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The spatiotemporal trajectory of US agricultural irrigation withdrawal during 1981–2015

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Abstract

Irrigation has enhanced food security and biofuel production throughout the world. However, the sustainability of irrigation faces challenges from climate variability and extremes, increasing consumption from irrigated cropland expansion, and competing demands from other water use sectors. In this study, we investigated the agricultural water withdrawal landscape of the contiguous United States (CONUS) over 1981–2015, assessed its spatial and temporal changes, and analyzed the factors driving the changes. We introduced the concept of 'center of mass' to calculate the spatiotemporal trajectory of water withdrawal, along with climatic and agricultural factors at state, regional and CONUS scales. At the CONUS level, the total agricultural water withdrawal has decreased during 1981–2015, and the centroid of water withdrawal consistently moved toward the east, caused by reduced water withdrawal in the western states and increased withdrawal in the eastern states. While the CONUS irrigation trajectory is not mainly affected by climatologic trends, extreme drought conditions (e.g. the mega droughts in western states since 2000) may interrupt the trend. In the Western US, irrigation withdrawal reduction was mainly achieved by adoption of high-efficiency irrigation technology, while the irrigated acreage remains relatively stable. Under drought conditions, irrigation withdrawal often switched from surface water to groundwater sources, posing challenges on groundwater sustainability under prolonged drought conditions. The Eastern US has experienced accelerating agricultural withdrawal from both surface water and groundwater sources. This was mainly driven by expansion in irrigated acreage in the Midwest and lower Mississippi River, with irrigated croplands supplied by mixed flood irrigation and high-efficiency irrigation methods. At the state level, some states exhibited discrepancy in agricultural withdrawal centroids from surface water and groundwater sources, as results of climate heterogeneity, water availability and infrastructure development. This study provides understanding of the driving forces in the spatiotemporal trends of CONUS agricultural water withdrawal in different regions and implications for predicting future agricultural withdrawal under changing climatic and socioeconomic uncertainties.

1. Introduction

Agricultural irrigation accounts for 72% of water withdrawal globally (Rosegrant *et al* 2002) and about 64% (excluding thermoelectric withdrawal) freshwater withdrawal in the USA (Dieter 2018).

As the largest water consumption sector, irrigation has enhanced food and biofuel production over the world. The sustainability of irrigation is facing substantial challenges from current and future renewable water availability, freshwater stock depletion, environmental flow deterioration and water right

conflicts (Qin *et al* 2019, Rosa 2022). While water supply is stressed by climate variability and extremes, there have been increasing demands within the agriculture sector due to irrigated cropland expansion as well as in other water using sectors with competing demands (Döll 2002, Döll and Siebert 2002). In addition, irrigation at large scales has far reaching environmental impacts, including depleting groundwater (Konikow 2011), altering land surface energy and water cycles (Ferguson and Maxwell 2012), degrading water quality (Skaggs *et al* 1994) and changing regional climate (Nocco *et al* 2019). Irrigation expansion (i.e. switching from rain-fed to irrigated agriculture) are expected as an adaptation strategy to climate change to enhance crop yields to mitigate the potential water scarcity under future climate (Rosa *et al* 2018, Rosa *et al* 2020b). The irrigation water resources may be constrained by physical scarcity (i.e. availability of local renewable water resources) (Sloat *et al* 2020), environmental sustainability concerns (e.g. aquifer depletion) (Scanlon *et al* 2012), economic scarcity (e.g. investment on irrigation infrastructure) (Rosa *et al* 2020a, Vallino *et al* 2020) and institutional arrangements (e.g. water right conflicts) (Molden 2007). As United States (US) is a major food producer and exporter, investigating these impacts calls for a quantitative analysis of how irrigation has developed and what climatic and socioeconomic factors have driven the irrigation development. Understanding on how irrigation can mitigate the impact of changing climate is fundamental to achieve the United Nations' Sustainable Development Goals (SDGs, specifically SDG 2 and 6) (Jägermeyr *et al* 2017, Mastrángelo *et al* 2019, Sadoff *et al* 2020).

Researchers have utilized various hydrologic and optimization models, along with observations, to estimate irrigation water withdrawal (Da Cunha *et al* 2015). Hydrologic models estimate irrigation withdrawal based on irrigated acreage and crop water demand and ignore the socioeconomic and institutional factors in determining irrigation (Mutlu *et al* 2010, Zhang *et al* 2020). Optimization models adopt the supply–demand approach and account for constraints from climatic, infrastructural, economic and environmental factors to quantify irrigation withdrawal (Cai and Rosegrant 2002, Rosenberg *et al* 2003). However, these models are usually implemented at basin or county scale and do not consider the impacts from spatial heterogeneity of climate and water availability for irrigation withdrawal. The estimation of irrigation withdrawal is further challenged by the lack of reliable irrigation records. Scattered and often scarce local scale irrigation records (e.g. derived from water balance, irrigation energy cost and monitoring meters) do not provide a comprehensive picture of national irrigation landscape (Cai and Rosegrant 2002). Remote sensing products have become widely used to estimate regional irrigation water use by multiplying irrigated

acreage by irrigation demand (Karthikeyan *et al* 2020). While irrigated acreage can be reasonable estimated by remote sensing in semi-arid and arid regions due to the sharp contrasts between irrigated land and surrounding, it remains challenging to estimate irrigated crop land semi-humid and humid regions (Xu *et al* 2019). Irrigation demand can be either estimated from remotely sensed soil moisture or crop evapotranspiration, but the estimation accuracy is limited by factors such as algorithm parameterization and lack of ground truth validation (Zaussinger *et al* 2019). In addition, remote sensing does not provide decades-long irrigation estimation, thus limiting their applications in trend analysis.

The US Geological Survey (USGS) National Water Use Information Program's (NWUIPs) 5 year water use data provides a consistent survey of county level water use at the national scale. The water use data includes various categories including public supply, domestic, irrigation, thermoelectric power, industrial, mining, livestock and aquaculture (Dieter 2018). Unlike model-based water use estimation subject to simplifications and assumptions that may not hold, this survey dataset reflects the observed water use and has the potential to reveal the driving forces of water use changes. Various studies have utilized this dataset to assess the temporal trend (Donnelly and Cooley 2015) or the spatial distribution (Kim *et al* 2018) of water use, respectively. However, the temporal analyses do not capture the spatial heterogeneity of climate and agricultural development, and the spatial analyses do not reflect how irrigation water withdrawal is affected by climate variability and anthropogenic changes. It remains unclear whether the US agricultural water withdrawal exhibits any spatial and temporal trends and how to interpret the driving forcings of the trends.

Using the USGS water use data and other national scale climate and agriculture datasets, this study adopted the concept of 'center of mass' (i.e. center of gravity, centroid) to characterize the spatiotemporal trajectory of water withdrawal and various climatic and agricultural factors at state, regional and national scales. The center of mass has been used to analyze the spatial and temporal change of population growth (Aboufadel and Austin 2006) and economic development (Quah 2011). The centroid quantifies the concentration of a spatially distributed variable, and the time series of centroids calculated from continuous records reveal the spatiotemporal trajectory. Therefore, the centroid of irrigation water withdrawal provides a simple index to capture the temporal variability and spatial trajectory from irrigation withdrawal under various climatic, agricultural, infrastructural, and socioeconomic settings. In addition, the centroids of water use and other variables can be calculated at national, regional and state scales to investigate the different drivers of irrigation water

withdrawal under various conditions (e.g. arid vs. humid climate).

This study aims at examining the spatiotemporal trends of contiguous US (CONUS, the lower adjoining 48 states excluding states of Alaska and Hawaii) agricultural water withdrawal over the last three decades across national, regional, and state scales, and understanding the driving forces of irrigation withdrawal trends at different regions. Using the USGS water use data together with other climate and agriculture datasets, this study tries to answer the following questions: (a) What is the spatial and temporal trend of agricultural water withdrawal over the last three decades at the CONUS scale? (b) What are the main drivers of agricultural water withdrawal changes? (c) Are there any differences in the agricultural water withdrawal and the driving forces for the arid Western US and humid Eastern US? (d) Is the spatial and temporal trend of agricultural water withdrawal resilient to climate variabilities and extremes? This study provides a benchmark for the retrospective analysis of CONUS agricultural water withdrawal. Insights from this study will help researchers to develop more realistic future water use scenarios for climate change mitigation and water resources managers to better design incentives for sustainable irrigation development.

2. Methods and data

The USGS's NWUIP compiles the nation's water use data in cooperation with local, state, and federal agencies and publishes county-level water use data on a five-year average basis (years ending in 0 and 5) (Maupin *et al* 2014, Dieter 2018). For each water withdrawal sector, the USGS water use data differentiates water withdrawal sources (surface and groundwater) and water type (fresh and saline water). While the USGS water use data dates back to 1950, our analysis focuses on the period during 1981–2015. During this period, the water accounting categories are consistent and comprehensive for all counties in CONUS. It is noted that water withdrawal (i.e. water taken from a source) is different from actual water consumption (i.e. water evaporated, transpired by crop into atmosphere, and/or incorporated into produces). Although thermoelectric power represents the largest water withdrawal in USGS water use report, the actual water consumption via evaporation by thermoelectric power is much less than agricultural sector as most of the cooling water returns to the source (Harris and Diehl 2019). Irrigation water withdrawal is subject to water delivery loss and irrigation return flow. The USGS water use data does not contain irrigation water consumption as there is no reliable irrigation efficiency information at the national scale. It is also worth mentioning that the USGS irrigation withdrawal is presented as daily average (Bgal d^{-1}) by uniformly distributing the annual

amount across the entire year. This results in underestimation of daily irrigation amount as irrigation is only applied when irrigation is needed.

The centroid location of agricultural water withdrawal during a five-year report period was calculated as:

$$\text{Lat} = \frac{\sum_i x_i \text{Lat}_i}{\sum_i x_i}, \ \text{Lon} = \frac{\sum_i x_i \text{Lon}_i}{\sum_i x_i} \qquad (1)$$
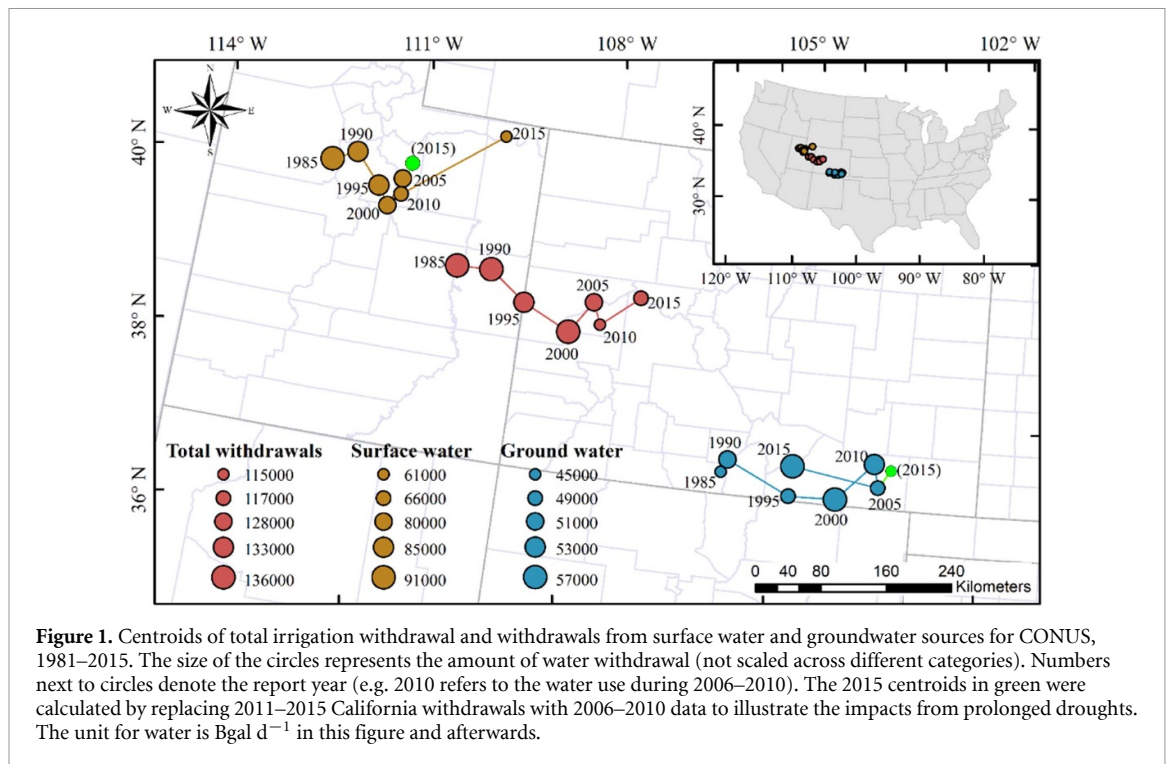
where x_i is the agricultural water withdrawal of county i, and the longitudes (Lat$_i$) and latitudes (Lon$_i$) of the geometric center of the county were obtained from US Census Bureau. We only included counties in the CONUS, since counties in Alaska and Hawaii will shift the centroids of water use due to their significantly different weights for longitudes and latitudes. For every report period during 1981–2015, we calculated the centroid locations of total agricultural water withdrawal as well as withdrawal from surface water and groundwater, respectively. These centroids, as a concise and interpretable visualization tool, enable us to characterize the shifting spatial distribution of agricultural irrigation water withdrawal.

In addition, the county level irrigated acreage data was obtained from US Department of Agriculture (USDA) National Agricultural Statistics Service (NASS). The USDA NASS census and survey data include total irrigated acreage, acreage using flood irrigation techniques (e.g. gravity-driven irrigation through on-field furrows) and acreage with watersaving irrigation (e.g. irrigation through sprinkler, micro/drip irrigation systems) (USDA NASS, 2017). Compared to the pressurized irrigation systems, the flood irrigation technique is generally less efficient, requires larger irrigation water withdrawal to meet the same crop water demand and generates more irrigation return flow. The centroids of irrigated crop land (total, flood irrigated, water-saving irrigated acreages) were calculated similarly to the centroids of water withdrawal using equation (1).

Hydroclimatic data was obtained from the gridded forcing data in North American Land Data Assimilation System phase 2 (NLDAS-2) (Mitchell *et al* 2004). The precipitation (P) in NLDAS is orographic adjusted based on the widely applied PRISM climatology (Daly *et al* 2000). The potential evaporation (PET) is calculated by the modified Penman scheme of Mahrt and Ek (1984). The 0.125° gridded NLDAS-2 hydroclimatic data was averaged over the grid nodes within each county boundary. The county level irrigation water demand was calculated as the evapotranspiration deficit times the irrigated acreage during growing season (May to October) as:

Irrigation Demand = (PET − P) × IrrigatedAcreage. (2)

It is noted that the irrigation demand is a simplified proxy of the climatic control on crop water

Figure 1. Centroids of total irrigation withdrawal and withdrawals from surface water and groundwater sources for CONUS, 1981–2015. The size of the circles represents the amount of water withdrawal (not scaled across different categories). Numbers next to circles denote the report year (e.g. 2010 refers to the water use during 2006–2010). The 2015 centroids in green were calculated by replacing 2011–2015 California withdrawals with 2006–2010 data to illustrate the impacts from prolonged droughts. The unit for water is Bgal d^{-1} in this figure and afterwards.

need and does not account for other factors such as crop water use efficiency, irrigation practices, irrigation technology and delivery loss.

Since the climatic conditions and agricultural practices are heterogeneous across CONUS, we also calculated the centroid locations of irrigation withdrawal, irrigated acreage and hydroclimatic variables for the arid and semi-arid Western US, humid and semi-humid Eastern US, and each state, respectively.

3. Results

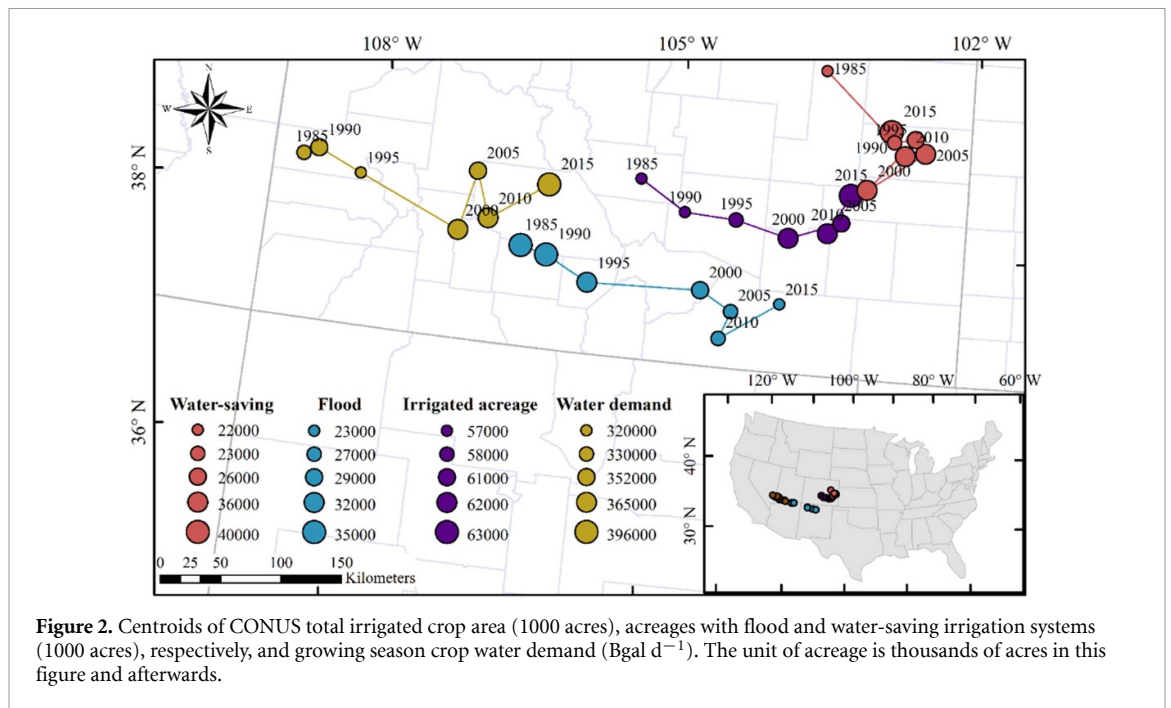### 3.1. Spatial-temporal trend of agricultural water withdrawal at CONUS level

At the CONUS level, the total irrigation withdrawal decreased by approximately 13.3% from 136 Bgal d^{-1}) to 118 Bgal d^{-1} during 1981–2015 (after reaching the peak in the 1976–1980 survey). As shown in figure 1, the centroids of CONUS irrigation water withdrawal were located around the border between Utah and Colorado. The centroids fell within the Western US as the western states experience more arid climate than the eastern states and thus need substantially more irrigation. The centroids of surface water irrigation were in northern Utah, as California, Idaho, and Colorado were three states with leading surface water irrigation withdrawal (Dieter 2018). The centroids of groundwater irrigation were in southern Colorado, as groundwater irrigation withdrawal mainly comes from major aquifers in California, Arkansas and states over the High Plains including Texas. Over last three decades, the centroids of total irrigation withdrawal continuously moved eastwards from Utah to Colorado

(figure 1). Although surface water withdrawal was consistently higher than groundwater withdrawal, it decreased from 91 Bgal d^{-1} to 61 Bgal d^{-1} during 1981–2015 and groundwater withdrawal increased after 2000. If the trend continues, groundwater will become the main irrigation source in future decades.

The abrupt shifts of irrigation centroids between 2010 and 2015 is likely caused by extensive regional droughts during this period. From 2010 to 2015, the centroid of groundwater withdrawal reversed its eastward-moving trend during past decades and shifted back to the west. Meanwhile, a huge eastward jump occurred for the centroid of surface water withdrawal. The extreme drought condition in California, the largest agricultural water user in the Western US, dramatically increased groundwater withdrawal to supplement the shortage in surface water resources. Assuming there was no drought condition in California and recalculating the centroid by replacing 2011–2015 California withdrawal with data from the previous survey period (i.e. 2006–2010), the new centroids (green points in figure 1) became consistent with their historical trajectories and resumed the eastward-moving trend.

3.2. Spatial-temporal trend of irrigated acreage and irrigation water demand

To identify the drivers of the observed eastward-moving centroids of agricultural water withdrawal, figure 2 shows the centroids of the total irrigated acreage, acreage with flood irrigation systems, acreage with water-saving irrigation systems, and crop water demand calculated in equation (2). The centroids of water demand and total irrigated acreage

Figure 2. Centroids of CONUS total irrigated crop area (1000 acres), acreages with flood and water-saving irrigation systems (1000 acres), respectively, and growing season crop water demand (Bgal d^{-1}). The unit of acreage is thousands of acres in this figure and afterwards.

exhibited similar eastward-moving trajectory with the centroids of total water withdrawal, demonstrating the robustness of the centroids calculating from different data sources. Although climate conditions showed inter-annual variability, no significant trend was detected in the centroid locations of climate variables P and PET (supplementary information, SI figure 1). The centroids of crop water demand calculated in equation (2) moved eastward. In addition, the centroids of irrigated acreage also showed similar movement to the irrigation water demand, indicating the trend is mainly caused by irrigated acreage change rather than the climate conditions. The trend in agricultural withdrawal centroids was mainly driven by the eastward trajectory of irrigated crop area centroids, which, in turn, was likely driven by increasing water demand in the Eastern U.S. The total irrigated acreage moved eastward during 1980–2000 and toward slightly northeast during 2001–2015. Nebraska and Arkansas contributed to the major increases in irrigated acreage, and reduction of irrigated acreage was mostly located in central and southern High Plains and California (USDA National Agricultural Statistics Service 2017).
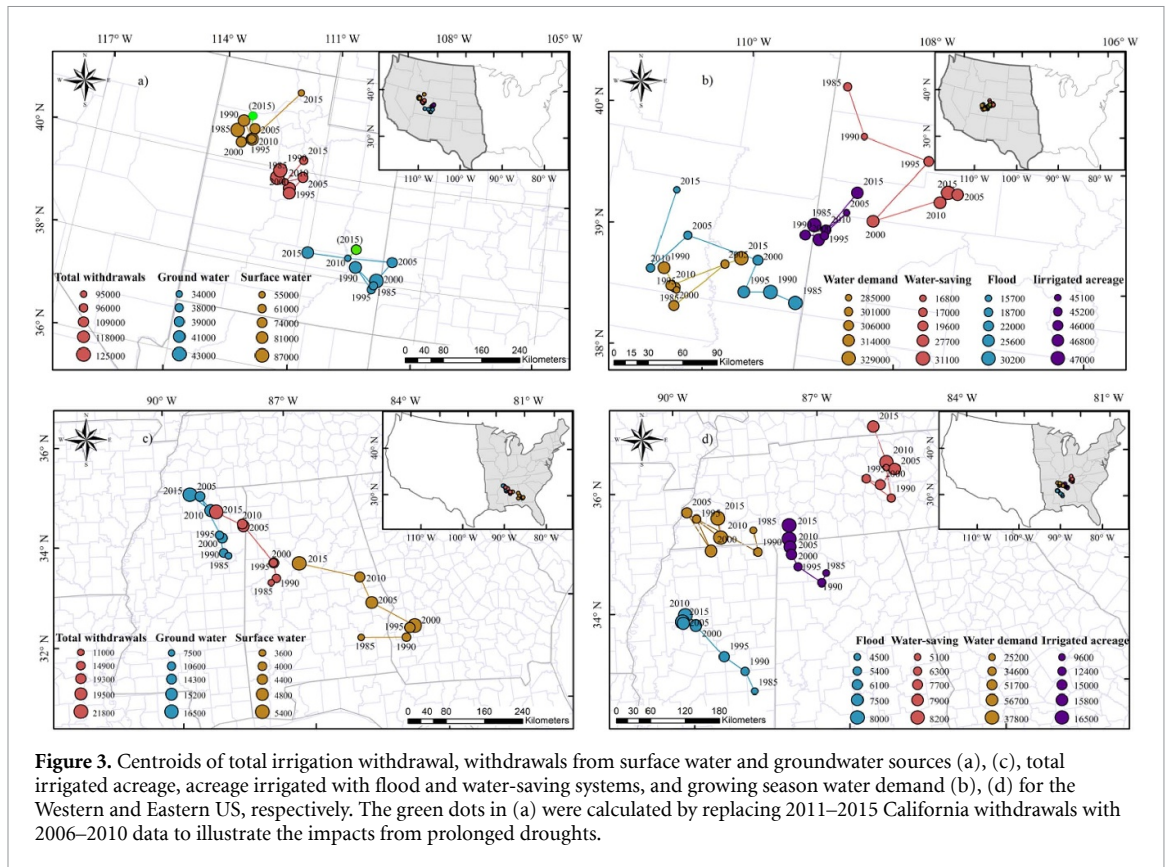
Improvement of irrigation efficiency also contributed to the declining trend in total agricultural withdrawal. The less efficient flood irrigation acreage decreased from 34.735 MAcres in 1985 survey to 23.3 MAcres in 2015 survey. The western states had more aggressive reduction in flood irrigation acreage, leading to the eastward-moving centroids of flood irrigated acreage. While pressurized water saving irrigation acreage increased from 22.1 MAcres (38.9%) in 1985 to 40.0 MAcres (61.1%) in 2015, the increase was relatively uniformly distributed in

all states as indicated by the stable centroids of water saving acreage.

3.3. Trends of agricultural water withdrawal and its drivers in the Western US
For the semi-arid and arid western states, the total withdrawal decreased during 1981–2015 without large shifts of the centroids except for the abrupt change between 2010 and 2015 caused by droughts (figure 3(a)). While centroids of surface water withdrawal remained relatively unchanged, the centroids of groundwater withdrawal moved towards the west after 2000. This was mainly caused by reduction in groundwater withdrawal in states over the Ogallala Aquifer, since these states are located on the east side of the centroids. Similarly as in figure 1, the impact of 2011–2015 drought condition in California on centroids of surface-water and groundwater withdrawals is notable in figure 3(a). Switching from surface water to groundwater sources during droughts in California pushed the centroids of surface water and groundwater withdrawals abruptly, deviating from previous years. If the centroids were calculated by replacing California water withdrawal during 2011–2015 (drought condition) with 2006–2010 (non-drought) data, they resumed the trend from previous years as shown by the green dots in figure 3(a).

The amount and centroids of irrigated acreage in the west remained relatively stable, while changes in the irrigation method can be clearly observed (figure 3(b)). The centroids of water saving acreage showed increasing and the westward-moving trend (mainly during 1981–2005), which were opposite to the decreasing and eastward-moving

Figure 3. Centroids of total irrigation withdrawal, withdrawals from surface water and groundwater sources (a), (c), total irrigated acreage, acreage irrigated with flood and water-saving systems, and growing season water demand (b), (d) for the Western and Eastern US, respectively. The green dots in (a) were calculated by replacing 2011–2015 California withdrawals with 2006–2010 data to illustrate the impacts from prolonged droughts.

trends (mainly during 2001–2015) of flood irrigation acreage. This indicates that significant irrigation efficiency improvement has taken place within the Western US to reduce the total irrigation withdrawal without decreasing the irrigated acreage. In addition, directions of centroid trajectory indicate that the states over the High Plains experienced more aggressive irrigation efficiency improvement than the Mountain States and Western Coastal States. This trend may be driven by groundwater-fed irrigation sustainability concerns over the High Plains, as the extensive over-exploit of the southern and central portions Ogallala Aquifers has caused challenges in water availability and water rights conflicts (Sophocleous 2010, Scanlon *et al* 2012).

3.4. Trends of agricultural water withdrawal and its drivers in the Eastern US

Although traditionally not major agricultural water users, the semi-humid and humid eastern states experienced rapid increase in irrigation withdrawal (from 11.0 Bgal d^{-1} to 21.8 Bgal d^{-1}) and irrigated acreage expansion (from 9.6 MAcres to 16.5 MAcres) during 1981–2015 (figures 3(c) and (d)). While no significant temporal trend was detected in surface water withdrawal, groundwater irrigation dramatically increased and was about three times as large as the surface water irrigation in the 2011–2015 report period. During 1981–2015, the centroids of irrigation withdrawal (including total, surface water

and groundwater withdrawal) all moved toward northwest.

With the climate condition remained relatively stable (SI figure 1), the irrigation withdrawal change in the east was primarily driven by increases in irrigated crop land (figure 3(d)). In contrast to the Western US where total irrigated acreage remained relatively stable (with slightly decrease from 47.2 MAcres to 46.0 MAcres during 1981–2015), the Eastern US experienced dramatic irrigation expansion. More specifically, the irrigated acreage using pressure-sprinkler irrigation systems increased, but its percentage in total irrigated acreage decreased from 54.5% in 1985 to 48.1% in 2015. On the other hand, the percentage of gravity irrigated acreage steadily increased from 45.5% to 51.9% over 1981–2015. The centroid of total irrigated acreage moved toward the west during 1981–2000 and toward the north after 2000. Similarly, the centroid of flood-irrigated acreage moved towards Arkansas during 1981–2000 and became stable afterwards mainly due to increased water-intensive rice production along the lower Mississippi River Valley. The northward trends after 2000 found in centroids of total irrigated acreage is mainly due to expansion of water-saving irrigated acreage (from 5.1 MAcres to 7.9 MAcres) in the eastern portion of the Corn Belt. The observed expansion of irrigated agriculture in the humid and semi-humid Eastern US indicates the promising sustainable irrigation development strategy for enhance crop yield under climate change without depleting the non-renewable water

storage and impairing environmental flow (Rosa *et al* 2018).

3.5. State scale results

The vast majority of CONUS crop irrigation occurred across four primary regions: (a) the Columbia and Snake River Basins of the Pacific Northwest, (b) the California Central Valley, (c) the High Plains and c) the Lower Mississippi Valley (SI figure 2). The centroids of irrigation withdrawal for most major agricultural water users in the western states remained stable, while they shifted spatially in a few western states (Texas, North Dakota and South Dakota) and many eastern states (SI figure 3). The expansion of irrigation from each eastern state combined together explained eastward-moving centroids at the CONUS level.

In the water scarce western states, the divergence of surface water and groundwater withdrawal centroids suggests availability of water sources (e.g. streams, aquifers and reservoirs) and infrastructure (e.g. pumping wells and water diversion projects) shaped the agricultural water use landscape (SI figure 4). High Plains states over the Ogallala Aquifer (i.e. North Dakota, South Dakota, Nebraska, Kansas, Colorado, Oklahoma, New Mexico and Texas) showed divergence between centroids of surface water and groundwater withdrawals. For example, the centroids of groundwater withdrawal in Texas are clustered in northern Texas which has access to groundwater stored in the southern High Plains Aquifer. In southern Texas, however, surface water is more accessible for irrigation from the stream network.

4. Discussion

Although the Western US has continuously made efforts to reduce irrigation withdrawal since 1981, extensive and prolonged regional drought conditions caused interruptions to the declining trend of irrigation withdrawal as well as its spatial distribution trajectory. For example, the 2011–2015 drought condition in California partially reversed the multi-decadal eastward-moving trend of groundwater irrigation withdrawal centroid (figure 1). While switching from surface water to groundwater may temporally mitigate drought impact, pumping from groundwater is not a sustainable solution in the long term if groundwater storage cannot be fully recharged (Marston and Konar 2017, Thomas *et al* 2017, Jasechko and Perrone 2020). The persistent drought condition in the Colorado River Basin in recent years triggered Tier 1 Shortage Declaration in 2021 and led to cut in surface water supply for agricultural sectors in California, Arizona and Nevada. Climatic and hydrologic models project more severe and frequent droughts in the Southwestern US (MacDonald 2010, Gao *et al* 2012). While studies have investigated future irrigation required

to adapt to climate change and mitigate crop yield loss (Döll and Siebert 2002, Fischer *et al* 2007, Elliott *et al* 2014), it remains uncertain whether groundwater storage and irrigation efficiency improvement efforts will suffice to buffer future drought conditions. Therefore, understanding the sensitivity of irrigation under extreme climatic and hydrologic conditions are fundamental to provide guidelines for sustainable irrigation adaptation policy making (Hrozencik *et al* 2017, Lu *et al* 2020).

The trajectory of irrigation withdrawal represents local irrigation water supply for agricultural production and does not reflect the demand and consumption locations of agricultural commodities (e.g. food, livestock feed, biofuel and trade). The development of agriculture is traditionally achieved by 'moving water to agriculture' facilitated by water resources infrastructures (e.g. reservoirs, pumping wells diversion channels) (Rushforth *et al* 2022). The eastward-moving centroids of irrigation withdrawal and irrigated acreage expansion in the semi-humid and humid Eastern CONUS suggest an emerging trend of 'moving agriculture to water', as the semi-arid and arid Western CONUS has already been stressed by water shortage. The traditionally rain-fed crops in the Midwest may require supplementary irrigation to maintain current crop yield under future climate (DeLucia *et al* 2019). Various studies have estimated future agricultural demand based on projected change of climatic drivers (Wisser *et al* 2008) with a focus on semi-arid climate zones (Nie *et al* 2021). However, the non-climatic drivers (e.g. irrigation efficiency and irrigation expansion) and semi-humid regions have played increasingly important roles in changing agricultural water use landscape in CONUS over the last decades. For example, Shafiee-Jood *et al* (2014) found that farmers in the Midwest installed irrigation for biofuel crops as the contracts with biofuel refineries and agricultural insurance provide incentives for stable yield. Xu *et al* (2019) found that the irrigation expansion in southwestern Michigan was concentrated in farms growing seed corn, because irrigation is usually required by the contracts between farmers and seed corn companies.

Unlike the centroids of irrigation withdrawal, the centroids of CONUS population had a consistent southwest-moving trend during over centuries (Aboufadel and Austin 2006). The divergence between the centroids of population (proxy for agricultural water demand) and irrigation withdrawal (proxy for irrigation water supply) indicates the important role of virtual water flow to redistribute the agricultural water use (Hoekstra and Chapagain 2006, Konar and Marston 2020). As agriculture virtual water quantifies the water used throughout the production (i.e. evaporative consumptive use) and process of crops (Dalin 2012), the trade of agricultural commodities may bridge the spatial imbalance between food demand and crop supply.

For example, Dang *et al* 2015) found that agricultural virtual water flows within the US was equivalent to 51% international flows and mainly contributed by water-intensive commodities. The virtual water stored in grains, equivalent to 62% of U.S. dam water storage, provides buffering capacity to climatic variability (Ruess and Konar 2019). If the population keeps growing in the already water-stressed the Western US, the increasing demand from other water use sectors and uncertain climate may further drive the agricultural withdrawal centroid to the east. Globally, countries with imported virtual water from food irrigated with non-renewable groundwater source may expose to risks for future food security due to depleted aquifer storage (Dalin *et al* 2017).

The spatiotemporal trajectory of agricultural water withdrawal centroids may have different environmental impacts in the Eastern and Western US. As major agricultural water users, the western states are continuing reducing water withdrawal by improving irrigation efficiency while maintaining the irrigated crop area. For example, most irrigated fields within Kansas High Plains have switched from central pivot irrigation to central pivot with low energy precise application to reduce wind drift-caused loss and non-consumptive canopy evaporation (Perez-Quesada and Hendricks 2021, Zwickle *et al* 2021). The increased irrigation efficiency is achieved by reducing crop non-consumptive use and lowering irrigation return flows (e.g. effluent into streams and recharge into aquifers), which may provide critical ecosystem services in the arid and semi-arid Western US. Studies have recommended to account for the tradeoffs between irrigation efficiency and return flow-dependent ecosystem services when designing incentives to improve irrigation efficiency (Jägermeyr *et al* 2017, Borsato *et al* 2020, Pérez-Blancoand Sapino 2022). Despite the efforts to mitigate the over-exploited aquifer freshwater storage in the Western US (e.g. the California Central Valley and the Ogallala Aquifer), groundwater resources may be further stressed due to cut in surface water allocation (e.g. Tier 1 and 2 water cut from Colorado River in the on-going 2020 drought). The groundwater governance in these regions require equitable and reasonable utilization of groundwater resources during decision making, while facing the complex social (e.g. water rights allocation among different water users), economic (e.g. benefits from various water sections) and environmental (e.g. sustainability of non-renewable aquifer water storage) tradeoffs (Neal *et al* 2016).

The semi-humid and humid Eastern US has the potential to support sustainable irrigation expansion, as the relatively abundant of surface water resources avoid over-exploit of non-renewable aquifer freshwater storage (Rosa *et al* 2018). However, the increasing irrigation return flow due to irrigation expansion (especially gravity irrigation systems) may worsen the water quality problems caused by nutrients (nitrate and phosphorus) and soil erosion from field drainage (Smith *et al* 1997, Parry 1998). Better agricultural practices at the field scale, such as recycling of irrigation drainage water (Reinhart *et al* 2019), crop selection (Gamble *et al* 2022) and nitrogen recovery (van Grinsven *et al* 2015), would mitigate the environmental impact of irrigation return flow if they are implemented at regional scale.

5. Conclusion

The CONUS agricultural total water withdrawal exhibited a decreasing and eastward-moving trend during 1981–2015. The migration of CONUS irrigation withdrawal centroids is mainly caused irrigation efficiency improvement and irrigation expansion in different regions, while the climatology conditions (e.g. P and PET amount and their centroids) remains relatively stable during the study period. Specifically, the eastward migration of irrigation withdrawal is caused by (a) reduction of irrigation withdrawal in the western states with improved irrigation efficiency by converting flood irrigated crop land to water-saving irrigation, (b) increased irrigation withdrawal in the eastern states by converting rain-fed crop land to irrigated land. The spatial and temporal trend of irrigation withdrawal exhibited resilience to climate variability, but the trend may be interrupted by climate extremes. For example, the prolonged drought in California during 2011–2015 reversed the trends of centroids in groundwater and surface water withdrawal, as the components of irrigation water sources showed abrupt changes during the droughts.

The semi-arid and arid Western US had decreasing withdrawal from both surface water and groundwater sources, and their centroids remained relatively stable. The centroids of groundwater moved towards the west after 2001, mainly due to reduction in groundwater withdrawal in states over the Ogallala Aquifer. The reduction of irrigation withdrawal in the Western US was mainly achieved by irrigation efficiency improvement, while the irrigated acreage and its centroids remained relatively stable.

The semi-humid and humid Eastern US exhibited emerging irrigation withdrawal increase from both surface water and groundwater sources. The centroids of the eastern withdrawal moved toward the northwest. The eastern CONUS irrigation withdrawal was driven by persistent increasing in irrigated acreage. While the development of flood irrigation acreage (mainly in the Mississippi Valley) stabilized after 2000, the water-saving irrigation development (mainly in the Midwest) accelerated after 2000.

Although the withdrawal centroids do not exhibit spatial trend at the state level, some states (e.g. Texas, Colorado, Nebraska Kansas, North Dakota, South Dakota, Arizona and Utah) showed different

centroid locations for surface water and groundwater withdrawals. This was attributed to state-wide heterogeneity of water resources (e.g. rivers, aquifers) and infrastructures (e.g. aquifers, reservoirs, and delivery channels).

The spatiotemporal trajectories of CONUS irrigation withdrawal and its drivers at the national, state and local scales provide insights into predict future irrigation demand and investigate the environmental and social impacts of irrigation development.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: www. hydroshare.org/resource/37ee01c8fd6d4c63bc2fdf5c e67a681c.

Conflict of interest

The authors declare no competing interests.

Author contributions

R Zeng developed the conceptual work, conducted the analysis, and led the writing of the paper. W Ren conducted the analysis, plotted the figures, and revise the paper.

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References

Aboufadel E and Austin D 2006 A new method for computing the mean center of population of the United States *Prof. Geogr.* **58** 65–69

Borsato E, Rosa L, Marinello F, Tarolli P and D'Odorico P 2020 Weak and strong sustainability of irrigation: a framework for irrigation practices under limited water availability *Front. Sustain. Food Syst.* **4** 17

Da Cunha D A, Coelho A B and Féres J G 2015 Irrigation as an adaptive strategy to climate change: an economic perspective on Brazilian agriculture *Environ. Dev. Econ.* **20** 57–79

Dalin C, Konar M, Hanasaki N, Rinaldo A and Rodriguez-Iturbe I 2012 Evolution of the global virtual water trade network *Proc. Natl Acad. Sci.* **109** 5989–94

Dalin C, Wada Y, Kastner T and Puma M J 2017 Groundwater depletion embedded in international food trade *Nature* **543** 700–4

Daly C, Taylor G H, Gibson W P, Parzybok T W, Johnson G L and Pasteris P A 2000 High-quality spatial climate data sets for the United States and beyond *Trans. ASABE* **43** 1957–62

Dang Q, Lin X and Konar M 2015 Agricultural virtual water flows within the United States *Water Resour. Res.* **51** 973–86

DeLucia E H *et al* 2019 Are we approaching a water ceiling to maize yields in the United States? *Ecosphere* **10** e02773

Dieter C A 2018 Water availability and use science program: estimated use of water in the United States in 2015 *Circ. US Geol. Surv.* **1411** 26

Döll P 2002 Impact of climate change and variability on irrigation requirements: a global perspective *Clim. Change* **54** 269–93

Döll P and Siebert S 2002 Global modeling of irrigation water requirements *Water Resour. Res.* **38** 8–1

Donnelly K and Cooley H 2015 *Water Use Trends* (Oakland, CA: Pacific Institute)

Elliott J *et al* 2014 Constraints and potentials of future irrigation water availability on agricultural production under climate change *Proc. Natl Acad. Sci.* **111** 3239–44

Ferguson I M and Maxwell R M 2012 Human impacts on terrestrial hydrology: climate change versus pumping and irrigation *Environ. Res. Lett.* **7** 044022

Fischer G, Tubiello F N, van Velthuizen H and Wiberg D A 2007 Climate change impacts on irrigation water requirements: effects of mitigation, 1990–2080 *Technol. Forecast. Soc. Change* **74** 1083–107

Gabriela P-Q and Hendricks N P 2021 Lessons from local governance and collective action efforts to manage irrigation withdrawals in Kansas *Agric. Water Manage.* **247** 106736

Gamble J, Baker J, Dalzell B, Wente C and Feyereisen G 2022 Ecohydrology of irrigated silage maize and alfalfa production systems in the upper Midwest US *Agric. Water Manage.* **267** 107612

Gao Y, Leung L R, Salathé E P Jr, Dominguez F, Nijssen B and Lettenmaier D P 2012 Moisture flux convergence in regional and global climate models: implications for droughts in the southwestern United States under climate change *Geophys. Res. Lett.* **39** L09711

Harris M A and Diehl T H 2019 Withdrawal and Consumption of Water by Thermoelectric Power Plants in the United States, 2015 No. 2019–5103 (US Geological Survey)

Hoekstra A Y and Chapagain A K 2006 Water footprints of nations: water use by people as a function of their consumption pattern *Integrated Assessment of Water Resources and Global Change* (Dordrecht: Springer) pp 35–48

Hrozencik R A, Manning D T, Suter J F, Goemans C and Bailey R T 2017 The heterogeneous impacts of groundwater management policies in the Republican River Basin of Colorado *Water Resour. Res.* **53** 10757–78

Jägermeyr J, Pastor A, Biemans H and Gerten D 2017 Reconciling irrigated food production with environmental flows for Sustainable Development Goals implementation *Nat. Commun.* **8** 1–9

Jasechko S and Perrone D 2020 California's Central Valley groundwater wells run dry during recent drought *Earth's Future* **8** e2019EF001339

Junyu L, Carbone G J, Huang X, Lackstrom K and Gao P 2020 Mapping the sensitivity of agriculture to drought and estimating the effect of irrigation in the United States, 1950–2016 *Agric. For. Meteorol.* **292** 108124

Karthikeyan L, Chawla I and Mishra A K 2020 A review of remote sensing applications in agriculture for food security: crop growth and yield, irrigation, and crop losses *J. Hydrol.* **586** 124905

Kim S, Devineni N, Lall U and Kim H S 2018 Sustainable development of water resources: spatio-temporal analysis of water stress in South Korea *Sustainability* **10** 3795

Konar M and Marston L 2020 The water footprint of the United States *Water* **12** 3286

Konikow L F 2011 Contribution of global groundwater depletion since 1900 to sea-level rise *Geophys. Res. Lett.* **38** L17401

MacDonald G M 2010 Water, climate change, and sustainability in the southwest *Proc. Natl Acad. Sci.* **107** 21256–62

Mahrt L and Ek M 1984 The influence of atmospheric stability on potential evaporation *J. Appl. Meteorol. Climatol.* **23** 222–34

Marston L and Konar M 2017 Drought impacts to water footprints and virtual water transfers of the Central Valley of C alifornia *Water Resour. Res.* **53** 5756–73

Mastrángelo M E *et al* 2019 Key knowledge gaps to achieve global sustainability goals *Nat. Sustain.* **2** 1115–21

Maupin M A, Kenny J F, Hutson S S, Lovelace J K, Barber N L and Linsey K S 2014 Estimated use of water in the United States in 2010. No. 1405 (US Geological Survey)

Mitchell K E *et al* 2004 The multi-institution North American Land Data Assimilation System (NLDAS): utilizing multiple GCIP products and partners in a continental distributed hydrological modeling system *J. Geophys. Res.* **109** D07S90

Molden D 2007 *Water for Food Water for Life: A Comprehensive Assessment of Water Management in Agriculture* (London: Routledge)

Mutlu O, Rodell M, Beaudoing H K and Toll D L 2010 Simulating the effects of irrigation over the United States in a land surface model based on satellite-derived agricultural data *J. Hydrometeorol.* **11** 171–84

Neal M J, Greco F, Connell D and Conrad J 2016 The social-environmental justice of groundwater governance *Integrated Groundwater Management* ed A J Jakeman, O Barreteau, R J Hunt, J D Rinaudo and A Ross (Cham: Springer) p 253

Nie W, Zaitchik B F, Rodell M, Kumar S V, Arsenault K R and Badr H S 2021 Irrigation water demand sensitivity to climate variability across the contiguous United States *Water Resour. Res.* **57** 2020WR027738

Nocco M A, Smail R A and Kucharik C J 2019 Observation of irrigation-induced climate change in the Midwest United States *Glob. Change Biol.* **25** 3472–84

Parry R 1998 Agricultural phosphorus and water quality: a US Environmental Protection Agency perspective *J. Environ. Qual.* **27** 258–61

Pérez-Blanco C D and Sapino F 2022 Economic sustainability of irrigation-dependent ecosystem services under growing water scarcity. Insights from the Reno River in Italy *Water Resour. Res.* **58** e2021WR030478

Qin Y, Mueller N D, Siebert S, Jackson R B, AghaKouchak A, Zimmerman J B, Tong D, Hong C and Davis S J 2019 Flexibility and intensity of global water use *Nat. Sustain.* **2** 515–23

Quah D 2011 The global economy's shifting centre of gravity *Glob. Policy* **2** 3–9

Reinhart B D, Frankenberger J R, Hay C H and Helmers M J 2019 Simulated water quality and irrigation benefits from drainage water recycling at two tile-drained sites in the US Midwest *Agric. Water Manage.* **223** 105699

Rosa L 2022 Adapting agriculture to climate change via sustainable irrigation: biophysical potentials and feedbacks *Environ. Res. Lett.* **17** 063008

Rosa L, Chiarelli D D, Rulli M C, Dell'Angelo J and D'Odorico P 2020a Global agricultural economic water scarcity *Sci. Adv.* **6** eaaz6031

Rosa L, Chiarelli D D, Sangiorgio M, Beltran-Peña A A, Rulli M C, D'Odorico P and Fung I 2020b Potential for sustainable irrigation expansion in a 3 C warmer climate *Proc. Natl Acad. Sci.* **117** 29526–34

Rosa L, Rulli M C, Davis K F, Chiarelli D D, Passera C and D'Odorico P 2018 Closing the yield gap while ensuring water sustainability *Environ. Res. Lett.* **13** 104002

Rosegrant M W, Cai X and Cline S A 2002 World water and food to 2025: dealing with scarcity *Int. Food Policy Res. Inst.* **1** 32

Rosenberg N J, Brown R A, Izaurralde R C and Thomson A M 2003 Integrated assessment of hadley centre (HadCM2) climate change projections on agricultural productivity and irrigation water supply in the conterminous United States: i. Climate change scenarios and impacts on irrigation water supply simulated with the HUMUS model *Agric. For. Meteorol.* **117** 97–122

Ruess P J and Konar M 2019 Grain and virtual water storage capacity in the United States *Water Resour. Res.* **55** 3960–75

Rushforth R R, Zegre N P and Ruddell B L 2022 The three Colorado Rivers: hydrologic, infrastructural, and economic flows of water in a shared River Basin *J. Am. Water Resour. Assoc.* **58** 269–81

Sadoff C W, Borgomeo E and Uhlenbrook S 2020 Rethinking water for SDG 6 *Nat. Sustain.* **3** 346–7

Scanlon B R, Faunt C C, Longuevergne L, Reedy R C, Alley W M, McGuire V L and McMahon P B 2012 Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley *Proc. Natl Acad. Sci.* **109** 9320–5

Shafiee-Jood M, Cai X, Chen L, Liang X and Kumar P 2014 Assessing the value of seasonal climate forecast information through an end-to-end forecasting framework: application to US 2012 drought in central Illinois *Water Resour. Res.* **50** 6592–609

Skaggs R W, Brevé M A and James W G 1994 Hydrologic and water quality impacts of agricultural drainage∗ *Crit. Rev. Environ. Sci. Technol.* **24** 1–32

Sloat L L, Davis S J, Gerber J S, Moore F C, Ray D K, West P C and Mueller N D 2020 Climate adaptation by crop migration *Nat. Commun.* **11** 1–9

Smith R A, Schwarz G E and Alexander R B 1997 Regional interpretation of water-quality monitoring data *Water Resour. Res.* **33** 2781–98

Sophocleous M 2010 Groundwater management practices, challenges, and innovations in the High Plains aquifer, USA—lessons and recommended actions *Hydrogeol. J.* **18** 559–75

Thomas B F, Famiglietti J S, Landerer F W, Wiese D N, Molotch N P and Argus D F 2017 GRACE groundwater drought index: evaluation of California Central Valley groundwater drought *Remote Sens. Environ.* **198** 384–92

USDA National Agricultural Statistics Service 2017 NASS—quick stats (USDA National Agricultural Statistics Service) (available at: https://data.nal.usda.gov/dataset/nass-quick-stats) (Accessed 25 May 2020)

Vallino E, Ridolfi L and Laio F 2020 Measuring economic water scarcity in agriculture: a cross-country empirical investigation *Environ. Sci. Policy* **114** 73–85

van Grinsven H J M, Bouwman L, Cassman K G, van Es H M, McCrackin M L and Beusen A H W 2015 Losses of ammonia and nitrate from agriculture and their effect on nitrogen recovery in the European Union and the United States between 1900 and 2050 *J. Environ. Qual.* **44** 356–67

Wisser D, Frolking S, Douglas E M, Fekete B M, Vörösmarty C J and Schumann A H 2008 Global irrigation water demand: variability and uncertainties arising from agricultural and climate data sets *Geophys. Res. Lett.* **35** L24408

Cai X and Rosegrant M W 2002 Global water demand and supply projections: part 1. A modeling approach *Water Int.* **27** 159–69

Xu T, Deines J M, Kendall A D, Basso B and Hyndman D W 2019 Addressing challenges for mapping irrigated fields in subhumid temperate regions by integrating remote sensing and hydroclimatic data *Remote Sens.* **11** 370

Zaussinger F, Dorigo W, Gruber A, Tarpanelli A, Filippucci P and Brocca L 2019 Estimating irrigation water use over the contiguous United States by combining satellite and reanalysis soil moisture data *Hydrol. Earth Syst. Sci.* **23** 897–923

Zhang Z, Barlage M, Chen F, Yanping L, Helgason W, Xu X, Liu X and Li. Z 2020 Joint modeling of crop and irrigation in the central United States using the Noah-MP land surface model *J. Adv. Model. Earth Syst.* **12** e2020MS002159

Zwickle A, Feltman B C, Brady A J, Kendall A D and Hyndman D W 2021 Sustainable irrigation through local collaborative governance: evidence for a structural fix in Kansas *Environ. Sci. Policy* **124** 517–26