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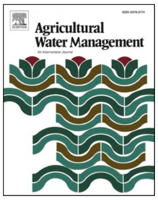

# Long-term croplands water productivity in response to management and climate in the Western US Corn Belt

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ABSTRACT

Global population growth and water scarcity are raising concerns about agricultural systems' ability to meet future food, fuel, feed, and fiber demands. Water productivity (*WP*), the ratio of crop production to water use, is crucial for assessing agricultural resilience and sustainability. Yet, research on *WP* often lacks long-term observational data to understand the impact of management and climate variability. Long-term monitoring of crop yield and water use, using Eddy Covariance technique, allows for accurate assessment of crop performance and their response to climate change in major cropping systems. In this study, we used data collected over a 20-year period (2001–2020) to investigate the interannual variability in yield (*Y*), crop evapotranspiration (*ET*), and water productivity (*WP*, ratio of *Y* and *ET*), and their response to management and climate in three major cropping systems located in Eastern Nebraska: irrigated continuous maize, irrigated maize-soybean rotation, and rainfed maize-soybean rotation. Our results showed significant differences ($p < 0.05$) in *WP* between irrigated and rainfed sites, mainly attributed to variations in *Y* rather than *ET*, while there was no significant effect of crop rotation on measured responses. *WP* was 18.4% higher in irrigated maize in rotation relative to the rainfed site. Water input (mm, sum of precipitation and irrigation) was the main management factor in rainfed maize *WP* ($R$=0.67, $p = 0.05$) and *Y* ($R$=0.79, $p < 0.05$). Vapor pressure deficit was negatively correlated with *Y* in rainfed maize ($R$=−0.72, $p < 0.05$) and therefore was considered a determinant in *WP* ($R$=−0.7, $p < 0.05$). For soybean, soil water content had the highest correlations with *Y* and *WP* (irrigated: $R$=−0.77; rainfed: $R$=0.49, only significant in irrigated sites). These findings can aid in formulating strategies to enhance water productivity and resilience in the US Corn Belt.

## 1. Introduction

Global food and water security are important issues at both local and global scales (O'Hara and Toussaint, 2021; FAO, 2022). The increasing demand for food, fuel, feed, and fiber, coupled with declining natural resources, is expected to further exacerbate the threat to agricultural systems in the coming decades (Rosa et al., 2020), highlighting the need for urgent action. Water security, in particular, poses a significant global environmental challenge (Srinivasan et al., 2012), and is a critical barrier for achieving food security, particularly in semi-arid and arid regions (Maroufpoor et al., 2021). Agriculture alone accounts for 90% of the global freshwater consumption (Hoekstra and Mekonnen, 2012; Huang et al., 2018), with irrigation accounting for roughly 70% of water withdrawals from surface and groundwater (Cai and Rosegrant, 2002; Wisser et al., 2008; Huang et al., 2019). The U.S. produces ~30% of the global maize supply and ~29% of global soybean supply, largely within the U.S Midwest Corn Belt (Wang et al., 2020; FAO, 2017) with maize and soybean as the most commonly irrigated crops in the country (Hrozencik and Aillery, 2021). These statistics demonstrate the limitation of expanding croplands and the need for sustainable crop production under irrigation, particularly given the competing demands for water from other sectors, such as industries, urbanization, and the environment (Vadez et al., 2014; WWAP, 2018). As such, there is an urgent need for more sustainable and efficient use of water resources, as well as innovative solutions to address the challenges facing the global food system.

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Biomass production per unit of plant water uptake is a commonly used metric for plant water productivity (Tanner and Sinclair, 1983; Blum, 2009; Linares and Camarero, 2012; Cernusak et al., 2019). While there is a lack of a consistent definition for this metric across disciplines (Perry et al., 2009; Fernández et al., 2020), there is greater consensus on using the term Water Productivity (*WP*) to describe the ratio between crop production and water use (Fernández et al., 2020). For instance, there are multiple methods proposed in the literature to calculate *WP*, with some focusing on leaf transpiration as a measure of water use (Condon et al., 2002; 2004; Zhang et al., 2019), while others extend the definition to evapotranspiration (*ET*), arguing that water loss through interception and soil evaporation is directly related to plant growth (Hatfield et al., 2001). The assimilated carbon considered in the determination of *WP* also varies depending on spatial (i.e., stomatal to ecosystem) and temporal (i.e., instantaneous gas exchange of plants to seasonal yield) scales of *WP* calculation (Condon, 2020). In this study, we report *WP* (kg $m^{-3}$) as the amount of dry grain *Y* per unit of water loss through crop *ET* (details on *WP* calculations are presented in Section 2.2.2). This approach minimizes uncertainties associated with estimating plant biomass and complex *ET* partitioning (Kool et al., 2014) and is more accurate given the advances in the measurement of the real crop *ET* such us the Eddy Covariance (*EC*) technique (e.g., Baldocchi et al., 1988) that has been widely used in recent years to measure gas exchanges between ecosystems and the atmosphere (Aubinet, 2023; Babaeian and Tuller, 2023).

Long-term experimental data records, at the field-scale, are important for improving our understanding of the dynamics of *WP* in response to cropping systems, climate variability and water accessibility. Process based models have been widely implemented to generate long-term simulated data records for analyzing changes in *WP* (Baumhardt et al., 2009; Farahani et al., 2009; Yang and Grassini, 2014; Liu and Song, 2020 among others). However, parameter model uncertainty as an intrinsic property of all models (Li et al., 2015; Orth et al., 2015) and the observational data limitation in parametrizing and validating both crop *Y* and plant water use (Tao et al., 2018) could significantly impact results. On the other hand, studies using field data to estimate *WP* are limited in temporal and spatial scales due to the complexity and high cost of maintaining such experiments for a long period across the landscape. In this study, we utilized data collected over a 20-year period (including annual dry *Y* and *ET* from *EC* measurements).

The primary objective of this study was to quantify and assess the differences in *WP*, *Y*, and *ET* among three major cropping systems in the Eastern Nebraska US Corn Belt (Irrigated continuous maize, irrigated maize soybean rotation, and rainfed maize soybean rotation), and to investigate their response to management and interannual climate and water variability. We hypothesized that higher *WP* will be observed in irrigated sites due to increased *Y* resulting from enhanced availability of water and nutrients through irrigation and crop rotation (Huynh et al., 2019; Agomoh et al., 2021). In contrast, the rainfed site is expected to exhibit more efficient water use under limited water conditions through stomatal closure (Serna, 2022), but this may reduce crop photosynthetic activity and ultimately *Y*, contributing to lower *WP*. To accomplish this, we used data from three proximate monitored sites in Eastern Nebraska (US) with similar climate and edaphic properties. We calculated the *Y*, *ET* and *WP* in the three cropping systems and estimated changes related to management and crop rotation. We also analyzed the correlations between *Y*, *ET* and *WP* and the selected climatic and water related variables to investigate the effect of inter-annual climate variability on *WP* and determine the drivers of its temporal variability. With a long-term monitoring record spanning over 20 years, encompassing management history, climate, and flux data, and with the sites sharing similar climate, topographic, and soil characteristics, these locations offer a unique opportunity to investigate the impact of management practices and climate variability on crop production and water utilization.

## 2. Materials and methods

### 2.1. Study sites

The study was conducted at three sites in the Eastern Nebraska Research, Extension and Education Center (ENREEC) of the University of Nebraska in Lincoln (UNL), within 1.6 km from each other 41°10’37.2"N 96°28’08.6"W (Fig. 1). The climate is continental, characterized by hot summers, cold winters, and overall humid conditions (Sharma and Irmak, 2012). Long-term average annual air temperature is around 10 °C with a January average minimum temperature of −9 °C and a July maximum temperature of 30 °C. Average annual precipitation is about 720 mm concentrated mainly between March and June (47% of annual precipitation falls between March and June). Soils are typical of eastern Nebraska formed by silty clay loams with four soil series at all three sites: *Filbert* (fine, smectitic, mesic Vertic Argialbolls), *Fillmore* (fine, smectitic, mesic Vertic Argialbolls), *Tomek* (fine, smectitic, mesic Pachic Argialbolls), and *Yutan* (fine-silty, superactive, mixed, mesic Mollic Hapludalfs) (Verma et al., 2005).

The three monitored sites are also part of the AmeriFlux (https://ameriflux.lbl.gov) and the Long Term Agro-Ecosystem Research (LTAR-USDA, https://ltar.ars.usda.gov) networks and are equipped with Eddy Covariance Flux towers since 2001 (US-Ne1, US-Ne2, and US-Ne3) (Verma et al., 2005). From 2000 to 2020, US-Ne1 (49 ha) and US-Ne2 (52 ha) were both irrigated with a center pivot irrigation system and cultivated with continuous maize (*Zea mays* L.) and maize-soybean (*Glycine max* (L.) Merr.) rotation, respectively, while US-Ne3 (65 ha) was a rainfed maize-soybean rotation. Planting cycle usually occurred between late April and mid-May with no tillage. Prior to each maize planting cycle, Nitrogen (*N*) fertilizer was applied in the form of liquid urea ammonium nitrate (32% *UAN* or 29% *UAN*) in three applications in the irrigated sites and in a single application in the rainfed site (Verma et al., 2005). At the irrigated sites, the second and third fertilizer applications were applied in the form of fertigation early July to improve maize *N* use efficiency. Total *N* fertilizer rates were adjusted to optimum levels during maize years based on measured residual nitrate in soil samples taken in the spring prior to each planting cycle (Verma et al., 2005; Wingeyer et al., 2012). Differences in applied *N* fertilizer (*Nf*) are due to available *N* in soil from sources other than mineral fertilizer (e.g., soybean *N* fixation and plant residue incorporated to the soil). *Nf* and planting density (*Pld*) are functions of the used varieties and expected *Y*. Despite differences in *Nf* and *Pld*, no clear effect on *Y* or *WP* was detected in this study (further detail in Section 3.2). *Pld*, *Nf*, irrigation, pesticide and herbicide application were determined following standard best management practices for production-scale maize and soybean systems. Irrigation, which depends on weather, crop status and field conditions, usually occurs between mid-June and early September. Table 1 shows average total irrigation (for US-Ne1 and US-Ne2), *N* rates, and planting densities during the study period.

### 2.2. Datasets

#### 2.2.1. Annual grain yield

Annual *Y* (kg $m^{-2}$) data at the three studied sites was collected between 2001 and 2020. Initially, *Y* was obtained in 15.5% and 13% moisture for maize and soybean, respectively and then for this study was transformed to dry estimates (0% moisture content) to account for net crop production. During this 20-year period, the US-Ne1 site was maintained as a continuous irrigated maize system and US-Ne3 a rainfed no-till maize-soybean rotation. For US-Ne2, the irrigated maize-soybean rotation was interrupted in 2010 and 2012 when maize was planted instead of soybean, resulting in 5 crop years of continuous maize (2009 to 2013). Data for 2010, 2012 and 2015 were excluded for all three sites due to severe hail damage (2010), non-matching rotation (2012), and important percentage of flux data gaps (2015). To isolate the effect of management from that of climate variability, we solely considered years

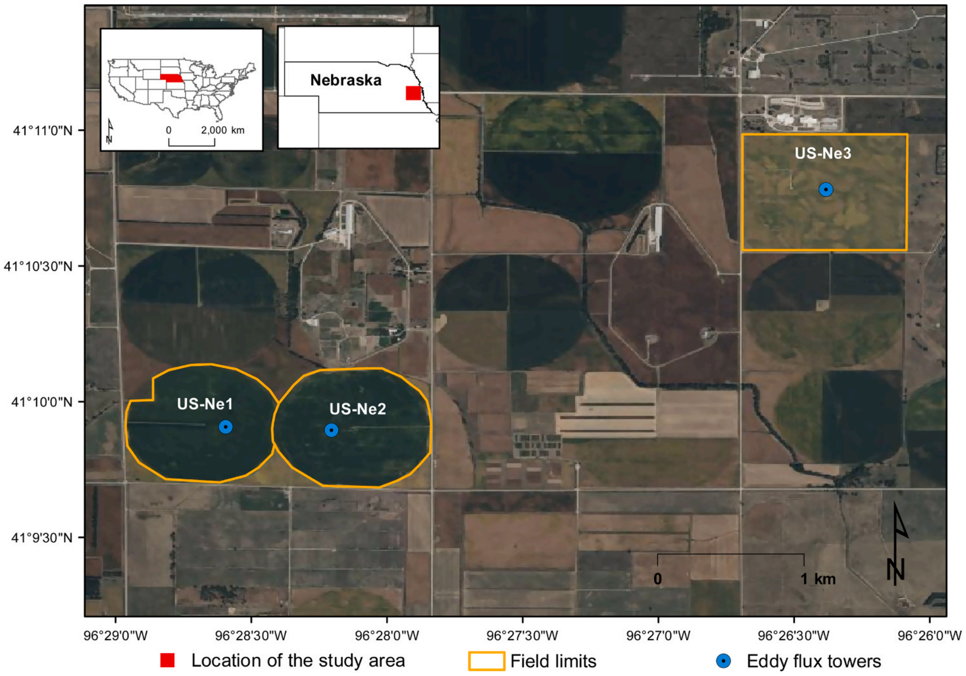


**Fig. 1.** US-Ne1, US-Ne2, and US-Ne3 field sites at the Eastern Nebraska Research, Education and Extension Center (ENREEC). US-Ne1 and US-Ne2 were irrigated with a center pivot irrigation system and cultivated with continuous maize (*Zea mays* L.) and maize-soybean (*Glycine max* (L.) Merr.) rotation, respectively. US-Ne3 (65 ha) was a rainfed maize-soybean rotation.

**Table 1**

Average irrigation, *N* fertilizer, and plant densities in the different study sites. US-Ne1: Irrigated continuous maize, US-Ne2: Irrigated maize soybean rotation, US-Ne3: Rainfed maize soybean rotation. Different letters indicate significant differences among means ($p < 0.05$). Small letters indicate maize differences and capital letters indicate soybean differences.

| | US-Ne1 Irrigated continuous maize | US-Ne2 Irrigated maize-soybean rotation | | US-Ne3 Rainfed maize-soybean rotation | |
|---|---|---|---|---|---|
| | Maize | Maize | Soybean | Maize | Soybean |
| Irrigation (mm) | 196 ± 102 a | 181 ± 96 a | 97 ± 63 | - | - |
| *N* Fertilizer (kg ha$^{-1}$) | 252 ± 46.3 a | 194 ± 26.3 b | - | 129 ± 21.7c | - |
| Planting density (plants ha$^{-1}$) | 78700 ± 4694 a | 78800 ± 2220 a | 297100 ± 37240 A | 58000 ± 5890 b | 285900 ± 20300 A |

where the studied crop is grown at all sites (three sites for maize and two sites for soybean). The final data record used in this manuscript includes 9 years of maize in the three sites and 8 years of soybean in sites US-Ne2 and US-Ne3 (Fig. 2).

### 2.2.2. Eddy covariance fluxes, climate data and estimation of WP

We used the Eddy Covariance (*EC*) flux measurements (e.g., Baldocchi et al., 1988) at the three sites to estimate crop *ET*. To only account for the crop water use, we solely considered the period between emergence and harvest for the analysis. Eddy covariance measurements include fluxes of latent and sensible heat and momentum. The measurements were conducted using a closed-path infrared $CO_2/H_2O$ gas analysis system (Li-Cor Inc., Lincoln, NE, Model LI6262), an open-path infrared $CO_2/H_2O$ gas analysis system (Li-Cor Inc., Lincoln, NE, Model LI7500), and an omnidirectional three-dimensional sonic anemometer (Gill Instruments Ltd., Lymington, UK, Model R3). To estimate the $CO_2$ below the eddy covariance sensors, an additional closed-path infrared $CO_2/H_2O$ gas analysis system (Li-Cor Inc., Lincoln, NE, Model LI6262) was used. The sensors were mounted at a height of 3.0 m above ground level in areas with canopies shorter than 1.0 m. For maize crops, the sensors were moved to a height of 6.0 m during the growing season to accommodate for crop height and ensure sufficient fetch for an accurate representation of the studied cropping systems. To account for any error in the sensor frequency response and variations in air density related to the transfer of water vapor, fluxes were appropriately corrected and adjusted (Suyker and Verma, 1993; Webb et al., 1980). Climate variables including air temperature, precipitation, solar radiation, relative humidity and soil water content were also measured. Detailed information on measurements, calculations and instrumentation can be found in Suyker et al. (2003), Verma et al. (2005); and Suyker and Verma (2009).

Hourly time series of latent heat (LE), air temperature (*TA*), water input (*WI*, include rainfall and irrigation in the case of irrigated sites), soil water content (top 1.0 m depth from a single location in each field) (*SWC*), incoming photosynthetic photon flux density (*PPFD*), and vapor pressure deficit (*VPD*) were obtained from the AmeriFlux BASE dataset (https://ameriflux.lbl.gov/data/download-data/) for the entirety of the study period (2001–2020). To better identify the effects of *VPD* on *WP*, we only selected the daytime values (between 8:00 am and 7:00 pm, main water loss period) to estimate the daily average. Details on quality control and gap-filling can be found in (Verma et al., 2005; Suyker and Verma, 2009).

Hourly crop *ET* was estimated from *LE* and *TA* using (Eq. 1):

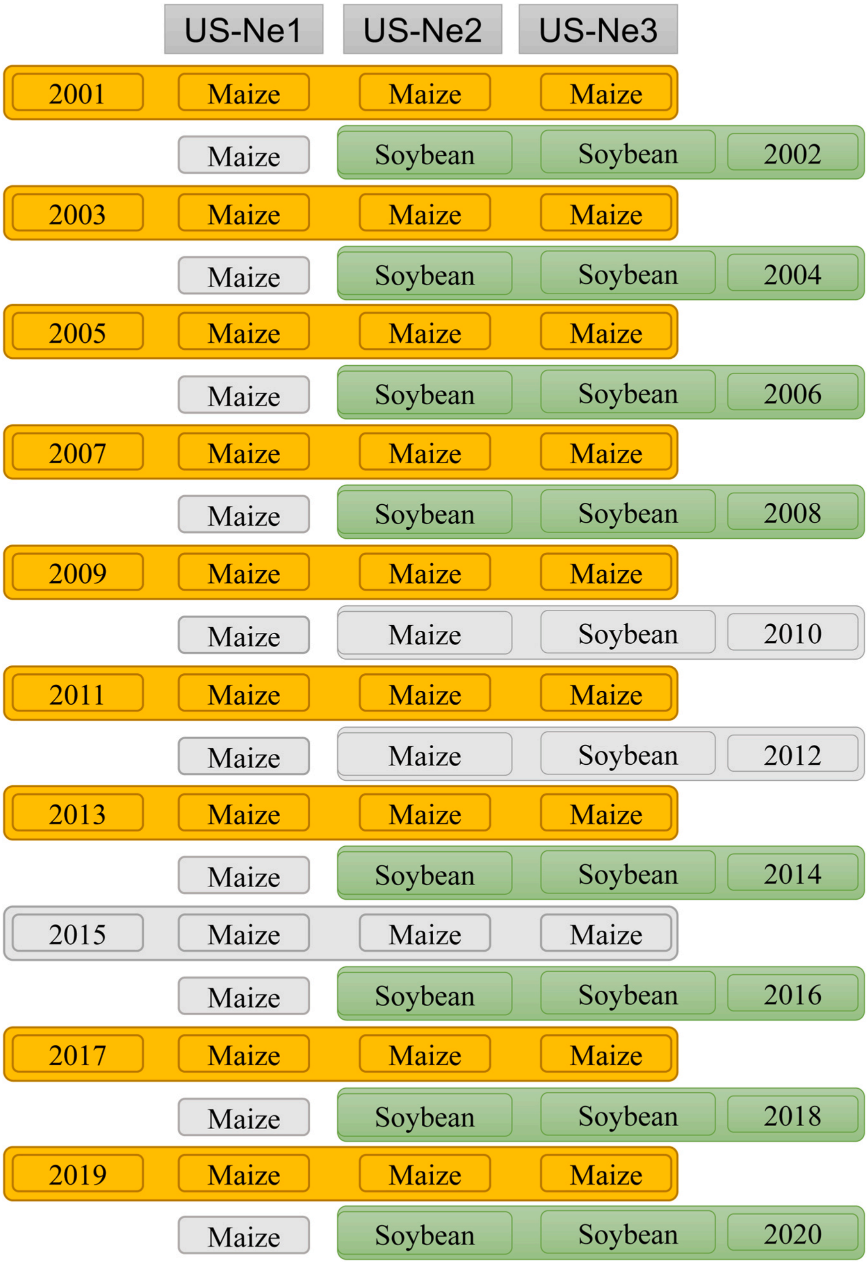
$$ET = \frac{LE}{\lambda} \tag{1}$$

where *LE* is latent heat in MJ m$^{-2}$, and λ is latent heat of vaporization in MJ kg$^{-1}$. The latent heat of vaporization (λ) is the amount of energy needed to transform a unit of water from liquid to vapor, and calculated using the equation provided by Allen et al. (1998):

$$\lambda = 2.501 - \left(2.361 * 10^{-3}\right) * TA \tag{2}$$

where *TA* is air temperature in °C.

Daily and annual time series of *ET* and climatic variables were then



| | US-Ne1 | US-Ne2 | US-Ne3 | |
|---|---|---|---|---|
| 2001 | Maize | Maize | Maize | |
| | Maize | Soybean | Soybean | 2002 |
| 2003 | Maize | Maize | Maize | |
| | Maize | Soybean | Soybean | 2004 |
| 2005 | Maize | Maize | Maize | |
| | Maize | Soybean | Soybean | 2006 |
| 2007 | Maize | Maize | Maize | |
| | Maize | Soybean | Soybean | 2008 |
| 2009 | Maize | Maize | Maize | |
| | Maize | Maize | Soybean | 2010 |
| 2011 | Maize | Maize | Maize | |
| | Maize | Maize | Soybean | 2012 |
| 2013 | Maize | Maize | Maize | |
| | Maize | Soybean | Soybean | 2014 |
| 2015 | Maize | Maize | Maize | |
| | Maize | Soybean | Soybean | 2016 |
| 2017 | Maize | Maize | Maize | |
| | Maize | Soybean | Soybean | 2018 |
| 2019 | Maize | Maize | Maize | |
| | Maize | Soybean | Soybean | 2020 |

**Fig. 2.** Selected years for sites comparison. Orange represents selected maize years and green soybean years while grey stands for the excluded seasons. US-Ne1: Irrigated continuous maize, US-Ne2: Irrigated maize soybean rotation, US-Ne3: Rainfed maize soybean rotation.

computed from the hourly time series and yearly crop *WP* (kg $m^{-3}$) was estimated using (Eq. 3):

$$WP = \frac{Y}{ET} \tag{3}$$

To understand differences between cropping systems and crops we obtained data on gross primary production (*GPP*) for the period 2001–2014. *GPP* is estimated from (Eq. 4):

$$GPP = NEE - \mathrm{Re} \tag{4}$$

Where *NEE* is Net Ecosystem $CO_2$ Exchange (directly measured by eddy covariance technique) and *Re* is daytime Ecosystem Respiration (estimated). Note that *GPP* is always positive for carbon uptake and *Re* is always negative for carbon loss. The data was obtained from Ameriflux dataset at an hourly time scale and converted to generate daily time series.

### 2.3. Statistical analyses

We examined the variations in means among cropping systems across various variables. In the case of maize years, the *ANOVA* was performed using the three sites as groups, with year as the repeated effect. The Tukey's Honestly Significant Difference test (TukeyHSD) (Tukey, 1949) was also employed to determine the differences between groups where *ANOVA* indicated significant differences. For soybean years, a T-test was utilized to compare the two soybean treatments. To study the effects of climate variability on the three studied variables, Pearson and Spearman's correlation coefficients were implemented in the analysis (normality of the data was visually assessed to select the used parametric or non-parametric tests). To study the variance between the three cropping systems including all the studied variables we applied the Principal Component Analysis (*PCA)* on the sets of maize and soybean years. All calculations and statistical analysis were conducted using

R 4.2.1. A 95% confidence interval was selected to test the significance of p-value under the different statistical tests.

## 3. Results

### 3.1. Seasonal effects

#### 3.1.1. Average climate and water input

Average growing season crop cycle, climate conditions, and *WI*, for each of the three cropping systems, during the study period, are shown in Table 2. Maize and soybean had an average growing season of approximately 165 and 138 days, respectively. *PPFD*, *TA*, and *VPD* did not vary significantly among the three sites, as they were all located within 1.6 km and averaged around 774–785 μmol m$^{-2}$ s$^{-1}$, 20 °C, and 1.3 kPa, respectively. In the irrigated sites, the total *WI* applied to the crops, including precipitation and irrigation, ranged from 630 to 646 mm for maize and 586 mm for soybean. In the rainfed site, the average cumulative precipitation was 450 mm during maize years and 490 mm during soybean years. As a result of irrigation, *SWC* was significantly higher in the irrigated sites (~ 32%) than in the rainfed sites (~27%) for both crop types.

Supplementary Figure 1 displays the temporal daily pattern averaged over the growing season for *PPFD*, *TA*, *VPD*, *WI*, and *SWC* in the three sites. *PPFD* and *TA* exhibited similar patterns, with the highest incoming radiation occurring in July and exceeding the threshold of 900 μmol m$^{-2}$ s$^{-1}$ before declining to its lowest value at the end of the growing season. The peak *PPFD* coincided with the highest *TA* during the growing season, with average daily values reaching 25 °C. *VPD*, on the other hand, had the highest values during the early season and was slightly higher in the rainfed site than in the irrigated sites due to supplementary irrigation that was applied between mid-June and the end of August. As expected, the irrigated sites had higher *SWC* throughout the growing season, with significant differences observed compared to the rainfed site between early July and the end of the season.

#### 3.1.2. Daily and seasonal vegetation patterns

Fig. 3 depicts the average hourly and daily patterns of *ET* and *GPP*. The general temporal patterns of *ET* and *GPP* were similar among the different cropping systems across the growing season. Maize exhibited higher *GPP* than soybean during most of the growing season, whereas *ET* presented a different pattern with higher water loss in maize during the first half of the growing season and slightly lower daily *ET*, compared to soybean, towards the end of the season. The peak *ET* at all sites coincided with highest *GPP* levels, which occurred around mid-July for maize and end of July/beginning of August for soybean. Differences in *ET* and *GPP* between maize and soybean were most significant during the first half of the growing season (June and July). Daily values of maize's *ET* and *GPP* during the growing season ranged between 2 to 7 mm and 0 to 0.03 kgC m$^{-2}$, respectively, while soybean had daily averages of 2 to 5 mm and 0 to 0.02 kgC m$^{-2}$, respectively. Differences in *ET* and *GPP* between the three sites, although were minimum, were more apparent between the irrigated sites and the rainfed site.

Average hourly *ET* and *GPP* patterns were similar between sites and crops throughout the season. Average hourly *ET* and *GPP* increased progressively after sunrise to reach their highest values around noon before progressively declining to their lowest values at night. To further understand these similarities between *ET* and *GPP* and study the effect of climatic variables on *GPP*, we examined the correlations between their daily values over a narrow temporal window between 12 h and 13 h, where hourly *GPP* and *ET* values were maximum and nearly constant (Supplementary Figure 2 and 3). For both maize and soybean, *ET* was significantly correlated with *GPP* with correlation reaching *R*= 0.76 for maize and *R*= 0.83 for soybean at US-Ne2. Additionally, for maize, among the climatic variables, *TA*, *VPD*, and *PPFD* were significantly correlated with *GPP* with *PPFD* exhibiting the highest correlation exceeding *R*= 0.6, particularly at the end of July and beginning of August. On the other hand, correlations with *SWC* were mostly non-significant pointing to a lag effect between the two variables. For soybean, the difference in the association between *GPP* and *ET* were clear. In the irrigated site (US-Ne2), crop water use was significantly related to *GPP* reaching an *R*= 0.83 in the second half of July while correlation at the rainfed site (US-Ne3) were significant but lower. Likewise, climatic variables showed different association with *GPP*. At US-Ne2, *PPFD*, *TA* and *VPD* showed significant association with *GPP*, however correlations were similar with the three variables. For US-Ne3, correlations between *GPP* and climatic variables were low and, in most cases, non-significant. *SWC* at the two sites showed low to non-significant correlations.

### 3.2. Long-term cropping systems effects

Annual average *Y*, *ET*, and *WP* for the different cropping systems are reported in Table 3. Significant differences were observed between irrigated and rainfed sites, while the rotation effect was non-significant. In general, irrigated crops had a higher annual *Y*, *ET*, and *WP* compared to rainfed crops. For maize, the average annual *Y* was 1.11 kg m$^{-2}$ in the irrigated continuous site and increased to 1.17 kg m$^{-2}$ (5.6%) under irrigated rotation, compared to 0.85 kg m$^{-2}$ (decline by 23.5%) in rainfed rotation. Similarly, the changes to *ET* and *WP* were similar to those of *Y*. Average seasonal *ET* was 534 mm for irrigated continuous maize, 527 mm for irrigated rotation, and 465 mm for rainfed rotation. *ET* declined by 1.3% due to crop rotation (from irrigated continuous maize to irrigated rotation) while increased by 11.8% from rainfed rotation to irrigated rotation. The highest average *WP* was found under irrigated maize rotation 2.23 kg m$^{-3}$ which is 7.2% higher than that of irrigated continuous maize (2.08 kg m$^{-3}$) and 18.4% higher than that of the rainfed maize in rotation (1.82 kg m$^{-3}$).

For soybean, while the difference in *Y* was significant, differences in *ET* and *WP* were non-significant between irrigated and rainfed rotations. Average annual *Y* was 0.38 kg m$^{-2}$ for irrigated soybean in rotation and 0.33 kg m$^{-2}$ for the rainfed site. While *ET* increased by 5.1% from rainfed to irrigated soybean (from 446 mm to 470 mm), *WP* increased by 7.4% (from 0.75 kg m$^{-3}$ to 0.81 kg m$^{-3}$).

Differences between the three cropping systems and crop types were also identifiable from their temporal patterns. Fig. 4 shows the temporal

**Table 2**

Average annual environmental conditions for the study period (2001–2020) under different cropping systems at ENREEC. PPFD: Photosynthetic photon flux density, TA: Air temperature, VPD: Vapor pressure deficit, WI: Water input, SWC: Soil water content. Note: water input in the irrigated sites includes both precipitation and irrigation. Different letters indicate significant differences among means ($p < 0.05$). Small letters indicate maize differences and capital letters indicate soybean differences.

| | US-Ne1 Irrigated continuous maize | US-Ne2 Irrigated maize-soybean rotation | | US-Ne3 Rainfed maize-soybean rotation | |
|---|---|---|---|---|---|
| | Maize | Maize | Soybean | Maize | Soybean |
| Crop duration (days) | 166 ± 15 a | 166 ± 13 a | 139 ± 8 A | 165 ± 13 a | 138 ± 9 A |
| *PPFD* (μmol m$^{-2}$ s$^{-1}$) | 774 ± 27 a | 784 ± 26 a | 785 ± 35 A | 779 ± 29 a | 788 ± 40 A |
| *TA* (°C) | 20 ± 1 a | 20 ± 1 a | 21 ± 2 A | 20 ± 1 a | 21 ± 2 A |
| *VPD* (kPa) | 1.3 ± 0.2 a | 1.3 ± 0.2 a | 1.3 ± 0.2 A | 1.4 ± 0.2 a | 1.3 ± 0.2 A |
| *WI* (mm) | 646 ± 95 a | 630 ± 100 a | 586 ± 144 A | 450 ± 141 b | 490 ± 146 B |
| *SWC* (%) | 34 ± 4 a | 32 ± 4 a | 31 ± 4 A | 27 ± 4 b | 29 ± 2 B |

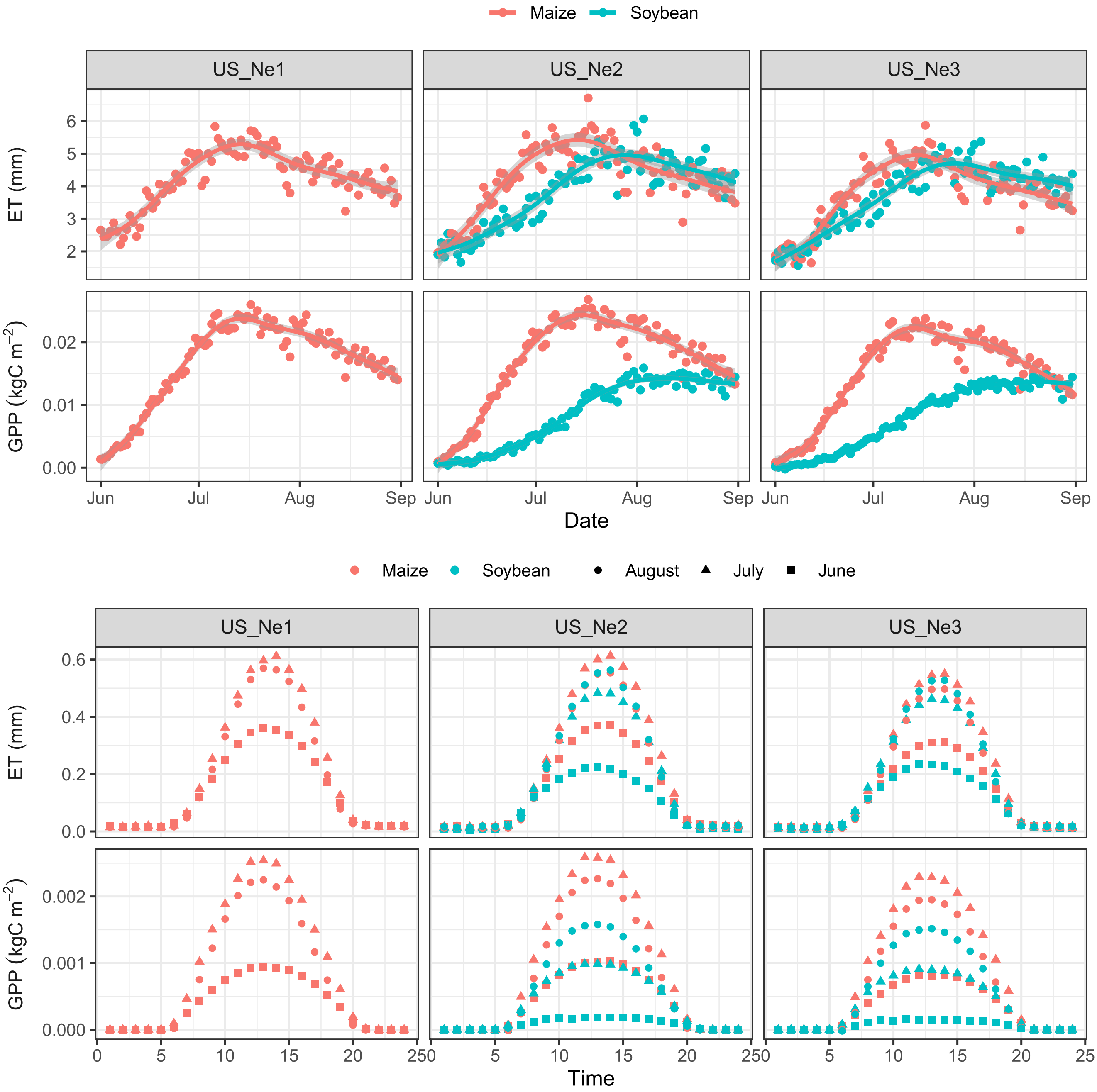


**Fig. 3.** Average daily and hourly evapotranspiration (*ET*), gross primary production (*GPP*), during the growing season in the three sites for the period 2001–2014 at ENREEC. US-Ne1: Irrigated continuous maize, US-Ne2: Irrigated maize soybean rotation, US-Ne3: Rainfed maize soybean rotation.

**Table 3**
Annual means ± standard deviation for yield (Y), evapotranspiration (ET), and water productivity (WP) from 2001 to 2020. Changes to irrigated continuous maize and irrigated soybean in rotation are shown in parenthesis. Note: in the case of rainfed maize, the percentages between parenthesis represent changes to irrigated maize and irrigated maize in rotation respectively. US-Ne1: Irrigated continuous maize, US-Ne2: Irrigated maize soybean rotation, US-Ne3: Rainfed maize soybean rotation. Different letters indicate significant differences. Small letters indicate maize differences and capital letters indicate soybean differences.

| Site | Irrigation | Crop | *Y* (kg m$^{-2}$) | *ET* (mm) | *WP* (kg m$^{-3}$) |
|---|---|---|---|---|---|
| US-Ne1 | yes | maize | 1.11 ± 0.09 a | 534 ± 29 a | 2.08 ± 0.20 a |
| US-Ne2 | yes | maize | 1.17 ± 0.08 (5.6%) a | 527 ± 26 (−1.3%) a | 2.23 ± 0.21 (7.2%) a |
| US-Ne3 | no | maize | 0.85 ± 0.12 (−23.5%, −27.6%) b | 465 ± 20 (−12.9%, −11.8%) b | 1.82 ± 0.24 (−12.5%, −18.4%) b |
| US-Ne2 | yes | soybean | 0.38 ± 0.04 A | 470 ± 28 A | 0.81 ± 0.07 A |
| US-Ne3 | no | soybean | 0.33 ± 0.04 (−12.9%) B | 446 ± 34 (−5.1%) A | 0.75 ± 0.09 (−7.4%) A |

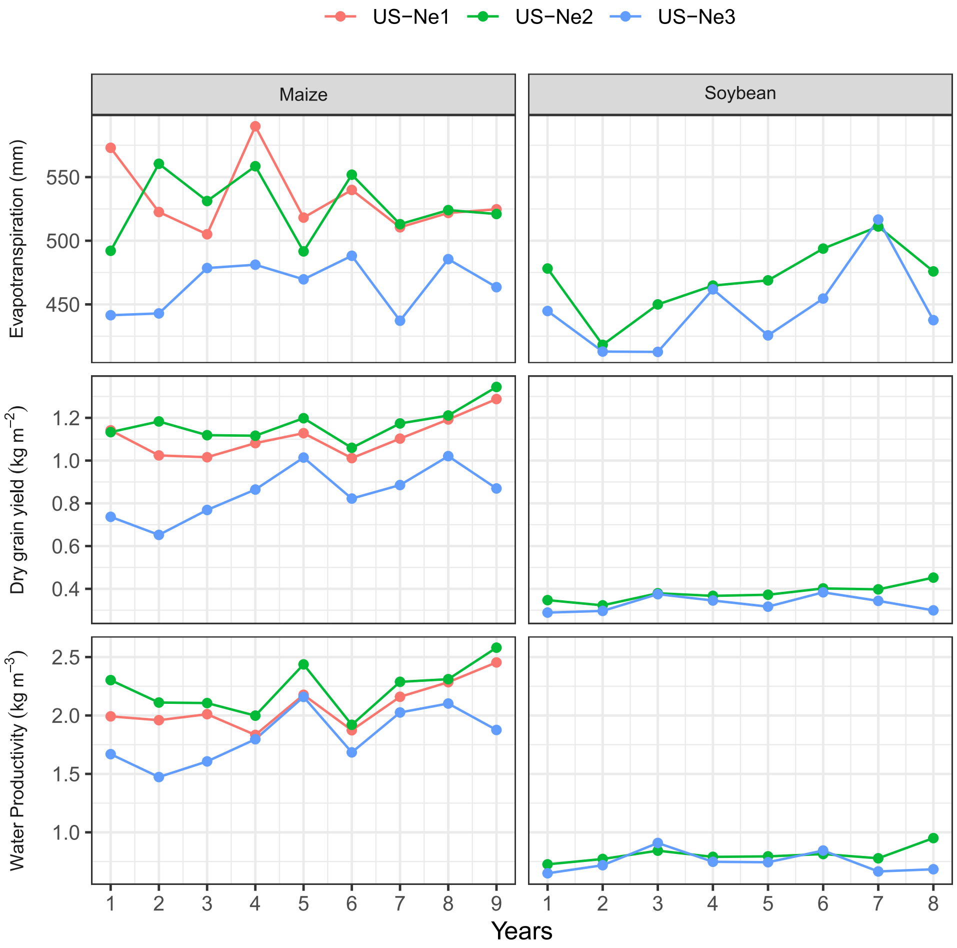


**Fig. 4.** Temporal pattern of yield (*Y*), evapotranspiration (*ET*), and water productivity (*WP*) of the selected growth seasons. US-Ne1: Irrigated continuous maize, US-Ne2: Irrigated maize soybean rotation, US-Ne3: Rainfed maize soybean rotation.

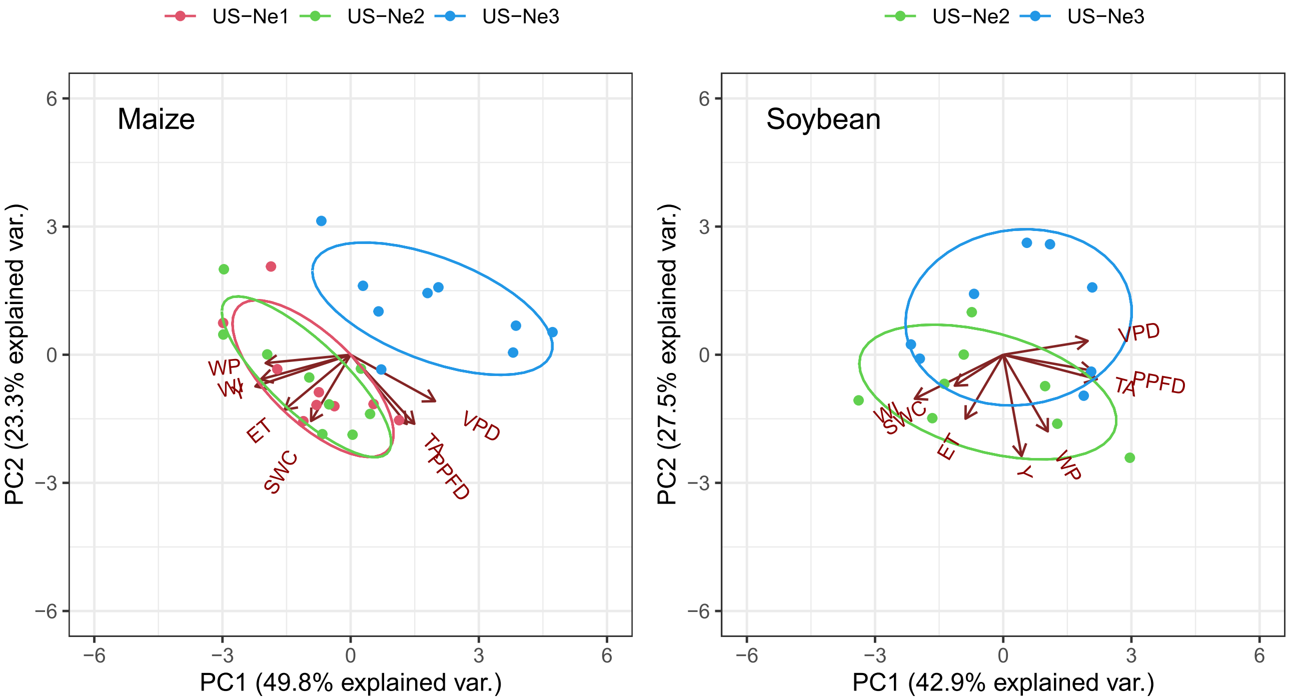


**Fig. 5.** Principal component analysis (*PCA*) results grouped by site. *PPFD*: Photosynthetic photon flux density, *TA*: Air temperature, *VPD*: Vapor pressure deficit, *WI*: Water input, *SWC*: Soil water content. US-Ne1: Irrigated continuous maize, US-Ne2: Irrigated maize soybean rotation, US-Ne3: Rainfed maize soybean rotation.

annual pattern of *Y*, *ET*, and *WP* for the selected years, where irrigated cropping systems showed higher annual values. Consistent with Table 3, while years with soybean crop showed lower *Y* and *WP* compared to maize years, soybean maintained a relatively high annual *ET* comparable to that of maize. For both maize and soybean, the general temporal pattern of *WP* was clearly attributed to that of *Y*. Peak *WP* mostly coincided with peak annual *Y* while seem to be indifferent to changes in *ET*.

Pearson's correlation between *WP*, *Y* and *ET* independent of cropping system (Supplementary Figure 4), showed that *WP* was significantly correlated with *Y* but not with *ET*. The correlation coefficient between *WP* and *Y* was 0.9 for maize and 0.83 for soybean. Additionally, to test the effect of management on *WP* and *Y*, we performed correlation analysis between the two variables and three key management parameters (*N* fertilizer rate (*Nf*), Planting density (*Pld*), and water input (*WI*)) in the selected maize years (Supplementary Figure 5 and 6). *WI* showed the highest correlations with *WP* ($R$=0.67, p = 0.05, rainfed site) and *Y* ($R$=0.79, $p < 0.05$, rainfed site) among the three management parameters while no clear relationship was found with *Pld* and *Nf* as their correlation were non-significant.

### 3.3. Long-term climate and moisture effects

To study the possible effects of climate variability on *Y*, *ET*, and *WP* and evaluate the functioning of the different cropping systems, we used a principal component analysis (*PCA*) including five climate variables (Fig. 5). The analysis was carried out separately for each of the two crop types and grouped by cropping systems. For maize, the first two components of the *PCA* explained 73.1% of the variance. There was a clear separation between the irrigated and rainfed sites. The first component *PC1* explained 49.8% of the variance and had *Y* and *WI* as main negative drivers and *VPD* and *TA* as main positive factors. The second component explained 23.3% of the variance and had *TA* and *PPFD* as main negative driving factors. For soybean, the *PCA* analysis did not show any significant separation between irrigated and rainfed sites. The first two component explained 70.4% of the variance. The variation along the first component was explained by *TA* and *PPFD* in the positive side of the axes and *WI* and *SWC* on the negative side while, along the second component, *Y* and *WP* explained most of the variation.

To study the net effect of climate on each of the cropping systems, we performed a correlation analysis including the five previously defined climate variables (Fig. 6). Since differences were not significant between

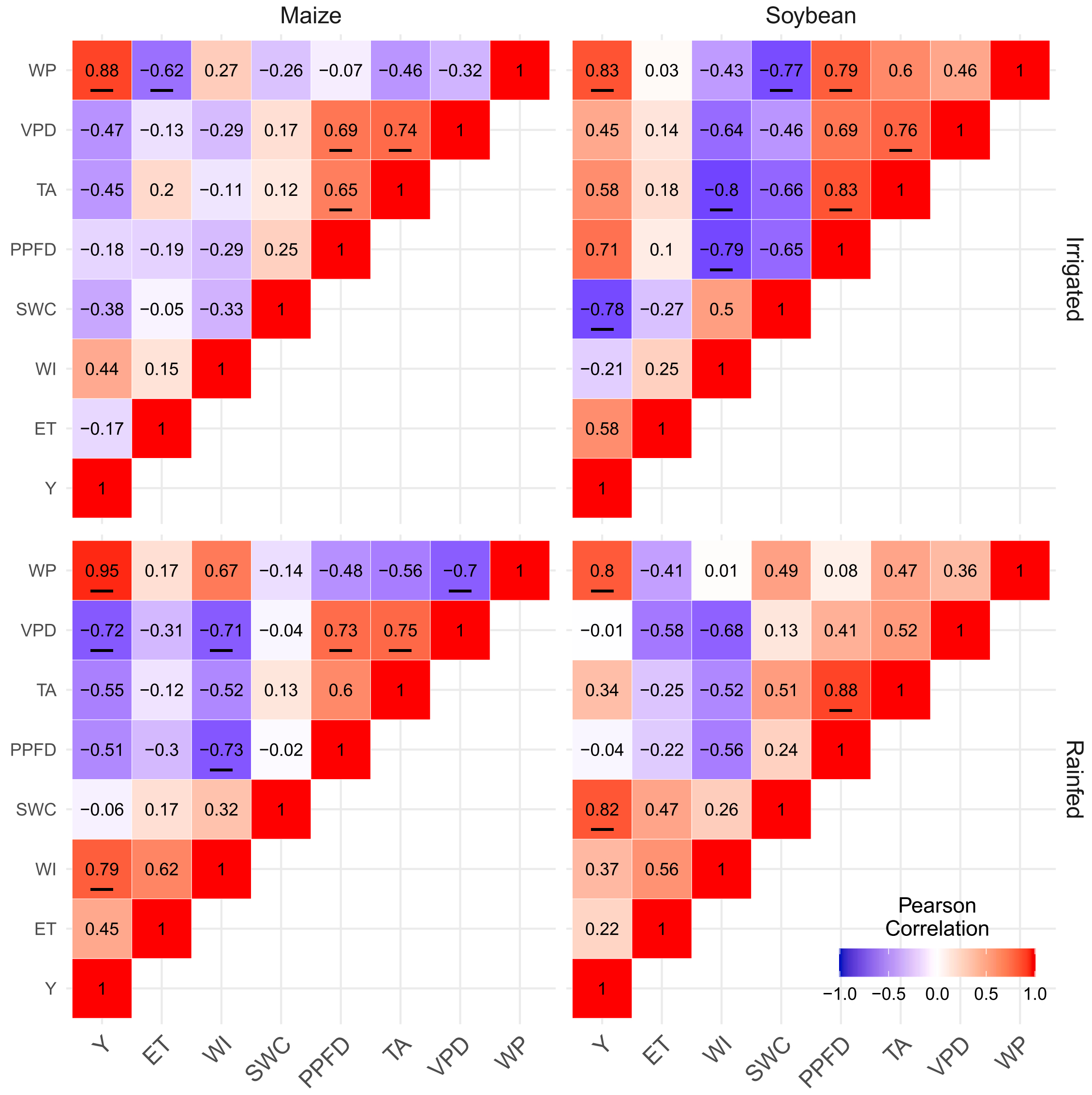


**Fig. 6.** Correlation matrix of evapotranspiration (*ET*), yield (*Y*), and water productivity (*WP*) with climate and water input under the different cropping systems. *PPFD*: Photosynthetic photon flux density, *TA*: Air temperature, *VPD*: Vapor pressure deficit, *WI*: Water input, *SWC*: Soil water content. Please note that water input in the irrigated sites include both precipitation and irrigation. Underscores indicate significant correlation ($p < 0.05$).

irrigated continuous maize and irrigated maize in rotation, we combined the two-cropping systems in the same model. For both crop types, *WP* was highly correlated with *Y*, with correlations higher than 0.8 (0.95 under rainfed maize in rotation). For irrigated maize, the atmospheric evaporative demand had the highest negative effect on *WP* with *ET*, *TA*, and *VPD* showing the highest correlations (significant only with *ET*, $R=-0.62$). In the rainfed site, *VPD*, *TA* and *PPFD* as negatively affecting *Y* ($R=-0.72$, $-0.55$, $-0.51$ respectively, only significant with *VPD*) were also negatively correlated with *WP* ($R=-0.7$, $-0.56$, $-0.48$ respectively, only significant with *VPD*) while *WI* had the highest, though non-significant, positive effect ($R=0.67$,). Soybean's *WP* in the irrigated site, together with *Y*, were negatively affected by *SWC* ($-0.77$ and $-0.78$ respectively, $p < 0.05$) while *PPFD*, directly affected by *TA*, had positive correlations with both variables ($R=0.79$ with *WP* and $R=0.71$ with *Y*, only significant with *WP*). In the rainfed site, *SWC* was the most important variable exhibiting a positive correlation of $R= 0.82$, $p < 0.05$ on *Y* and $R = 0.49$ (non-significant) on *WP* while the rest of variables showed lower correlations.

## 4. Discussion

### 4.1. Long-term changes to water productivity

The Field scale and long-term observational data and the proximity of the ENREEC sites offered a unique opportunity to reliably evaluate three major cropping systems in the midwestern of the US: irrigated continuous maize, irrigated maize-soybean rotation, and rainfed maize-soybean rotation. Despite the complexity of interpreting results attributed to the absence of replicates within years which is mainly due to the elevated cost of maintaining such experiment and the complexity of the used techniques, the dataset allowed us to isolate the effects of management (cropping system) from those of climate variability to understand changes in *WP*. Our results indicated that irrigated maize in rotation had the highest *WP* (2.23 kg m$^{-3}$) compared to irrigated continuous maize (2.08 kg m$^{-3}$) and rainfed maize in rotation (1.82 kg m$^{-3}$), with significant differences only observed between irrigated and rainfed systems. For soybean, the irrigated rotation had higher *WP* (0.81 kg m$^{-3}$), though differences were non-significant, compared to the rainfed rotation (0.75 kg m$^{-3}$). These findings are consistent with previous studies evaluating maize-soybean cropping systems in the Great Plains region in the U.S, although differences do exist due to various factors such as management practices, soils, climate and methodologies used for the calculation of *WP*. For instance, Dietzel et al. (2016), combined observed and simulated crop measurements and found *WP* values ranging from 12 to 18 kg ha$^{-1}$ mm$^{-1}$ for maize and ~3 kg ha$^{-1}$ mm$^{-1}$ for soybean as averaged over rainfed continuous maize and maize-soybean rotations in Iowa, U.S. Kukal and Irmak (2017), integrated ground-based (meteorological stations) and satellite data at the county level and estimated maize and soybean *WP* between 1982 and 2017 for the Great Plains regions (including 9 states); they found slightly lower average *WP* values ranging between 0.78 and 1.95 kg m$^{-3}$ for maize and 0.26 and 0.5 kg m$^{-3}$ for soybean. Irmak and Sharma (2015) reported long-term *WP* averages in irrigated croplands in the state of Nebraska, U.S., ranging between 2.07 kg m$^{-3}$ in subhumid environment and 1.33 kg m$^{-3}$ in the semi-arid regions of the state while irrigated soybean had averages *WP* between 0.54 and 0.81 kg m$^{-3}$, which are comparable to our findings. In a global analysis of crop *WP*, Mbava et al. (2020) reported that cereals had a higher average *WP* (2.37 kg m$^{-3}$) compared to oilseeds (0.69 kg m$^{-3}$) and identified maize as the most water use efficient crop (3.78 kg m$^{-3}$).

In this study, we found that *WP* increased by18.4% under irrigated maize rotation compared to rainfed rotation. In contrast, the increase in *WP* was only 7.2% when comparing irrigated continuous maize to irrigated maize in rotation. The results suggest that *Y* is more determinant in the year-to-year changes to *WP* than *ET*, as significant correlations were found between *Y* and *WP* under both maize and soybean crops. This study is consistent with previous research by Brauman et al. (2013) and Hussain et al. (2019) who reported a link between *WP* and *Y* in national and global analysis of crop *WP*. However, the absence of significant differences in *Y* between irrigated continuous and rotation maize were unexpected given the enhanced nutrient availability and improved soil health in maize-soybean rotations compared to reduced *Y* in continuous maize systems (Stanger and Lauer, 2008; Gentry et al., 2013). These inconsistencies may be mainly related to management practices such as fertilizer rates, planting densities or irrigation. Our results suggested that *WI* is the main driver of *WP* and *Y* among *Nf* and *Pld* (highest significant correlations), which is consistent with Li et al. (2020) who concluded that *WI* is more relevant in increasing maize *Y* compared to *N* input. However, the combination of the three management parameters (*WI*, *Nf* and *Pld*) among others may explain better the variability of results. Grassini et al. (2011), pointed out that crop rotation, sowing date, tillage system and plant population density are among the most sensitive factors affecting maize yields in Nebraska. El-Hendawy et al. (2008) suggested that maize *WP* and *Y* could be increased by increasing irrigation rates while reducing *Pld* and highlighted significant interactions between the two management parameters in a sandy soil site in Egypt. Lai et al. (2022) pointed out a significant effect of *Pld* and *Nf* and their interaction on maize *Y* in a study in northwest China and suggested that yields increased and then declined with increased *N* rates.

Crop water use is directly influenced by physiological attributes which are, in return, affected by various management practices, such as irrigation, fertilizer application, population densities, and crop type. Crops' photosynthetic activity is the main driver for plants water use, which is strongly related to canopy conductance, leaf area index and biomass (Good et al., 2014; Wang et al., 2014). In our study, irrigated maize had the highest daily average *ET* compared to rainfed systems and soybean. These differences in water use are mainly explained by differences in *GPP*, where irrigated maize exhibited the highest daily averages during the growing season and daily *ET* showed significant correlation with daily *GPP*.

### 4.2. Effect of climate variability

This study highlights the importance of climate variability and management in determining crops *WP*. The results of the PCA model showed that the five inter-related climatic variables, along with *Y* and *ET* explained most (up to 73.1%) of the variance under the different cropping systems analyzed. Our analysis also demonstrated a clear distinction between irrigated and rainfed cropping systems, and similarities between continuous and rotation maize systems. We identified *Y*, *WI*, *VPD* and *TA* as the primary factors affecting the temporal variability of maize *WP* in both irrigated and rainfed systems. In rainfed maize systems, the positive correlation between *Y* and *WI* suggests that increasing water availability can improve crop productivity, while higher *VPD* and *TA* increase the atmospheric water demand and can result in stomatal closure, reducing plant carbon uptake through photosynthesis and *Y* (Damour et al., 2010; Massmann et al., 2019). Conversely, *WI* can alleviate water stress and increase *Y*, thereby enhancing maize *WP*. However, in irrigated maize systems, water availability is not a limiting factor for photosynthesis, reducing the probability for stomatal disruption and resulting in higher *ET* and lower impacts of *VPD* on *WP*. These findings highlight the importance of considering climate variability together with management practices when assessing *WP*, especially in rainfed systems where *WI* is a limiting factor for *Y*.

The separation between irrigated and rainfed soybean was less apparent than that of maize, however, 70.4% of the variance in soybean years was explained by the studied climatic variables. We found, that in the irrigated site, *PPFD* had a significant positive correlation with *WP* ($R= 0.79$), while *SWC* and *WI* showed negative correlations ($R=-0.77$, $R=-0.43$ respectively, only significant with *SWC*). Under non-limited water and nutrient conditions, higher *PPFD* enhances the photosynthetic activity (Hatfield and Carlson, 1978; Wagle et al., 2017) and increases *Y* (correlation between *Y* and *PPFD* $R=0.71$) contributing to improve *WP*. However, increased water availability through irrigation or within soil layers does not necessarily result in increased *WP*. The unused available water is prone to evaporation, particularly during drought events (Liu et al., 2022), increasing the water cost of the crop and decreasing its *WP*. These findings are consistent with Ma et al. (2021) who studied the effects of irrigation and nitrogen application on dry matter accumulation and yields of summer maize in an arid region in China and reported decreases in *Y* under increased water supply. We conclude that optimizing irrigation scheduling could enhance *WP* through increasing maize *Y* and maintaining minimum evaporation rates (Perry et al., 2009).

In rainfed soybean years, *SWC* was the main driver of *Y* and indirectly *WP* (correlation with *Y* and *WP* respectively, $R=0.82$; $R=0.49$). This highlights that in rainfed systems, enhanced water availability in soil layers sustains crop *Y* and *WP* during critical plant growth stages, while persistent water stress during the season could be a major limitation to soybean *Y* (Dai, 2013; Zipper et al., 2016). In fact, Wijewardana et al. (2018) considered soil moisture stress as the most damaging abiotic stress to soybean yields in the U.S.

### *4.3. Implications of results*

This study revealed important insights related to management of maize and soybean cropping systems in the midwestern US. We found that *Y* is the main driver of the year-to-year variations in *WP* which may indicate that strategies to enhance *WP* should focus on improving *Y* before focusing on reducing crop water use as suggested by Brauman et al. (2013). This is also highlighted by Yang and Grassini (2014), who pointed that increasing irrigated and rainfed maize *WP* depends on eliminating all non-water constraints to crop *Y* (e.g., nutrients deficiencies, pests and diseases). However, substantial improvements in *WP* are limited given that transpiration as the real portion of water used by plants is directly linked to plant production (Garcia y Garcia et al., 2009; Perry et al., 2009) making of the ratio between crop production and plant water use a relatively unchangeable variable (Tanner and Sinclair, 1983). Our results also emphasize that increasing fertilizer application may not necessarily lead to improved *WP*, as increased *N* levels enhance crop transpiration contributing to higher *ET* (Srivastava et al., 2020). The higher crop water use associated with increasing *Y* could accelerate the depletion of groundwater resources in the High Plains Aquifer region (including Nebraska) where 39% of existing resources are expected to be pumped in the next 40 years under current trends (Steward et al., 2013). Increases in *WP* are tied to a more efficient use of water resources through water management and irrigation technologies (Tanner and Sinclair, 1983). Deficit irrigation and proper irrigation scheduling, variable rate fertilizer application, and plant breeding are also convenient solutions to reaching optimum water and nutrient productivity and reduce emissions from agroecosystems. In this study *VPD* was one of the main drivers of maize's *WP* by reducing *Y* and consequently *WP* particularly in the rainfed site. *VPD* is expected to increase in the upcoming decades due to a combination of temperature rise and, depending on region, reduced relative humidity (Byrne, O'Gorman, 2013) which may severely decrease *Y* in rainfed maize systems and reduce its *WP*. In fact, the expected decline in maize *WP* could reach 150% in irrigated systems and 54% in rainfed systems (Anapalli et al., 2021) In contrast, we found that *SWC* was determinant in soybean's *Y* in both irrigated and rainfed systems. Therefore, enhancing soil water holding capacity through improving soil chemical and biological properties and reducing water losses through soil evaporation could be crucial to enhance soybean's *WP*. Matching crop production with regions of low atmospheric evaporative demand as suggested by Tanner and Sinclair (1983), may be essential to achieving substantial improvements of *WP* under current climate change circumstances. Our findings are important not only for understanding local agroecosystems but also for informing broader strategies in water resource management, agricultural decision-making, and climate change adaptation and mitigation on a larger scale.

## 5. Conclusions

The findings of this study provide valuable insights into the relationship between *WP*, *Y*, and *ET* with management and climate variability in three major cropping systems in the midwestern U.S. We found that irrigated maize systems had the highest *WP* among the studied cropping systems with irrigated maize in rotation being the most efficient system. Compared to rainfed systems, *WP*, *Y*, and *ET* were 18.4%, 27.6% and 11.8%, respectively, higher in irrigated maize rotation and 7.4%, 12.9%, and 5.1%, respectively, higher in irrigated soybean rotation. The year-to-year changes in *WP* were mainly related to changes in *Y* rather than *ET* and were mainly due to differences in crops *GPP* as result of differences in management and particularly *WI*. Although management practices can enhance maize and soybean *Y*, significant improvements of *WP* through increases in *Nf* and *WI* are fairly limited given the strong link between crop growth and crop water use.

We also found that climate variability had a significant effect on *WP*, explaining a substantial part of its temporal variation. *VPD* was the most important determinant of maize *WP*, with the highest effect on *Y* (correlation $R=-0.7$, $p < 0.05$), *SWC* showed the highest correlations with *WP* in irrigated ($R=-0.77$, $p < 0.05$) and rainfed ($R=0.49$, $p > 0.05$) soybean systems. These results are important for developing sustainable, productive, and resilient cropping systems that meet the growing demand for food under current and anticipated future climate variability and change.

## CRediT authorship contribution statement

**M. Khorchani:** Conceptualization; Data Curation; Writing - Original Draft; Writing - Review & Editing; Visualization; Software; Formal analysis. **T. Awada:** Conceptualization, Writing - original draft, Writing - review & editing, Supervision, Funding acquisition. **M. Schmer:** Conceptualization; Writing - Original Draft; Writing - Review & Editing; Supervision. **V. Jin:** Writing - Original Draft; Writing - Review & Editing; Supervision; Funding acquisition. **G. Birru:** Writing - Original Draft; Writing - Review & Editing. **S.R.S. Dangal:** Writing - Original Draft; Writing - Review & Editing. **A. Suyker:** Data Curation; Writing - Review & Editing. **A. Freidenreich:** Writing - Original Draft; Writing - Review & Editing

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data Availability

Data will be made available on request.

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## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2023.108640.

## References

Agomoh, I.V., Drury, C.F., Yang, X., Phillips, L.A., Reynolds, W.D., 2021. Crop rotation enhances soybean yields and soil health indicators. Soil Sci. Soc. Am. J. 85, 1185–1195. https://doi.org/10.1002/saj2.20241.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M. (1998). Crop evapotranspiration - Guidelines for computing crop water requirements. FAO Irrigation and drainage Paper 56. http://www.fao.org/3/x0490e/x0490e00.htm (accessed 13 June 2023).

Anapalli, S.S., Pinnamaneni, S.R., Fisher, D.K., Reddy, K.N., 2021. Vulnerabilities of irrigated and rainfed corn to climate change in a humid climate in the Lower Mississippi Delta. Clim. Change 164, 5. https://doi.org/10.1007/s10584-021-02999-0.

Aubinet, M., 2023. The known unknowns: measurement techniques. In: Hiscox, A.L. (Ed.), Conceptual Boundary Layer Meteorology, pp. 59–100. https://doi.org/10.1016/B978-0-12-817092-2.00011-4.

Babaeian, E., Tuller, M., 2023. Proximal sensing of evapotranspiration. In: Goss, M.J., Oliver, M. (Eds.), Encyclopedia of Soils in the Environment (Second Edition), pp. 610–617. https://doi.org/10.1016/B978-0-12-822974-3.00156-7.

Baldocchi, D.D., Hincks, B.B., Meyers, T.P., 1988. Measuring biosphere-atmosphere exchanges of biologically related gases with micrometeorological methods. Ecology 69, 1331–1340. https://doi.org/10.2307/1941631.

Baumhardt, R.L., Gowda, P.H., Colaizzi, P.D., Howell, T.A., Staggenborg, S.A., 2009. Modeling irrigation management strategies to maximize cotton lint yield and water use efficiency. Agron. J. 101, 460–468. https://doi.org/10.2134/agronj2008.0041xs.

Blum, A., 2009. Effective use of water (EUW) and not water-use efficiency (WUE) is the target of crop yield improvement under drought stress. Field Crops Res. 112 (2–3), 119–123. https://doi.org/10.1016/j.fcr.2009.03.009.

Brauman, K.A., Siebert, S., Foley, J.A., 2013. Improvements in crop WP increase water sustainability and food security - a global analysis. Environ. Res. 8 (2), 024030 https://doi.org/10.1088/1748-9326/8/2/024030.

Byrne, M.P., O'Gorman, P.A., 2013. Land-ocean warming contrast over a wide range of climates: convective quasi-equilibrium theory and idealized simulations. J. Clim. 26 (12), 4000–4016. https://doi.org/10.1175/JCLI-D-12-00262.1.

Cai, X., Rosegrant, M.W., 2002. Global water demand and supply projections. Water Int. 27, 159–169. https://doi.org/10.1080/02508060208686989.

Cernusak, L.A., Haverd, V., Brendel, O., Le Thiec, D., Guehl, J.M., Cuntz, M., 2019. Robust response of terrestrial plants to rising $CO_2$. Trends Plant Sci. 24 (7), 578–586. https://doi.org/10.1016/j.tplants.2019.04.003.

Condon, A.G., 2020. Drying times: plant traits to improve crop water use efficiency and yield. In: Evans, J. (Ed.), J. Exp. Bot., 71, pp. 2239–2252. https://doi.org/10.1093/jxb/eraa002.

Condon, A.G., Richards, R.A., Rebetzke, G.J., Farquhar, G.D., 2002. Improving intrinsic water-use efficiency and crop yield. Crop Sci. 42, 122–131. https://doi.org/10.2135/cropsci2002.1220.

Dai, A., 2013. Increasing drought under global warming in observations and models. Nat. Clim. Change 3 (1), 52–58. https://doi.org/10.1038/nclimate1633.

Damour, G., Simonneau, T., Cochard, H., Urban, L., 2010. An overview of models of stomatal conductance at the leaf level. Plant Cell Environ. 33 (9), 1419–1438. https://doi.org/10.1111/j.1365-3040.2010.02181.x.

Dietzel, R., Liebman, M., Ewing, R., Helmers, M., Horton, R., Jarchow, M., Archontoulis, S., 2016. How efficiently do corn- and soybean-based cropping systems use water? A systems modeling analysis. Glob. Chang Biol. 22 (2), 666–681. https://doi.org/10.1111/gcb.13101.

El-Hendawy, S.E., Abd El-Lattief, E.A., Ahmed, M.S., Schmidhalter, U., 2008. Irrigation rate and plant density effects on yield and water use efficiency of drip-irrigated corn. Agric. Water Manag. 95 (7), 836–844. https://doi.org/10.1016/j.agwat.2008.02.008.

FAO, 2017. FAOSTAT: Food and agriculture organization of the United Nations statistical database. Retrieved from https://www.fao.org/faostat/en/.

FAO, 2022. Impact of the Ukraine-Russia conflict on global food security and related matters under the mandate of the Food and Agriculture Organization of the United Nations (FAO). Hundred and Seventieth Session. https://www.fao.org/3/nj164en/nj164en.pdf (accessed 13 June 2023).

Farahani, H.J., Izzi, G., Oweis, T.Y., 2009. Parameterization and evaluation of the AquaCrop model for full and deficit irrigated cotton. Agron. J. 101, 469–476. https://doi.org/10.2134/agronj2008.0182s.

Fernández, J.E., Alcon, F., Diaz-Espejo, A., Hernandez-Santana, V., Cuevas, M.V., 2020. Water use indicators and economic analysis for on-farm irrigation decision: a case study of a super high density olive tree orchard. Agric. Water Manag. 237, 106074 https://doi.org/10.1016/j.agwat.2020.106074.

Garcia y Garcia, A., Guerra, L.C., Hoogenboom, G., 2009. Water use and water use efficiency of sweet corn under different weather conditions and soil moisture regimes. Agric. Water Manag. 96, 1369–1376. https://doi.org/10.1016/j.agwat.2009.04.022.

Gentry, L.F., Ruffo, M.L., Below, F.E., 2013. Identifying factors controlling the continuous corn yield penalty. J. Agron. 105 (2), 295–303. https://doi.org/10.2134/agronj2012.0246.

Good, S.P., Soderberg, K., Guan, K., King, E.G., Scanlon, T.M., Caylor, K.K., 2014. δ2H isotopic flux partitioning of evapotranspiration over a grass field following a water pulse and subsequent dry down. Water Resour. Res. 50 (2), 1410–1432. https://doi.org/10.1002/2013WR014333.

Grassini, P., Thorburn, J., Burr, C., Cassman, K.G., 2011. High-yield irrigated maize in the Western U.S. Corn Belt: I. On-farm yield, yield potential, and impact of agronomic practices. Field Crops Res. 120 (1), 142–150. https://doi.org/10.1016/j.fcr.2010.09.012.

Hatfield, J.L., Carlson, R.E., 1978. Photosynthetically active radiation, $CO_2$ uptake, and stomatal diffusive resistance profiles within soybean canopies. Agron. J. 70 (4), 592–596. https://doi.org/10.2134/agronj1978.00021962007000040018x.

Hatfield, J.L., Sauer, T.J., Prueger, J.H., 2001. Managing soils to achieve greater water use efficiency. Agron. J. 93, 271–280. https://doi.org/10.2134/agronj2001.932271x.

Hoekstra, A.Y., Mekonnen, M.M., 2012. The water footprint of humanity. Proc. Natl. Acad. Sci. U. S. A. 109 (9), 3232–3237. https://doi.org/10.1073/pnas.1109936109.

Hrozencik, R.A., Aillery, M. 2021. Trends in U.S. Irrigated Agriculture: Increasing Resilience Under Water Supply Scarcity, EIB-229, U.S. Department of Agriculture, Economic Research Service. Available online at https://www.ers.usda.gov/publications/pub-details/?pubid=102927.

Huang, Z., Hejazi, M., Li, X., Tang, Q., Vernon, C., Leng, G., Liu, Y., Döll, P., Eisner, S., Gerten, D., Hanasaki, N., Wada, Y., 2018. Reconstruction of global gridded monthly sectoral water withdrawals for 1971-2010 and analysis of their spatiotemporal patterns. Hydrol. Earth Syst. Sci. 22 (4), 2117–2133. https://doi.org/10.5194/hess-22-2117-2018.

Huang, Z., Hejazi, M., Tang, Q., Vernon, C.R., Liu, Y., Chen, M., Calvin, K., 2019. Global agricultural green and blue water consumption under future climate and land use changes. J. Hydrol. 574, 242–256. https://doi.org/10.1016/j.jhydrol.2019.04.046.

Hussain, M.Z., Hamilton, S.K., Bhardwaj, A.K., Basso, B., Thelen, K.D., Robertson, G.P., 2019. Evapotranspiration and water use efficiency of continuous maize and maize and soybean in rotation in the upper Midwest U.S. Agric. Water Manag. 221, 92–98. https://doi.org/10.1016/j.agwat.2019.02.049.

Huynh, H.T., Hufnagel, J., Wurbs, A., Bellingrath-Kimura, S.D., 2019. Influences of soil tillage, irrigation, and crop rotation on maize biomass yield in a 9-year field study in Müncheberg, Germany. Field Crops Res. 241, 107565 https://doi.org/10.1016/j.fcr.2019.107565.

Irmak, S., Sharma, V., 2015. Large-scale and long-term trends and magnitudes in irrigated and rainfed maize and soybean WP: Grain yield and evapotranspiration frequency, crop water use efficiency, and production functions. Trans. ASABE 58 (1), 103–120. https://doi.org/10.13031/trans.58.10784.

Kool, D., Agam, N., Lazarovitch, N., Heitman, J.L., Sauer, T.J., Ben-Gal, A., 2014. A review of approaches for evapotranspiration partitioning. Agric. Meteorol. 184, 56–70. https://doi.org/10.1016/j.agrformet.2013.09.003.

Kukal, M., Irmak, S., 2017. Spatial and temporal changes in maize and soybean grain yield, precipitation use efficiency, and crop WP in the U.S. great plains. Trans. ASABE 60 (4), 1189–1208. https://doi.org/10.13031/trans.12072.

Lai, Z., Fan, J., Yang, R., Xu, X., Liu, L., Li, S., Zhang, F., Li, Z., 2022. Interactive effects of plant density and nitrogen rate on grain yield, economic benefit, WP and nitrogen use efficiency of drip-fertigated maize in northwest China. Agric. Water Manag. 263, 107453 https://doi.org/10.1016/j.agwat.2021.107453.

Li, H., Xu, C.Y., Beldring, S., 2015. How much can we gain with increasing model complexity with the same model concepts? J. Hydrol. 527, 858–871. https://doi.org/10.1016/j.jhydrol.2015.05.044.

Li, Y., Cui, S., Zhang, Z., Zhuang, K., Wang, Z., Zhang, Q., 2020. Determining effects of water and nitrogen input on maize (*Zea mays*) yield, water- and nitrogen-use efficiency: a global synthesis. Sci. Rep. 10, 9699 https://doi.org/10.1038/s41598-020-66613-6.

Linares, J.C., Camarero, J.J., 2012. From pattern to process: linking intrinsic water-use efficiency to drought-induced forest decline. Glob. Chang. Biol. 18 (3), 1000–1015. https://doi.org/10.1111/j.1365-2486.2011.02566.x.

Liu, M., Wang, G., Liang, F., Li, Q., Tian, Y., Jia, H., 2022. Optimal irrigation levels can improve maize growth, yield, and water use efficiency under drip irrigation in Northwest China. Water 14 (23), 3822. https://doi.org/10.3390/w14233822.

Liu, Y., Song, W., 2020. Modelling crop yield, water consumption, and water use efficiency for sustainable agroecosystem management. J. Clean. Prod. 253, 119940 https://doi.org/10.1016/j.jclepro.2019.119940.

Ma, L., Zhang, X., Lei, Q., Liu, F., 2021. Effects of drip irrigation nitrogen coupling on dry matter accumulation and yield of Summer Maize in arid areas of China. Field Crops Res 274, 108321. https://doi.org/10.1016/j.fcr.2021.108321.

Maroufpoor, S., Bozorg-Haddad, O., Maroufpoor, E., Gerbens-Leenes, P.W., Loáiciga, H. A., Savic, D., Singh, V.P., 2021. Optimal virtual water flows for improved food security in water-scarce countries. Sci. Rep. 11 (1), 21027 https://doi.org/10.1038/s41598-021-00500-6.

Massmann, A., Gentine, P., Lin, C., 2019. When does vapor pressure deficit drive or reduce evapotranspiration? J. Adv. Model. Earth Syst. 11 (10), 3305–3320. https://doi.org/10.1029/2019MS001790.

Mbava, N., Mutema, M., Zengeni, R., Shimelis, H., Chaplot, V., 2020. Factors affecting crop water use efficiency: a worldwide meta-analysis. Agric. Water Manag. 228, 105878 https://doi.org/10.1016/j.agwat.2019.105878.

O'Hara, S., Toussaint, E.C., 2021. Food access in crisis: food security and COVID-19. Ecol. Econ. 180, 106859 https://doi.org/10.1016/j.ecolecon.2020.106859.

Orth, R., Staudinger, M., Seneviratne, S.I., Seibert, J., Zappa, M., 2015. Does model performance improve with complexity? A case study with three hydrological models. J. Hydrol. 523, 147–159. https://doi.org/10.1016/j.jhydrol.2015.01.044.

Perry, C., Steduto, P., Allen, R.G., Burt, C.M., 2009. Increasing productivity in irrigated agriculture: agronomic constraints and hydrological realities. Agric. Water Manag. 96 (11), 1517–1524. https://doi.org/10.1016/j.agwat.2009.05.005.

Rosa, L., Chiarelli, D.D., Rulli, M.C., Dell'Angelo, J., D'Odorico, P., 2020. Global agricultural economic water scarcity. Sci. Adv. 6 (18), eaaz6031 https://doi.org/10.1126/sciadv.aaz6031.

Serna, L., 2022. Maize stomatal responses against the climate change. Front. Plant Sci. 13, 952146 https://doi.org/10.3389/fpls.2022.952146.

Sharma, V., Irmak, S., 2012. Mapping spatially interpolated precipitation, reference evapotranspiration, actual crop evapotranspiration, and net irrigation requirements in Nebraska: Part I. Precipitation and reference evapotranspiration. Trans. Asabe. 55 (3), 907–921. https://doi.org/10.13031/2013.41523.

Srinivasan, V., Lambin, E.F., Gorelick, S.M., Thompson, B.H., Rozelle, S., 2012. The nature and causes of the global water crisis: syndromes from a meta-analysis of coupled human-water studies, 2011WR011087 Water Resour. Res. 48. https://doi.org/10.1029/2011WR011087.

Srivastava, R.K., Panda, R.K., Chakraborty, A., Halder, D., 2020. Quantitative estimation of water use efficiency and evapotranspiration under varying nitrogen levels and sowing dates for rainfed and irrigated maize. Theor. Appl. Climatol. 139, 1385–1400. https://doi.org/10.1007/s00704-019-03005-5.

Stanger, T.F., Lauer, J.G., 2008. Corn grain yield response to crop rotation and nitrogen over 35 years. J. Agron. 100 (3), 643–650. https://doi.org/10.2134/agronj2007.0280.

Steward, D.R., Bruss, P.J., Yang, X., Staggenborg, S.A., Welch, S.M., Apley, M.D., 2013. Tapping unsustainable groundwater stores for agricultural production in the High Plains Aquifer of Kansas, projections to 2110. Proc. Natl. Acad. Sci. 110 (37), E3477–E3486. https://doi.org/10.1073/pnas.1220351110.

Suyker, A.E., Verma, S.B., 1993. Eddy correlation measurement of $CO_2$ flux using a closed-path sensor: theory and field tests against an open-path sensor. Bound. Layer. Meteor. 64 (4), 391–407. https://doi.org/10.1007/BF00711707.

Suyker, A.E., Verma, S.B., 2009. Evapotranspiration of irrigated and rainfed maize–soybean cropping systems. Agric. . Meteorol. 149, 443–452. https://doi.org/10.1016/j.agrformet.2008.09.010.

Suyker, A.E., Verma, S.B., Burba, G.G., 2003. Interannual variability in net $CO_2$ exchange of a native tallgrass prairie. Glob. Chang Biol. 9 (2), 255–265. https://doi.org/10.1046/j.1365-2486.2003.00567.x.

Tanner, C.B., T.R. Sinclair. 1983. Efficient water use in crop production: Research or research?, p. 1–27. In: H.M. Taylor, W.R. Jordan, and T.R. Sinclair (Eds.) Limitations to Efficient Water Use in Crop Production. Amer. Soc. Agronomy, Crop Sci. Soc. Amer., and Soil Sci. Soc. Amer., Madison, WI. https://doi.org/10.2134/1983.limitationstoefficientwateruse.c1.

Tao, F., Rötter, R.P., Palosuo, T., Gregorio-Hernández Díaz-Ambrona, C., Mínguez, M.I., Semenov, M.A., Kersebaum, K.C., Nendel, C., Specka, X., Hoffmann, H., Ewert, F., Dambreville, A., Martre, P., Rodríguez, L., Ruiz-Ramos, M., Gaiser, T., Höhn, J.G., Salo, T., Ferrise, T., Bindi, M., Cammarano, D., Schulman, A.H., 2018. Contribution of crop model structure, parameters and climate projections to uncertainty in climate change impact assessments. Glob. Chang Biol. 24 (3), 1291–1307. https://doi.org/10.1111/gcb.14019.

Tukey, J.W., 1949. Comparing individual means in the analysis of variance. Biometrics 5, 99–114. https://doi.org/10.2307/3001913.

Vadez, V., Kholova, J., Medina, S., Kakkera, A., Anderberg, H., 2014. Transpiration efficiency: new insights into an old story. J. Exp. Bot. 65 (21), 6141–6153. https://doi.org/10.1093/jxb/eru040.

Verma, S.B., Dobermann, A., Cassman, K.G., Walters, D.T., Knops, J.M., Arkebauer, T.J., Suyker, A.E., Burba, G.G., Amos, B., Yang, H., Ginting, D., Hubbard, K.G., Gitelson, A.A., Walter-Shea, E.A., 2005. Annual carbon dioxide exchange in irrigated and rainfed maize-based agroecosystems. Agric. . Meteorol. 131, 77–96. https://doi.org/10.1016/j.agrformet.2005.05.003.

Wagle, P., Gowda, P.H., Anapalli, S.S., Reddy, K.N., Northup, B.K., 2017. Growing season variability in carbon dioxide exchange of irrigated and rainfed soybean in the southern United States. Sci. Total Environ. 593–594, 263–273. https://doi.org/10.1016/j.scitotenv.2017.03.163.

Wang, L., Good, S.P., Caylor, K.K., 2014. Global synthesis of vegetation control on evapotranspiration partitioning. Geophys. Res. Lett. 41 (19), 6753–6757. https://doi.org/10.1002/2014GL061439.

Wang, S., Di Tommaso, S., Deines, J.M., Lobell, D.B., 2020. Mapping twenty years of corn and soybean across the US Midwest using the Landsat archive. Sci. Data 7, 307. https://doi.org/10.1038/s41597-020-00646-4.

Webb, E.K., Pearman, G.I., Leuning, R., 1980. Correction of flux measurements for density effects due to heat and water vapor transfer. Q. J. R. Meteorol. Soc. 106 (447), 85–100. https://doi.org/10.1002/qj.49710644707.

Wijewardana, C., Reddy, K.R., Alsajri, F.A., Irby, J.T., Krutz, J., Golden, B., 2018. Quantifying soil moisture deficit effects on soybean yield and yield component distribution patterns. Irrig. Sci. 36 (4–5), 241–255. https://doi.org/10.1007/s00271-018-0580-1.

Wingeyer, A.B., Walters, D.T., Drijber, R.A., Olk, D.C., Arkebauer, T.J., Verma, S.B., Wedin, D.A., Francis, C.A., 2012. Fall conservation deep tillage stabilizes maize residues into soil organic matter. Soil Sci. Soc. Am. J. 76 (6), 2154–2163. https://doi.org/10.2136/sssaj2012.0121.

Wisser, D., Frolking, S., Douglas, E.M., Fekete, B.M., Vörösmarty, C.J., Schumann, A.H., 2008. Global irrigation water demand: Variability and uncertainties arising from agricultural and climate data sets. L24408 Geophys. Res. Lett. 35. https://doi.org/10.1029/2008GL035296.

WWAP (United Nations World Water Assessment Programme), UN-Water. 2018. The United Nations World Water Development Report 2018: Nature-Based Solutions for Water. Paris, UNESCO. https://www.unwater.org/publications/world-water-development-report-2018 (accessed 13 June 2023).

Yang, H., Grassini, P., 2014. Quantifying and Managing Corn Water Use Efficiencies under Irrigated and Rainfed Conditions in Nebraska Using the Hybrid-Maize Simulation Model. In Practical Applications of Agricultural System Models to Optimize the Use of Limited Water (eds L.R. Ahuja, L. Ma and R.J. Lascano). https://doi.org/10.2134/advagricsystmodel5.c5.

Zhang, Q., Ficklin, D.L., Manzoni, S., Wang, L., Way, D., Phillips, R.P., Novick, K.A., 2019. Response of ecosystem intrinsic water use efficiency and gross primary productivity to rising vapor pressure deficit. Environ. Res. Lett. 14, 074023 https://doi.org/10.1088/1748-9326/ab2603.

Zipper, S.C., Qiu, J., Kucharik, C.J., 2016. Drought effects on US maize and soybean production: spatiotemporal patterns and historical changes. Environ. Res. Lett. 11 (9), 094021 https://doi.org/10.1088/1748-9326/11/9/094021.