation and temperature [11, 12]. We characterized which agricultural sectors are more vulnerable to hydroclimatic change.

3. Materials And Methods

We obtained the current climate variables from a combination of Daymet [13] and the Parameter-elevation Regressions on Independent Slopes Model (PRISM) datasets [14]. Future climate variables were also obtained from the downscaled Multivariate Adaptive Constructed Analogs (MACA) datasets [10].

The current and future climatic variables were then inputted to the Variable Infiltration Capacity (VIC) hydrological model to project changes in water availability of HUC8 river basins inside the US croplands. Readers are referred to Heidari et al., (2020) [11] for the details about the VIC model calibration and evaluation.

Then, we determined changes in hydroclimatology of each cropland as a function of shifts in the Budyko space [8] (Figure 1). The Budyko space describes a relationship between evaporative and aridity indices [15]. The evaporative index is the ratio of actual evapotranspiration to precipitation [16] while the aridity index is the ratio of potential evapotranspiration to precipitation [17, 18].

A river basin can move over time on the Budyko space due to a combination of shifts in aridity and evaporative indices. Change in the aridity index can represent climatic shifts while changes in the evaporative index can show shifts in water availability of river basins.

The combination of shifts in the Budyko space can be identified by the direction and magnitude of movements [16, 19, 20]. The direction of movement can be defined by

$$Direction (D) = \arctan\left(\frac{\Delta y}{\Delta x}\right) \quad (1)$$

where Δy is change in the evaporative index and Δx is change in the aridity index (Figure 2). Subsequently, the magnitude of change in the Budyko space can be obtained as follows:

$$Magnitude (M) = \sqrt{x^2 + y^2} \quad (2)$$

Overall, moving to the right means warmer and drier climatic conditions, and moving to the left means less arid conditions. Besides, moving to down indicates a higher rate of river discharge or wetter conditions while moving to up indicates less water yield or streamflow for a given HUC8 river basin.

We quantified changes in hydroclimatic conditions of each cropland by average movements of river basins on the Budyko space. The direction represents regional differentiation and the magnitude of change identifies the most sensitive regions [21].

4. Results

The direction and magnitude of hydroclimatic changes are highly variable across the WET, MID, and DRY climate projections. Table 1 shows the average change in magnitude and direction of each U.S. croplands under the WET, MID, and DRY climate models. Additionally, the wind rose diagrams of changes in

hydroclimatology of U.S. croplands are shown in Figure 2. Each wind rose visualizes the summary of movements in the Budyko space including direction, magnitude, and frequency for all HUC8 river basins inside of croplands. This type of diagram has been commonly applied in global hydroclimatic change assessments [22]. Under the WET and MID climate models, Soybean is likely to experience the wettest conditions among all five crops while wheat has the highest magnitude of change indicating that the hydroclimatology of wheat cropping land will be more affected by climate change (Table 1).

Under the DRY climate model, all five crops move to the upper-right quadrant of the Budyko space indicating warmer and drier hydroclimatic conditions. Cotton has the worst direction and sorghum has the highest magnitude. Under all climate models, it can be concluded that the hydroclimatology of sorghum, cotton, and wheat is more likely to be affected under future climate change.

Table 1. Average changes in magnitude and direction of U.S. croplands.

	Crop	Average	WET	MID	DRY	Average
corn	direction	189.2	213.0	59.4	153.9	
	magnitude	0.18	0.13	0.45	0.25	
cotton	direction	166.8	131.3	46.3	114.8	
	magnitude	0.18	0.25	0.97	0.46	
sorghum	direction	161.7	131.7	32.3	108.6	
	magnitude	0.19	0.27	1.41	0.62	
soybean	direction	191.3	223.7	58.5	157.8	
	magnitude	0.16	0.09	0.29	0.18	
wheat	direction	179.5	172.9	83.8	145.4	
	magnitude	0.31	0.28	0.77	0.45	

5. Discussion

Water availability is a vital need for a wide range of agricultural activities [23]. Long-term hydroclimatic changes may have significant impacts on regional water resources [24]. The findings of this study can help decision-makers to be prepared and react appropriately to changes in regional hydroclimatic conditions of croplands and their potential consequences on water and food resources, particularly under ongoing severe situations like the COVID pandemic [25], water shortages [24, 26] and wildfires [27]. Long-term hydroclimatic changes may force farmers to change their crops based on the new regional hydroclimate conditions. Future projections of hydroclimatic changes in U.S. croplands can help managers, planners, and decision-makers to maximize crop production and prioritize water resources allocation by improving water resource management [7]. However, there are some important questions that should be addressed in this case as a prospect of this study.

The first question that can be raised here is how shifts in hydroclimatology of cropping regions may affect future crop productions. Although climate change may have positive impacts on agricultural productivity in some regions, it can reduce crop yields in regions that currently have optimal climate conditions [6, 28, 29]. For instance, Cho and McCarl (2017) [30] reported that cotton and sorghum are more appropriate under the warming temperature. Besides, sorghum, and spring wheat are more likely to be selected under drier conditions, while corn, cotton, and soybeans are better choices for wetter conditions [30]. Additionally, it is worth mentioning that while an increase in precipitation may be beneficial for most growing regions, it can have negative impacts on some cropping regions because of water-logging and pest disasters [6].

Another important question that should be addressed here is how much irrigation requirement would change in response to hydroclimatic change for maintaining current crop yields. Irrigation has been commonly used as an adaptation tool to increase crop yields and decrease the impacts of climate changes [31–33]. Considerable research has investigated the effects of climate variability on crop yield [34]. However, few studies have focused on the impacts of climate changes on irrigation water requirements [23]. Crop production can be stabilized by increasing irrigation [6, 35–38]. An increase in irrigation helps crop production meets the current food demand, which may decrease in response to climate change [6]. While irrigation plays a key role in agricultural productivity, the impact of hydroclimatic changes on irrigation water use has not been well studied [31]. The impacts of climate change on irrigation water use have been rarely studied due to limited data availability [31].

Additionally, there is a few research on how irrigated and rainfed crop yields respond differently to climate change over five major US cropping regions [6]. Assessing the response of both rainfed and irrigated crop yields to climate change can lead to the improved understanding of the role of irrigation on agricultural productions [6]. Although precipitation plays an important role in dryland production systems, there is still a lack of studies evaluating the impacts of climate change on irrigated crops.

A national, spatially assessing the impacts of hydroclimatic shifts on U.S agricultural regions is needed to be done to provide insight into changes in crop productivity and dependence on irrigation [39].

6. Declarations

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The authors declare no competing interests.

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Figures

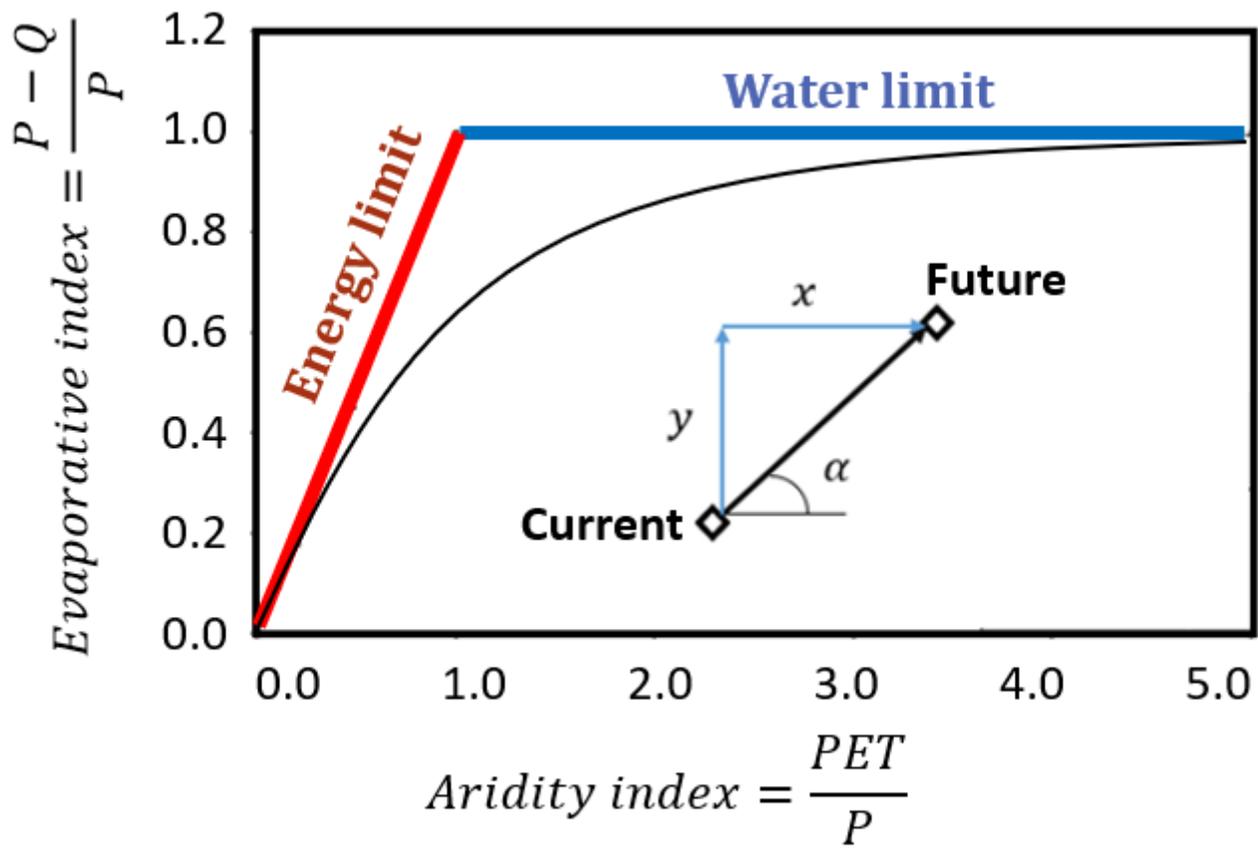


Figure 1

Characterization of magnitude and direction of movements in the Budyko space [11].

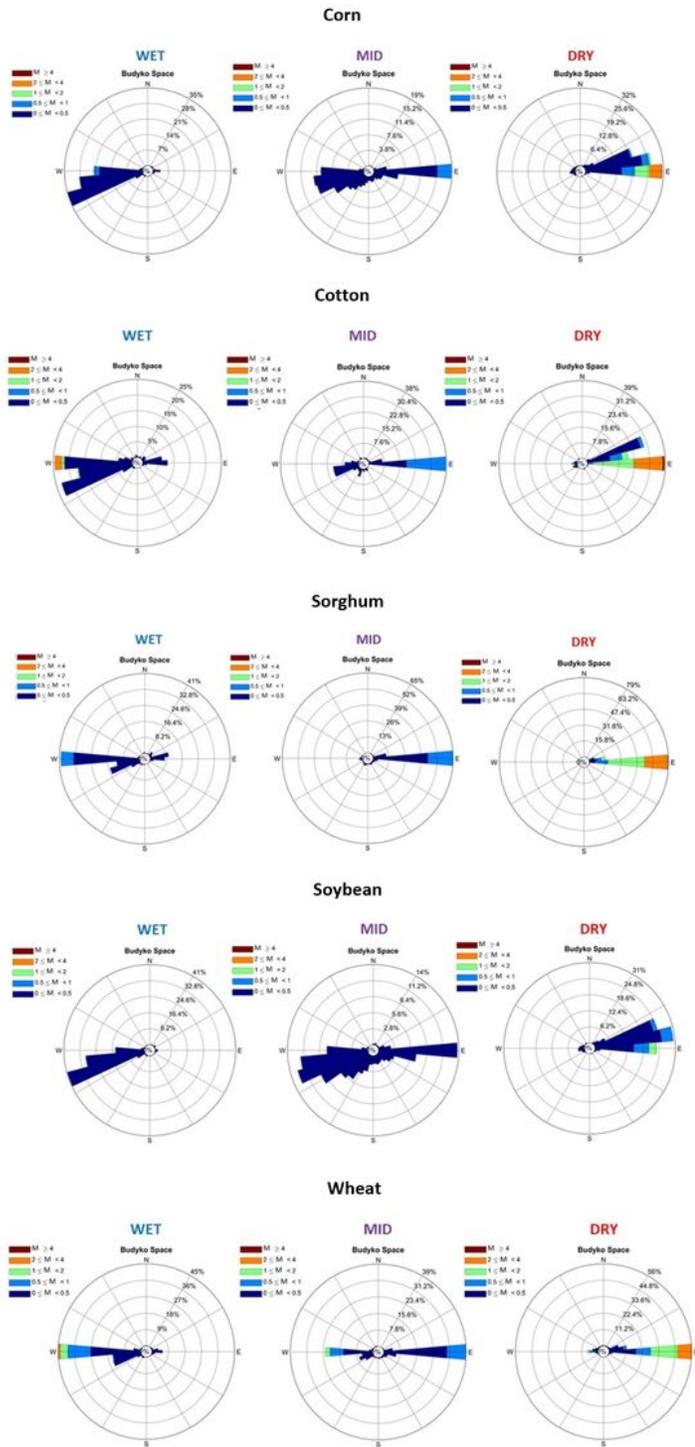


Figure 2

A wind rose diagram of changes in hydroclimatology of U.S. croplands (M represents the magnitude of changes).