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ORIGINAL ARTICLE

Water trading as a tool to combat economic losses in agriculture under climate change

Xiaoliang Han[1,2] · Proloy Deb[1,2] · Nicholas R. Magliocca[1,3] · Denis Nadolnyak[4] · Hamed Moftakhari[1,2] · Ruchie Pathak[1,3] · Hamid Moradkhani[1,2]

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Abstract

The agricultural water market (or water trade) is an effective water resource management tool to redistribute water from low-value to high-value agricultural farms. Water markets can play an important role in reducing the economic losses attributed to droughts by increasing flexibility in responding to water scarcity. Climate change has increased the scarcity and uncertainty of the agricultural water supply in the Mobile River Basin, mainly in Alabama, USA, which has imposed a huge risk to crop production in the region. In this study, agricultural water productivity is used to evaluate the value of irrigation water, and an analytical framework is developed to quantify potential economic efficiency gains within the river basin if water markets were to be implemented under future hydroclimate conditions. This approach circumvents the caveats of the traditional methods of estimating irrigation water demand. The results show that agricultural water markets can reduce the adverse impacts of climate change on the overall catchment-scale agricultural output in economic terms. The scenario approach presented in this study can provide preliminary estimates of the benefits of water trading, particularly in periods of drought and under future conditions of decreasing precipitation. The findings can aid in reducing the economic losses encountered by farmers under rainfed agricultural practices at a global scale.

Keywords Water trade · Drought · Agricultural economics · Mobile River Basin · Alabama

Introduction

Droughts are likely to become more frequent and intense in the twenty-first century, especially in arid and semiarid regions, as temperature rises under climate change (Engström et al. 2020; Liu and Chen 2021; Rodell et al. 2019; Xu et al. 2020). These rising temperatures are anticipated to change the hydrological cycle globally (Wu et al. 2021a, b), ultimately impacting agricultural productivity and water demand and supply (Fooladi et al. 2021; Wu et al. 2021a, b; Sheffield and Wood 2008; IPCC 2022). The adaptability of people under water-scarce conditions defines the socio-economic impacts of droughts at a given location (Jaeger et al. 2013). Globally, the agriculture sector consumes the majority of freshwater resources. Due to population growth and competing water demands from municipal and industrial sectors, meeting agricultural water demand has become more difficult, particularly during droughts (Ahmadi and Moradkhani 2019; Donohew 2009; Gavahi et al. 2020; Wang et al. 2012).

The water market, which refers to the transfer or selling of water or water rights from one person to another, is a potentially effective method for controlling scarce resources. Market-based reallocation of water use may help significantly reduce the economic consequences of climate change (Anderson et al. 2019). Market-based water pricing policy reforms have also been heavily studied, with approaches

Handled by Akiyuki Kawasaki, University of Tokyo, Japan.

✉ Xiaoliang Han
xhan29@crimson.ua.edu

✉ Hamid Moradkhani
hmoradkhani@ua.edu

1 Center for Complex Hydrosystems Research (CCHR), University of Alabama, Tuscaloosa, AL, USA

2 Department of Civil, Construction, and Environmental Engineering, University of Alabama, Tuscaloosa, AL, USA

3 Department of Geography, University of Alabama, Tuscaloosa, AL, USA

4 Department of Agricultural Economics and Rural Sociology, Auburn University, Auburn, AL, USA

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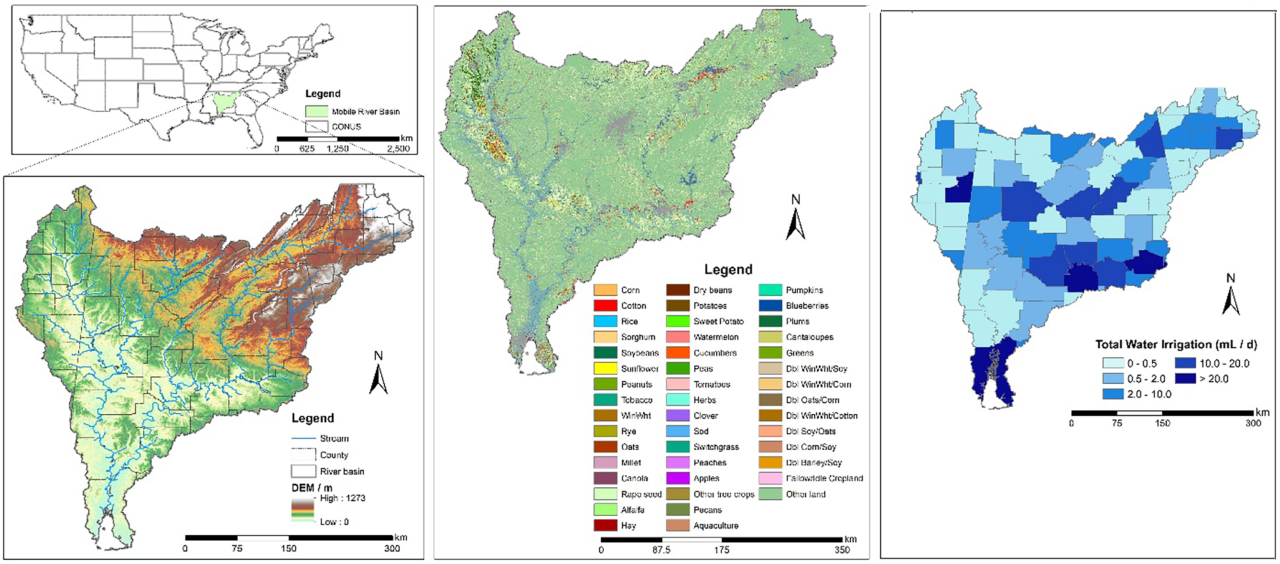
such as the primal–dual approach (Schaible 1997). Market-based approaches have been used to manage the environment in a number of contexts, including the regulation of NO*x*, SO_2, and CO_2 emissions, and have been shown to be less expensive than more prescriptive instruments (Fqwlie et al. 2012). However, it is difficult to establish a successful water market because of the wide variation in water values in different climate regimes. Due to the diversity of water users, available resources, water delivery systems, and institutional restrictions, the market-based allocation of water resources in a basin is a complicated task. Additionally, inequality in permit allocation, farmer conduct, and hydrological circumstances can all have an effect on the operation of the water market (Du et al. 2021; Deb and Kiem 2020; Deb et al. 2019). Moreover, inconsistencies in policies and laws that allocate water permits between states or countries make the implementation of water markets difficult. To date, there has been a wealth of theoretical, structural, and programming literature on the potential of water markets to reduce drought costs or increase the social surplus of existing water supplies (Essenfelder and Giupponi 2020; Schwabe et al. 2020; Pérez-blanco et al. 2020). However, there is a paucity of contextualized empirical evidence on the effects of water markets in certain basins, making it difficult to quantify the benefits of water trading.

Water trading enables individuals to allocate water from low-value or water-intensive crops to high-value or less water-requiring crops, thus reducing the overall negative economic impacts during droughts (Arellano-Gonzalez et al. 2021). This is especially true for water-intensive activities such as irrigated agriculture. To date, much research has focused on the ability of water markets to reduce the costs of drought or raise the social surplus of current water sources (Sunding et al. 2002). California is the first state in the USA to implement spot markets for water trading, which has been successfully applied to irrigated lands for decades (Ghosh 2019; Jenkins et al. 2004). Markets are identified as the most cost-effective method by using a model that predicts watershed agricultural behavior and streamflow in the Chiwalawala River Basin, USA (Willis and Whittlesey 1998). A plethora of research has shown that fully efficient agricultural markets greatly increase crop yields if two specific conditions are met: efficient irrigation scheduling and a stable water market system (Abbaszadeh et al. 2022; Du 2017; Gavahi et al. 2021; Hagerty 2017). Irrigation water markets reduce regional irrigation water distribution inequity and boost regional farmers' overall net profit (Bai 2008; Aghaie et al. 2020; Fang and Zhang 2020). Aside from income, several observational studies have also shown that farmers improve risk management by using water markets to ensure a consistent supply of irrigation water, especially when faced with the uncertainty of climate change (Muller et al. 2021; Sutcliffe et al. 2021).

The existing research methods on irrigation water use in agriculture focus largely on water demand estimation, which is usually modeled as input demand in the production process for a set of outputs (Azlan et al. 2019; Qin et al. 2019). However, the data on water demand in the agricultural sector can be difficult to obtain in regions where there is no cost to access surface water, such as in the Mobile River Basin (MRB). In such circumstances, the water price is estimated based on the energy costs of conveying surface water or pumping groundwater. Other approaches, including field experiments, mathematical programming, and hedonic methods, attribute a part of agricultural land values to access a particular quantity and quality of water (Young et al. 2005). A 2006 meta-analysis of the research on irrigation water demand in the USA over 1963 and 2004 indicated a mean price elasticity of − 0.48, with higher estimates in water-scarce and approaching zero in water-abundant regions (Scheierling et al. 2006). In more arid regions, the trade-off between the value of water for irrigation and instream uses has been an important consideration. Water markets in regions with problematic water quality would allow farmers to sell water to other uses and provide incentives to apply excessive irrigation. Research on allocating water among competing uses employs nonmarket valuation such as recreational demand, contingent valuation, and hedonic housing models (see Olmstead 2010, for an overview). Overall, the findings are that there are large discrepancies among marginal water values among different sectors attributable to inefficient pricing, federal-funded irrigation projects, and water rights allocations grounded in history.

The differences in water prices in the USA have been attributed to water being hydrologically and legally complex, a lack of traders in local markets of different sizes, and a lack of information to allow price convergence (Pullen and Colby 2008). The empirical estimates suggest that senior water rights (important in dry years) are more valuable. Additionally, higher volume trades have lower per unit prices (economies of scale), and more flexibility in licensing rights is more expensive (Colby et al. 1993; Loch et al. 2018). As expected, the water price declines with increased precipitation, but it elevates as income increases. Additionally, the volume of water trades is lower in areas with higher agricultural productivity. In the western USA, the positive difference in prices for agriculture-urban transfers and between agriculture transfers has been shown to grow over time (Brewer et al. 2008). Although an abundance of literature on water trading and demand has proven that the water market in water-scarce regions is functional, there is a lack of literature on the potential benefits of introducing water markets in agricultural regions where there is a (periodic) deficit of irrigation water and the property rights for it are well defined, as in the US Southeast. The region is also fit for such research because it has not been impacted by



(a) (b) (c)

Fig. 1 **a** Location of MRB within the CONUS, the streams, and digital elevation model of the MRB. **b** Crop data layer highlighting the crops grown within the MRB. Note: Data collected from United States Department of Agriculture (USDA) for the year 2015. **c** County-scale irrigation water application map for the year 2015

federal subsidies for irrigation projects that would distort such markets.

Sustainable irrigation is a good risk management approach in and of itself (Imran et al. 2019; Zaveri and Lobell 2019), but water markets can assist farmers in managing water-related risks by providing a stable supply of irrigation water or an additional source of income as required (Wheeler et al. 2014; Zuo et al. 2015). Although the abovementioned studies have shown the advantages of water trading, very little effort has been made to measure these adaptive advantages under changing climate or forecast water trading expansion. This makes it difficult to quantify the welfare benefits from the implementation of agricultural water markets, especially in the southeast Contiguous United States (CONUS) region, where rainfed agricultural practices are dominant.

It is crucial to measure the possible adaptive advantages of water trading for irrigation in the MRB in the USA under future projected hydroclimate conditions of decreased precipitation. In the MRB, due to the increase in the frequency and intensity of droughts, the crop water demand is unmet by precipitation for some water rights holders. This crop water shortage is also an emerging issue (Deb et al. 2022b). Therefore, agricultural outputs from these farms are lost if there are no additional water sources. The costs of the constraints of water are quantified by allocating usable water based on current irrigation water practice or irrigation water value (simulating the respective corresponding results of a market for irrigation water). In this study, current irrigation water practice data from 2015 were considered usable water. The cost associated with water curtailment due to the difference between the existing water allocation and water allocation based on the irrigation water value leads to a deadweight loss. This deadweight loss is preventable since it is flexible in nature and is the ability of the water distribution/allocation system to adapt to a more liberalized water market. As a result, the climate change adaptation advantages of water trading for irrigation are represented in this avoidable evolution. The findings of this study highlight the importance of water trading to the degree that water trades are facilitated among counties or agriculture sectors, especially under future climate change and during droughts.

Study area

This research uses the MRB as a case study (Fig. 1a). The MRB is the sixth-largest river basin in the USA, including parts of Alabama, Georgia, and Mississippi. Almost two-thirds of the 113,960 km^2 basin is in Alabama. The Upper Appalachian Plateau in the north generates the flow in the catchment, which flows into Mobile Bay in the south. Forest and agriculture cover 60% and 26% of the total area, respectively, while urban areas account for 3%. Furthermore, the remaining 11% of the catchment is made up of water bodies, including lakes and reservoirs (Warner et al. 2005). The catchment's average annual discharge is approximately 1760 m^3 s^{-1}, making it the fourth highest discharge in the USA. As seen in Fig. 1a, there are 101 counties that belong to the study area and are considered in our analysis. The annual precipitation and temperature averages 1270–1524 mm and 15–21 °C (in the north) and 21 °C (in the south), respectively. The main crops produced in the MRB are corn, soybean, cotton, wheat, and sorghum (Fig. 1b). Corn is grown throughout the Coastal Plain physiographic province, with the largest areas being in the Southern Hills and Fall Line Hills regions. Soybeans are the largest, almost as evenly distributed as corn, most concentrated in the Mississippi, and cotton is the second-largest crop, concentrated in specific areas of valleys and ridges of the physiographic region of the Cumberland Plateau. The largest areas of wheat cultivation are concentrated in the southern foothills, the black prairie belt, and the alluvial aquifers of the coastal plain. Sorghum acreage is not as common as other crops but is evenly distributed across the basin (Fig. 1b) (Johnson 2019). In a recent study, Price et al. (2022) used a multilevel statistical modeling approach to assess spatial and temporal influences on irrigation adoption across the state of Alabama including the MRB.

Data and methods

The market value of the irrigation water is calculated in this study by using data from different sources, including irrigation water data (surface and groundwater) for 2015, county-scale crop yield and crop price data, available water from precipitation,[1] spatial cropping patterns, and crop water requirement estimates retrieved from different sources given below.

Irrigation water data

Since the State of Alabama comprises over 70% of the MRB area where the right to use surface water is given only to property owners with riparian access (i.e., riparian rights), the seniority data (i.e., right to withdraw based on seniority) are unavailable. Therefore, in this study, the value of the irrigation water market is estimated using data on annual irrigation water use for 2015 (Fig. 1c). The year 2015 is considered a normal precipitation year for demonstrating normal crop management (including irrigation) and therefore can serve as a benchmark for agricultural water trade at the county scale. The MRB annual precipitation in 2015 was 1466 mm, which we considered as a normal precipitation year and benchmark data year for agricultural water trading. Information on county-scale irrigation water withdrawals for the MRB from both surface water and groundwater resources for 2015 is obtained from the United States Geological Survey (USGS) National Water Information System.

Value of agricultural production

The weighted average production value per hectare Y is determined by using Eq. 1 for each county (c) in the MRB.

$$Y_c = \sum_{i=1}^{N} s_{ic} y_{ic}, \tag{1}$$

where Y_c is the value of agricultural production in $ and y_{ic} is the agricultural production value per hectare for crop i in county c. s_{ic} is calculated as the ratio of $\frac{a_{ic}}{A_{ic}}$ expressed by farmland a for i crops in c counties with total farmland A ha in the county. s_{ic} is determined from the crop data layer (Han et al. 2012) for 2015 derived from the United States Department of Agriculture (USDA) using high-resolution (30 m × 30 m) land cover data. y_{ic} is acquired from agricultural records for all the counties (USDA) for 2015.

Actual agricultural water demand

The actual evapotranspiration (AET) data were used to calculate the actual agricultural water demand in this study. It is strongly emphasized that in this study, only actual water demand for agriculture was used. The AET is key to irrigation water application and basin-scale agricultural water demand assessment (Deb et al. 2022a). The AET data for 2015 are derived from a daily 900 m resolution Simplified Surface Energy Balance (SSEBop) dataset developed by the United States Geological Survey (Senay et al. 2011). Since the crop data layer used to identify the crop areas has a 30 m spatial resolution, resampling (using a bilinear approach) of the AET at a 30 m resolution is performed in the ArcGIS environment over the entire CONUS, which was further clipped for the MRB region. Additionally, the pixels in the crop data layer, which are classified as "agricultural land", are used to mask the AET data. These masked values are then aggregated to the county level to obtain the actual agricultural water demand. The net irrigation water demand was calculated by subtracting 4 km resolution daily precipitation data derived from the Parameter-elevation Regressions (PRISM) dataset (Daly et al. 1997) from the resampled AET (AET-P). The value of irrigation water is zero when precipitation exceeds crop water requirements. The total AET was measured at the county level considering only the agricultural lands as the total (spatial) average of 30 m AET per day for 2015. AET volumes were obtained by multiplying AET depths (total mm) by the county's agricultural land area.

[1] Given that the research is conducted on more than 30 different crops, soil type distribution varies widely, as do planting and irrigation methods; therefore, the effective precipitation carries some uncertainties. For that reason, we decided to use the measured precipitation.

Simulating water availability versus cumulative water value under different scenarios

The irrigation water value is a critical component in calculating the water availability versus the cumulative water value curves. Therefore, the calculation of the irrigation water value was performed by modifying the procedure suggested by Arellano-Gonzalez et al. (2021) such that the potential evapotranspiration was replaced with AET in this study, illustrating the crop-specific actual irrigation water value rather than the generalized value (from open water bodies, which potential evapotranspiration suggests). Moreover, this study is employed in both irrigated and rainfed conditions. In the calculation, in counties where the precipitation exceeds the crop water requirements, zero is assigned for the irrigation water value. The irrigation water value indicates the contribution of irrigation water to the agricultural output value. Basically, the irrigation water value is inversely proportional to the actual agricultural water demand and directly proportional to the agricultural production value.

The datasets derived from the irrigation water value and the irrigation water use data of 2015 were used to generate two cumulative demand curves: (1) conventional conditions (2015 case with irrigation) and (2) the agricultural water market. During droughts, the water availability for irrigation is often limited and does not meet the cumulative water demand (water is curtailed). In the first curve, the curtailments were based on the counties that were not in close proximity to a major stream within the catchment, i.e., the counties that do not have a stream flowing through or are located far from a stream were not allocated any water for irrigation. The second one intends to simulate an equilibrium outcome of water trading for irrigation where the county with a lower crop production value sells its share of the irrigation water to the higher-value user county during droughts. Additionally, a third demand curve was also created for the rainfed condition where the counties use only the water available from the precipitation for the agricultural practice. In the third demand curve, no curtailment was considered, as under reduced precipitation the cropping practice is negatively affected linearly. The potential benefits of the agricultural water market over the conventional irrigation condition and rainfed condition were estimated by comparing the crop production lost under the latter two cases relative to the agricultural water market. The Lorenz curve is an effective way to demonstrate inequitable income distribution among individuals (Seekell et al. 2011). In this study, the Lorenz curve is applied to solve the issue of irrigation water allocation in demonstrating the crop production loss for a given water curtailment. The Lorenz curve is applied in this paper because inequitable water resources and inequitable income have some similarities, both of which reflect the inequality of distribution, and this curve provides a visual representation of this distributional inequality. In this paper, the Lorenz curve can provide a better illustration of how limited irrigation water can be allocated more efficiently to maximize agricultural returns within the region. The methods of calculation of the points for the curves are given below for the three cases.

No irrigation (rainfed condition)

Let us assume that in all counties, $\alpha\%$ of agricultural water demand is available from precipitation. Therefore, under rainfed conditions, the cumulative water value was calculated as the fraction of the water value corresponding to $\alpha\%$ of agricultural water demand (met by precipitation) relative to 100% of agricultural water demand met by precipitation. These assumptions were based on the current reality of rainfed agriculture in the MRB. It can be calculated using Eq. 2.

$$\text{Cumulative water value }(\%) = \frac{\sum_{i=1}^{n} \alpha\% \times \text{water value}\left(\frac{\$}{\text{kGal}}\right)_i}{\sum_{i=1}^{n} 100\% \times \text{water value}\left(\frac{\$}{\text{kGal}}\right)_i}, \tag{2}$$

where n represents the number of counties (101 in this study), and the water value is in $/kGal.

Conventional condition (year 2015 irrigation data)

For this case, let us assume that for a county, $\alpha\%$ of agricultural water demand was available from precipitation and an additional x amount (in percentage of agricultural water demand) from irrigation (data from 2015 irrigation water withdrawal). Therefore, the cumulative water value was calculated as the ratio of the sum of water values corresponding to total agricultural water demand met and 100% of agricultural water demand for all counties (Eq. 3).

$$\text{Cumulative water value }(\%) = \frac{\sum_{i=1}^{n} (\alpha + x) \times \text{water value}\left(\frac{\$}{\text{kGal}}\right)_i}{\sum_{i=1}^{n} 100\% \times \text{water value}\left(\frac{\$}{\text{kGal}}\right)_i}. \tag{3}$$

Agricultural water market

In this case, let us assume that for the first county, $\alpha\%$ of agricultural water demand was met by precipitation, and an additional 10% of the water demand was met by the water market through irrigation; therefore, 100% of the water demand was met. However, for all counties, it is impossible to meet all the agricultural water demand, and therefore, for many of the counties, there is a curtailment in the irrigation water supply. Here, the water value was calculated similar to Eq. 3, except for replacing "x" with the exact value of water transfer through the water market for each county.

The future benefit of agricultural water markets was measured by comparing crop production lost as a result of conventional irrigation reductions to value-based reductions. This calculation thus indirectly preserves the crop mix, geographical distribution, and water demand under the 2015 standard. The only difference was the timing and volume of precipitation supply and the process of reduction of allocations and effects.[2] Of course, farmers can change their crop mix or the geographical distribution of crops grown considering the impact of climate change. However, this may complicate the predictability and, therefore, will not be considered in this study.

In future years where precipitation is less than the agricultural water demand, conventional irrigation will be reduced, and agricultural production from these farms will be lost. In this study, the allocation of irrigation water on the basis of either the current system or the water trading for irrigation was performed to quantify the costs of these restrictions. A deadweight loss associated with an inability to trade water resulted from the difference in the cost of reduction under these two allocation methods. The increase in deadweight loss resulting from climate change provides water trading for irrigation with adaptive advantages.

Future precipitation projection

To project future precipitation, four general circulation models (GCMs) were used from the World Climate Research Program (WCRP) Coupled Model Intercomparison Project 6 (CMIP6). The four selected GCMs are FGOALS-f3-L (He et al. 2019), ACCESS-CM2 (Bi et al. 2013), GFDL-ESM4 (Dunne et al. 2020), and NESM3 (Yang et al. 2020). The selection was based on existing literature comparing 31 GCMs performed over the CONUS (Ahmadalipour et al. 2017; Almazroui et al. 2021), and the best four GCMs for the southeast CONUS were selected for this study. The raw GCM data were bias corrected using the equidistant quantile mapping approach where observed historical precipitation data from PRISM were used (Ahmadalipour et al. 2018). GCM outputs were bias-corrected at a 4 km grid scale, which was further spatially aggregated to represent the county-scale precipitation for the socioeconomic pathway (SSP) 585 scenario, which is a socioeconomic-based representative concentration pathway scenario with high radiative forcing by the end of the century and is considered a superior dataset to the Representative Concentration Pathway (RCP) scenarios (Riahi et al. 2017). The future precipitation was projected at a daily time step for the period 2026–2055. The quantile mapping approach for bias correction was implemented in the Python programming language.

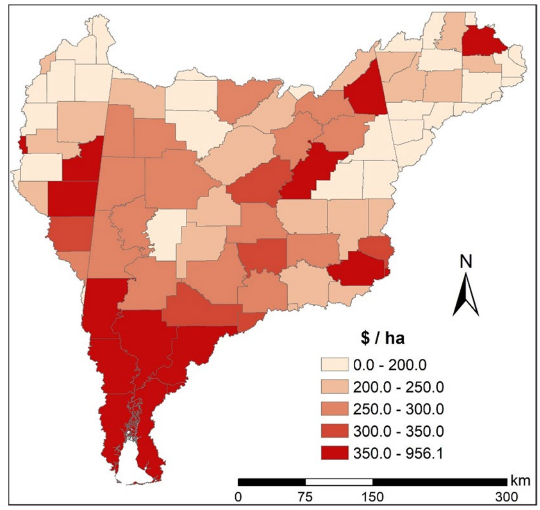


Fig. 2 County-scale agricultural production value calculated across the MRB

Results

Figure 2 shows the county-based heterogeneity in the value of agricultural production across the MRB. It can be clearly seen that the high estimates of agricultural value are concentrated in the western and southern regions of the MRB, particularly in the Clarke, Choctaw, Monroe, Washington, Mobile, and Baldwin (in the south) counties and Lowndes, Noxubee, and Kemper counties in the western region. According to the crop data layer, these areas are known for extensive cultivation of high-value commodity crops, including cotton and corn, with agricultural output values ranging from $350 to $956 per hectare ($/ha). On the other hand, in the eastern counties (Cleburne, Clay, Randolph (in Alabama), Polk, Haralson, Carroll, Douglas, and Cobb (in Georgia)) and the northwestern counties (Itawamba, Lee, Prentiss, Alcorn, and Tishomingo), soybean and rapeseed crops are generally grown, which indicates a low average agricultural production value per ha ranging from 0 to $200/ha.

Figure 3 displays the county-scale actual agricultural water demand calculated based on the AET. Darker blue indicates higher crop water demand, which can be seen for the counties in the central region of the catchment (specifically Bibb, Shelby, Chilton, and Coosa). Additionally, Walker, Winston, and Lawrence counties (in Alabama) also indicate high crop water demand ranging from 70 to 86 kL/

[2] The study was conducted using data from 2015 and simulation assumptions were thus based on the state of farm locations and crop mixes observed at that time. Accounting for time-varying crop mix and geographical distribution makes the prediction too complex and impractical, especially when it comes to agent-based behavior. Nonetheless, analyzing such factors is outside the scope of this study.

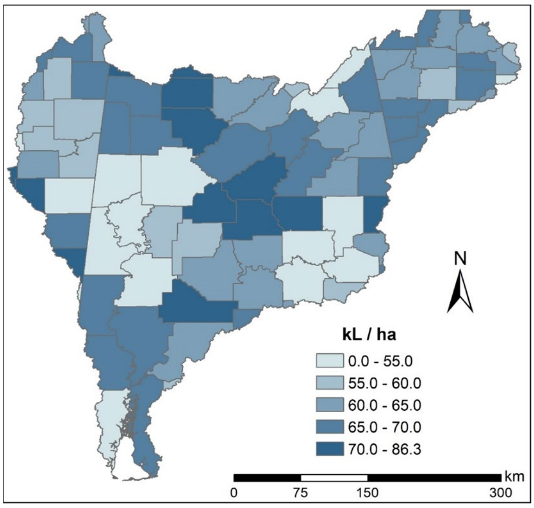


Fig. 3 AET based county-scale agricultural water demand across the MRB

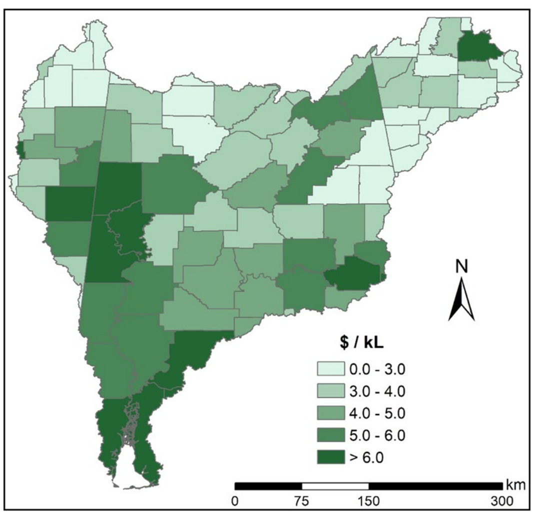


Fig. 4 Spatial variability in the value of irrigation water calculated across the MRB

ha. Furthermore, the western counties (Tuscaloosa, Pickens, Greene, Sumter, and Marengo) in the state of Alabama display a low crop water demand (in the range of 0–55 kL/ha) due to limited agricultural dominance in the region. Moreover, the farmers of these counties also grow vegetables in the winter season under a controlled environment (in greenhouses) at a small scale to avoid frost risk resulting in low crop water demand.

Figure 4 displays the spatial variation in the irrigation water value generated by dividing the value of agricultural production per ha (Fig. 2) by the actual agricultural water demand per ha (Fig. 3). This implies that the relationship between the irrigation water value and agricultural water demand can be calculated by Eq. 2. Additionally, *Yc* is negatively correlated with actual agricultural water demand to some extent due to the constraints of crops themselves (including management practices). For example, in Shelby County, the agricultural production value and actual agricultural water demand were 276 ($/ha) and 81 (kL/ha), respectively, in 2015. In this case, we assume that $\alpha\%$ is 90%. Dividing the agricultural production value by the actual agricultural water demand and multiplying by Eq. 2, the agricultural water value is 3.08 ($/kL). It can be clearly seen that the value of the irrigation water is higher in the western region of Alabama and the southern part of the MRB (irrigation water value > $6.0/kL). This is because although there is a low crop water demand in the western counties, the agricultural production value is average (ranging from $250–$300/ha) relative to the central and eastern counties in the MRB. Similarly, in the southern counties, the agricultural production value is high, reflecting a higher irrigation water value. Additionally, it is noteworthy that in the eastern region of the catchment, i.e., in Georgia, the irrigation water value is minimal within the range of 0.0 to $4.0/kL. Low soil productivity can lead to a low irrigation water value since crop productivity is relatively low in the eastern region of the catchment (Schaetzl et al. 2012), although similar crops are grown throughout the watershed.

The annual precipitation totals for the MRB from 2026 to 2055 are shown in Fig. 5a–d for four bias-corrected CMIP6 GCMs: FGOALS-f3-L, NESM3, ACCESS-CM2, and GFDL-ESM4, respectively, under the SSP585 scenario. The blue color in the figure shows the variability in the annual precipitation total for 2026–2055 throughout the MRB, whereas the red line on the graphs shows a linear trend fit for the precipitation in the MRB. Clearly, all four projections show a declining trend in the precipitation for the future at rates of 1.28 mm/year, 4.17 mm/year, 6.41 mm/year, and 5.13 mm/year for the FGOALS-f3-L, NESM3, ACCESS-CM2, and GFDL-ESM4 GCMs, respectively. The Mann–Kendall trend test for the time series data is performed for the bias-corrected annual precipitation totals (from the four GCMs) with the null hypothesis: no trend is present in the time series and is tested at a significance level of 0.05. The *p* values for the test suggest rejection of the null hypothesis (p-value < 0.05) (Table 1). Therefore, all four GCM projections have a statistically significant trend across the MRB. Given that the visual inspection from Fig. 5 suggests a negative trend, this implies lower water availability in the future and poses a threat to farmers' incomes in the event of drought.

During droughts, some irrigators will lose access to water due to water insufficiency. Under the conventional irrigation system in the MRB, the farmers of counties that are not in close proximity to a river will face water curtailments. With the same allocation system but with flexibility, curtailments

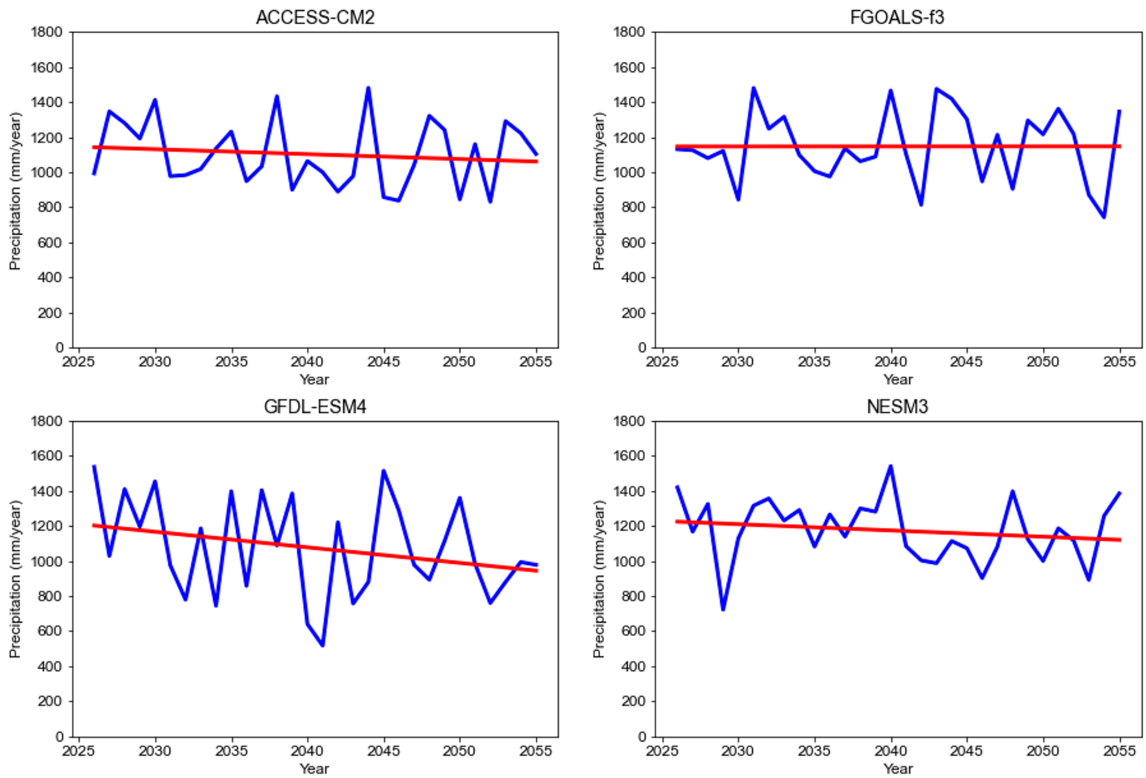


Fig. 5 Time series of annual precipitation totals for four selected GCMs spatially averaged for the MRB for the years 2026–2055

Table 1 *p*-values for Mann–Kendall trend test for the four GCMs used in this study

GCMs	*p*-value
FGOALS-f3-L	0.046
NESM3	0.021
ACCESS-CM2	0.029
GFDL-ESM4	0.041

will still accrue to these farmers; however, the farmers in counties where water use has a high value could purchase irrigation water from farmers who have access to rivers with lower agricultural production value. Hence, under such a market, the water curtailment is borne by the farmer with low agricultural production value who forgos production

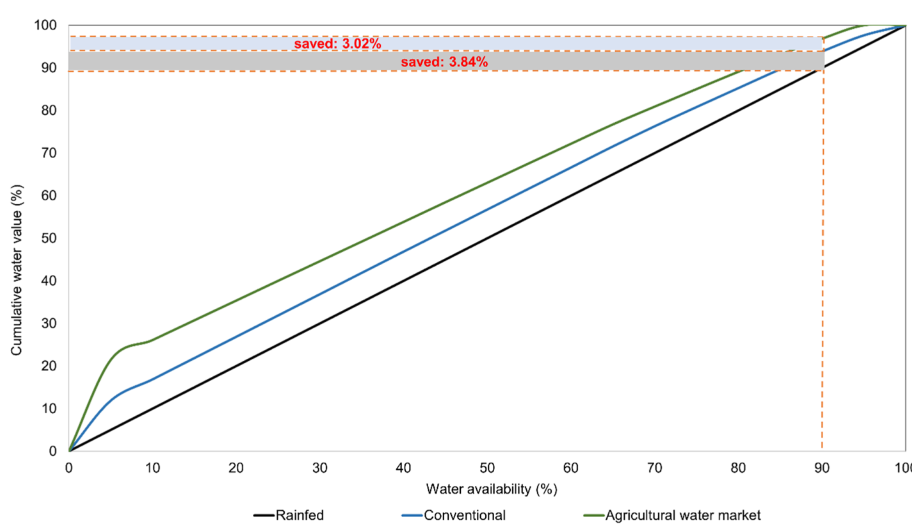


Fig. 6 Lorenz curves generated for the MRB displaying the cumulative agricultural water value under three different agricultural systems: (1) rainfed (black line), (2) conventional irrigation system (blue line), and (3) agricultural water markets (green line). Water availability is denoted by the *x*-axis, which demonstrates an example of 10% water curtailment for agriculture and its corresponding cumulative water value for the three agricultural systems

benefiting from selling their water asset. The differences in the value of crop production between rainfed conditions, conventional systems, and agricultural water markets demonstrate a deadweight loss from the conventional system and rainfed conditions. This also illustrates the potential benefit from an agricultural water market within a watershed.

Figure 6 illustrates the value of agricultural produce lost due to water restrictions in MRB using Lorenz curves under three allocation scenarios: rainfed conditions (black line), conventional conditions (blue line), and market-based conditions (green line). The Lorenz curves are representations of the rainfed condition (Eq. 2), conventional condition (Eq. 3), and market-based condition. Since the effect of precipitation on the cumulative water value is linear, the black line (1:1) is evident. In other words, taking the water value calculated in 2015 as the benchmark value, each proportion reduction (%) in water availability results in the same proportion (%) curtailment of cumulative water value. Similarly, although the conventional irrigation correlates strongly with the agricultural production value, curtailments for the blue line lie close to the rainfed line (black line). Furthermore, for every additional reduction in the water supply, with provided irrigation (either from surface or groundwater), a similar pattern (as under rainfed conditions) of economic losses is expected from water curtailment. In contrast, in a water trading allocation system, users (farmers) in counties with low water value first halt production, resulting in reduced economic costs (i.e., the green curve lies significantly above the blue and black lines).

Considering the whole MRB, a 10% curtailment of available water will result in a gross agricultural revenue loss of 10% for the rainfed condition, whereas in the case of the conventional system, a revenue loss of 6.16% is observed. This implies that a reduction of 3.84% in revenue loss can be achieved with conventional irrigation relative to rainfed agricultural practices (which are dominant in the MRB). Furthermore, under a market-based system, an agricultural production value equivalent to 96.8% can be achieved for 2015. This is an additional 3.02% (also called deadweight loss) in revenue compared to that of the revenue generated based on conventional irrigation in the MRB. Overall, deadweight loss determines the benefit of water trading for irrigation (i.e., the line of separation between the different Lorenz curves, as shown in Fig. 6).

Figure 7 represents the percentage of potential gain of cumulative water value from a market-based system relative to the conventional irrigation system using the precipitation projection from the GCM ensemble for the years 2026–2040 and 2041–2055. Clearly, under a flexible market, the increase in the cumulative water values is 3.95% and 4.5% for 2026–2040 and 2041–2055, respectively. The uncertainties from the GCM projections are 0.84% and 0.54% for the corresponding 15-year time periods, respectively. These results indicate that when the water availability for crops cannot meet crop needs, changing water allocation can resist the loss of cumulative water value. This is especially important for the MRB, where rainfed agricultural practices are dominant since production is highly dependent on precipitation water availability.

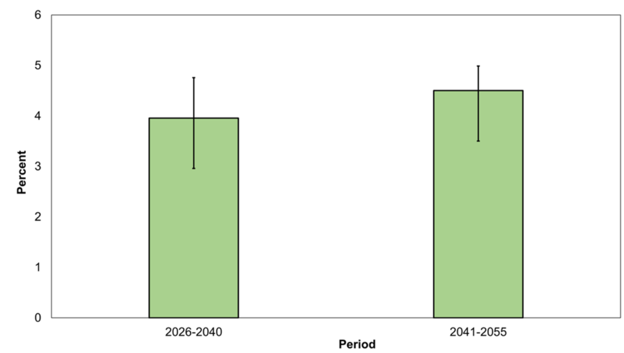


Fig. 7 Expected gain (%) (in cumulative water value) from agricultural water markets relative to conventional irrigation for the years with curtailment obtained from the annual precipitation projection from GCM ensemble for 2026–2040 and 2041–2055 years under SSP585 scenario using the Lorenz curves from Fig. 8. Error bars indicate the standard deviation of the GCM model uncertainty

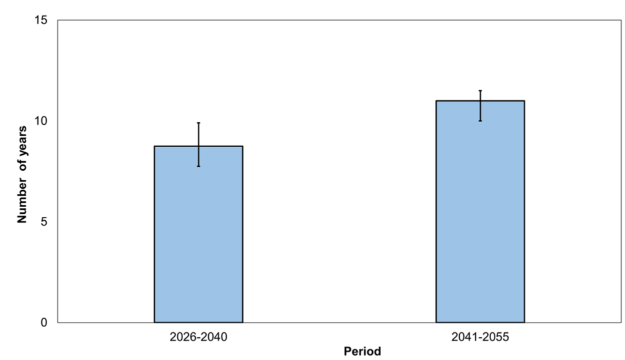


Fig. 8 Potential number of years with water curtailments within the 15 year time periods (2026–2040, and 2041–2055) when the irrigation water is unavailable to meet the 100% water demand. The error bars represent the standard deviation due to GCM uncertainties in the precipitation projection

Figure 8 represents the percentage of future years when 100% of irrigation water is unavailable under the SSP585 scenario. Clearly, for the 2026–2040 and 2041–2055 time periods, the number of years is 8.75 and 11, which contributes to 58% and 73.33% of years, respectively. This reduction in water availability can be attributed to the reduction in precipitation ranging from 12.1 to 17.24% and 18.21 to 24.86% for 2026–2040 and 2041–2055, respectively, relative to 2015 precipitation attributed to climate change. The uncertainties from the GCM projections are 1.5% and 0.5% for the corresponding 15-year time periods, respectively.

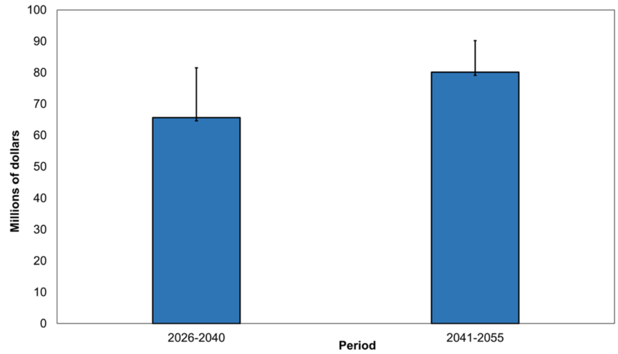


Fig. 9 Expected benefits from agricultural water markets relative to the conventional irrigation for the years with curtailment obtained from the annual precipitation projection from GCM ensembles for 2026–2040 and 2041–2055 years under SSP585 scenario using the Lorenz curves from Fig. 8. The bar represents the average benefit for each year. Error bars indicate the standard deviation of the GCM model uncertainty

These results indicate that under the SSP585 scenario, the percentage of years in which crop water requirements cannot be satisfied will gradually increase in the future, leading to higher water curtailments for irrigation, where the water allocation through water markets can play a significant role in increasing the overall revenue throughout the MRB.

Figure 9 represents the future benefits from the agricultural water market relative to the conventional irrigation system using the precipitation projection from the GCM ensemble for the years 2026–2040 and 2041–2055. To calculate the money saved under a liberalized water allocation system, the inflation rate using the Producer Price Index is considered, which is derived from USDA for all the crops grown within the MRB. The results indicate that the potential savings under a flexible agricultural water allocation system are $65.63 million and $80.13 million per year for the time periods 2026–2040 and 2041–2055, respectively, relative to the total income of $1.70 billion in 2015 (USDA 2015). These results indicate that agricultural water markets will effectively reduce agricultural losses in the MRB basin as a result of climate change in the future. This ability to withstand the loss of income caused by drought is growing, particularly when potential precipitation is projected to steadily decrease.

Limitations and future scope

Agricultural water markets have some imperfections, as discussed in the introduction section. Therefore, some specific challenges in the study region are discussed here as well. First, agricultural water use in the MRB involves complex, legal, political, and environmental issues between the states of Alabama, Mississippi, and Georgia. Due to data limitations, in this paper, we aimed to show the expected benefits from the market allocation of irrigation water in a rain-dominant basin rather than defining which counties or farms can exchange water among themselves. Therefore, a general analysis was conducted to show what counties should be availed (curtailed) with (from) irrigation water. To understand how agricultural water markets migrate from one county to another, follow-up research is required, which will involve capital expenses, technical costs, and special constraints such as transfer limits for irrigation water. The results of such a study would be useful to farmers and policy makers of the states within the MRB and provide guidance for shifting from traditional rainfed agricultural practice to irrigation using water markets. Furthermore, the authors of this study plan to analyze the water market at the farm scale in future studies.

Second, under the agricultural water market system proposed in this study, improper water market policies and pricing may impose a new economic burden on farmers. Since irrigation systems require significant infrastructure investment, farmers may be less willing to participate if policy subsidies are insufficient, particularly in the early stages. Lack of market participation can distort prices and lead to inefficient irrigation water allocation. The average value of irrigation water is capped when crop yield is non-linearly related to irrigation. In such cases, the marginal value of water can deviate from the average. However, the adoption of water-efficient irrigation technologies may lower water prices. In addition, the transfer process of irrigation water still requires costs, including irrigation facilities and electricity. If these are taken into account, the advantages of water trading for irrigation will be marginal. Moreover, in addition to the cost of the transfer process of irrigation water, agriculture requires other inputs, including land, capital, fertilizers, energy, etc. Therefore, this study overestimates the benefits of water trading. Third, the impact of climate change on precipitation only was considered in this study; however, further research is needed to evaluate the combined impact of climate change on precipitation, AET, crop water use efficiency, crop adaptation and the impact of land use change (Lavergne et al. 2019; Han et al. 2018; Deb et al. 2015; Scheff and Frierson 2014). While measuring the costs of curtailments, the condition of the perennial crops and their yields were also unaccounted for because perennial crops need more water in their early stages of growth, and if sufficient irrigation is not provided early on, they suffer from permanent damages. Moreover, perennial crops do not provide normal returns early on. Therefore, the average water value to farmers who plant perennial crops may be higher than those calculated in this study. In this research, we used experimental data from 2015; therefore, the simulation assumptions were based on the state of the farm, location, and crop mix observed at the time. This may have led to an overestimation of the water trading benefit in this study because farmers' adaptation, specifically by adjusting the tillage cultivation intensity and planting species, will change the model's results. Nonetheless, analyzing such factors is outside the scope of this study. In addition, limiting the research only to commodity crops understates the full benefits of an efficient water market.

Finally, there are several broader challenges associated with water markets that were not considered explicitly in this study but should be noted for their potential as impediments to efficient water markets. 'Third-party effects' from water trading occur when the benefits or costs of a trade are not exclusive to just the parties involved in a water trade and may result in externalities such as changes in instream flows and downstream uses, unreliable supply and/or delayed (water) delivery to the user (Heaney et al. 2006), overdraft of water tables, poor water quality, waterlogging, and other adverse environmental effects.

Discussion and conclusion

The efficient allocation of agricultural water improves the sector's productivity and is crucial for adaptation to climate change. Agricultural water markets should lead to allocative efficiency by channeling the water from areas with low agricultural water value to those with high agricultural water value, thus equating the net marginal product of water among producers. Numerous studies have demonstrated the benefits of agricultural water markets as the most cost-effective system, especially during drought years, which also incentivizes producers to grow high-value, water-saving crops. The water market is expected to increase farmers' ability to handle water-related risks (Peterson et al. 2005; Zuo et al. 2015).

There are potential equity issues raised by an irrigation water market in the study context that should be noted. Efficiency gains through water markets are realized by transferring water rights from low- to high-value agricultural uses in times of water scarcity. However, when determining the price for irrigation water rights, i.e., compensation to low-value agricultural producers, it is important to account for the current and historical conditions that created differential production values. Certainly, variability in yields and water use efficiencies are related to heterogeneity in biophysical farming conditions throughout the region, but those differences are reflected by and reinforce socioeconomic inequities among farmers (Bajaj et al. 2022). In particular, the Black Belt region, which corresponds roughly to the Blackland Prairie regions in Fig. 1a and extends into Georgia and Mississippi, has a history of plantation agriculture and extensive slave labor and contemporary majority African American demographics and persistent poverty (Mutaleb et al. 2014; Zekeri 2004). In addition to an admitted history of negligence of African American farmers by the USDA (Asare-Baah et al. 2018; Furman et al. 2014), farmers in this region face a lack of appropriate technological information, low prices received for produce, low farmland prices, shortage of labor, limited access to insurance and credit, and underdeveloped marketing strategies for greater access to buyers (Baharanyi et al. 2012). Without proper consideration of the socioeconomic value of water to these farmers (Grim 2002), water rights transfers through a water market may have the potential to perpetuate and exacerbate existing inequities among farmers within the MRB if not properly implemented.

Water trading enables rapid adjustments to be made in water allocation in response to fluctuating water demand. By developing appropriate water laws and regulations and by strengthening institutions to administer them, water markets have the potential to effectively address the growing demand for groundwater and surface water. Water markets make it possible to supply irrigation water and facilitate a transition away from an inefficient distribution of water rights and toward a market approach that is both more efficient and wastes less water (Ann Wheeler and Garrick 2020). This research is an exploratory analysis conducted through the framework of water trading so that policy makers can get inspired. In the process of implementation, more supporting policies are needed, such as the treatment of riparian rights, the pricing mechanism of water trading (Bjornlund et al. 2007) and the compensation of downstream third parties (Heaney et al. 2006).

In this paper, a synthetic case study of the efficiency gains of agricultural water markets (water trade) was quantified, particularly in the event of future water shortages under climate change. The study uses a novel approach that circumvents the shortcomings of existing methods. The present study applied the Lorenz curve to an agricultural water market assessment of net crop water demand (AET-P) using county-level irrigation water data while accounting for inflation. The results indicate that the agricultural water market is a viable strategy for reducing the costs of climate change, especially in a rainfed dominant region, because it facilitates the diversion of water to higher-value uses. Areas with high agricultural production value, such as the south of the MRB, and areas with relatively high agricultural output value but low water demand, such as the northern counties, can be seen in Figs. 2, 3, and 4. In comparison to conventional irrigation, this study estimates that the agricultural water market would save $65.63 million and $80.13 million per year (during 2026–2040 and 2041–2055, respectively) in costs to meet the decreased rainfall resulting from climate change (under the SSP585 scenario). These significant savings represent the cost savings from market-based allocation. It should be noted that the intention of this paper is not to design irrigation water diversion structures or to identify counties exchanging water among themselves, but to highlight that the agricultural water market is an efficient tool for reducing economic losses under projected climate change. The scenario approach presented in this study can provide preliminary estimates of the benefits of alternative water management strategies, particularly in periods of drought and under future conditions of decreasing precipitation. This approach can be a useful exploratory analysis in any region of the world where droughts are frequent and rainfed agriculture is dominant.

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Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

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