Agricultural Systems 219 (2024) 104055

Contents lists available at ScienceDirect

Agricultural Systems

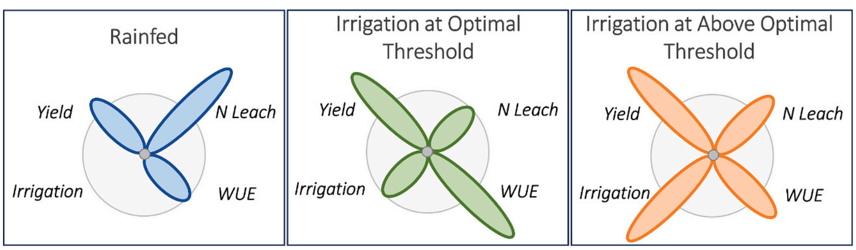
journal homepage: www.elsevier.com/locate/agsy

Irrigation expansion shows potential for increased maize yield and reduced nitrogen leaching in the Midwest US

Kelsie M. Ferin *, Christopher J. Kucharik

Department of Plant and Agroecosystem Sciences, University of Wisconsin-Madison, 1575 Linden Dr., Madison, WI 53705, USA

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Leonard Rusinamhodzi

Keywords:
Agroecosystem modeling
Agro-IBIS
Climate change
Nitrogen
Water use efficiency
Maize yield

ABSTRACT

CONTEXT: Yield gaps in Midwest US rainfed maize (*Zea mays* L.) are likely to continue to increase as the frequency of extreme weather events associated with future climate change increase (i.e., high temperatures, precipitation variability). One solution to closing this gap is the expansion of irrigation in regions that currently do not utilize this practice. While irrigation expansion has the potential to increase maize yields and crop productivity, there is also the potential to see improvement in nitrogen loss. However, it remains unclear at what point irrigation should be triggered (i.e., plant available water content (AWC) thresholds) to obtain a balance between crop productivity and environmental improvements.
OBJECTIVE: The objective of this study is to assess the effects of irrigation management on maize yield, nitrogen leaching, and water use efficiency under the expansion of irrigation across the entire Midwest US and to determine the optimal plant AWC threshold to trigger irrigation for achieving a substantial increase in maize yield and reduction in nitrogen leaching while using the minimal amount of required irrigation.
METHODS: We use an agroecosystem model, Agro-IBIS, to simulate both rainfed and irrigated maize production and nitrogen leaching under likely future climate conditions (i.e., wet-warm, dry-warm). To determine the optimal plant AWC threshold for irrigation, irrigation scenarios were conducted for a range of plant AWC thresholds (0.2 to 0.8) across the entire Midwest US.
RESULTS AND CONCLUSIONS: Our results show that Midwest US regions that do not currently utilize irrigation could experience an 11–37% increase in maize yield and a 12–32% decrease in nitrogen leaching when irrigation (39.0 to 96.8 mm yr^{-1}) is triggered at the lower end of the plant AWC threshold (e.g., 0.3). Maize grown under dry-warm and wet-warm climate conditions will likely experience increased yields and reduced nitrogen loss with minimal irrigation. While these findings suggest that the expansion of irrigation could help close yield gaps while improving other ecosystem services, future work should focus on simulating these conditions under a wider

* Corresponding author.
E-mail address: kferin@wisc.edu (K.M. Ferin).

https://doi.org/10.1016/j.agsy.2024.104055
Received 15 December 2023; Received in revised form 24 June 2024; Accepted 26 June 2024
Available online 29 June 2024

range of precipitation extremes and fertilizer management to better understand the potential interactions under a changing climate.
SIGNIFICANCE: This study outlines the optimal plant AWC threshold for irrigation to maximize maize yields in the Midwest while minimizing nitrogen loss and can provide valuable insights for making informed decisions about landscape management under future conditions.

1. Introduction

Over the past several decades, climate change has contributed to noticeable reductions in agricultural production across the Midwest US (Dai et al., 2016; dos Santos et al., 2022; Hatfield, 2010; Lesk et al., 2016; Lobell et al., 2011). This includes yield reductions due to drought-induced water stress, flooding of agricultural fields, and increased temperatures. These conditions are one of the many contributing factors of yield gaps (difference between potential and actual yields) in this region of the US (Hatfield et al., 2020; Li et al., 2020; Lobell et al., 2009). Previous studies have determined that rainfed maize (*Zea mays* L.) yields in the Midwest US are typically 20–30% below the maximum potential yields (Kucharik et al., 2020; Lobell et al., 2009). As the frequency of these extreme climate events are likely to increase (Rosenzweig et al., 2014; Seneviratne et al., 2021; Wilson et al., 2023), this yield gap has the potential to increase if there are no significant modifications to agricultural management (Balboa et al., 2019; Burchfield et al., 2020; DeLucia et al., 2019; Nandan et al., 2021; Snyder et al., 2021).

One example of modified agricultural management that could potentially increase yields in this largely rainfed region is the expansion of irrigation (DeLucia et al., 2019; Grassini et al., 2015; USDA ERS, 2022). While irrigation expansion has already begun to take place across the US (Brown and Pervez, 2014; Hussain et al., 2019), it will likely be required in regions of the rainfed Midwest especially under more extreme weather conditions (DeLucia et al., 2019; Snyder et al., 2021). Irrigation has the potential to reduce water stress and boost crop productivity, especially under warm, dry conditions or on soils that have low water-holding capacity (Baker et al., 2012; Huang et al., 2021; Huang and Hartemink, 2020; Paul et al., 2020; Schauberger et al., 2017; Troy et al., 2015). Crop productivity may also increase due to the cooling effect provided by irrigation (Nocco et al., 2019), in which increased transpiration reduces canopy temperature and alleviates heat stress through evaporative cooling (Li et al., 2019, 2020; Luan et al., 2021). Additionally, irrigation has been shown to reduce variability in maize yields for multiple conditions across the US (Baker et al., 2012; Irmak et al., 2022; Kucharik et al., 2020; Troy et al., 2015) as well as increase and potentially maximize water use efficiency (Huang and Hartemink, 2020; Irmak and Sharma, 2015).

Supplemental irrigation in agricultural systems may also impact nitrogen losses from agricultural fields. For instance, depending on the rate (i.e., above optimal or recommended) and timing of the fertilizer application, soil moisture and texture, and climate, nitrate leaching may increase if irrigation is applied to a field (Chatterjee, 2020; Gehl et al., 2005; Huang and Hartemink, 2020; Quemada et al., 2013; Scanlon et al., 2007; Zhou and Butterbach-Bahl, 2014). Increased nitrogen loss from Midwest farm fields may further contribute to water quality issues both in local groundwater as well as downstream to the Gulf of Mexico (Bailey et al., 2020; David et al., 2010; Goolsby et al., 2000; Hatfield et al., 2009; Jones et al., 2016, 2018; Schilling and Zhang, 2004; Schilling et al., 2020). However, if the optimal rates of both fertilizer (i.e., university extension recommendations for economic optimum) and applied irrigation are used, there may be potential for reduced nitrate leaching rates (Baker et al., 2012; Gehl et al., 2005; Quemada et al., 2013; Singh et al., 2023; Zamora-Re et al., 2020; Zhou and Butterbach-Bahl, 2014). Irrigation will likely reduce water stress in plants, therefore resulting in increased crop productivity due to greater nitrogen uptake and improved nutrient use efficiency (NUE) (Irmak et al., 2023; Lassaletta et al., 2023). This management practice could also decrease the likelihood of weather whiplash consequences on nitrogen leaching. The potential reduction in nitrogen loss due to increased NUE when irrigation is introduced may play a major role in reducing nitrogen loss in regions currently experiencing poor water quality issues, especially under wet-warm and dry-warm climate conditions (Ren et al., 2023). To the best of our knowledge, an assessment of this potential while using an agroecosystem model has yet to occur for the Midwest US.

Previous studies have shown that irrigation has the potential to increase maize yield under current and future climate conditions (Balboa et al., 2019; DeLucia et al., 2019; Paul et al., 2020; Snyder et al., 2021). For instance, Balboa et al. (2019) showed that the effects of additional nitrogen, increased plant density, and narrowing rows on increasing crop yield are negligible when irrigation is not included for a dry region in the Midwest. A large-scale assessment of potential maize yields under future climate conditions showed that irrigation expansion to rainfed states in the Midwest will be essential to maintain current yields (DeLucia et al., 2019). Kucharik et al. (2020) analyzed historical USDA National Agricultural Statistics Service (NASS) yield data and showed that the smallest yield gaps are in counties with irrigation and that variability in maize yield decreases when irrigation is applied under current climate conditions. Additionally, a modeling study also saw reductions in yield variability while irrigating maize but under future climate conditions (Irmak et al., 2022). While some of these studies have either used agroecosystem models for a single field site or used simplifying assumptions for crop growth, productivity, and irrigation requirements over a large region, they did not include a range of plant available water content (AWC) thresholds to determine the most optimal threshold for triggering irrigation or analyzed the implications that additional irrigation may have on the fate of nitrogen loss (Balboa et al., 2019; DeLucia et al., 2019; Kucharik et al., 2020; Partridge et al., 2023). Therefore, utilizing a physically based agroecosystem model that accounts for hourly and daily calculations related to water and nitrogen cycling in the soil-plant-atmosphere system is warranted to assess the feedback of expanding irrigation on maize yield and nitrogen loss.

While it is generally well known that supplemental irrigation may reduce crop yield gaps especially under dry-warm conditions, less is known on the potential effects of different irrigation thresholds on nitrogen leaching across the Midwest US. To address this gap, we conducted multiple simulations using an agroecosystem model to simulate maize growth under rainfed and irrigated conditions triggered by a range of plant AWC thresholds for the Midwest US. Our study aims to assess the effects of irrigation management on maize yield, nitrogen leaching, and water use efficiency if irrigation were expanded across the entire region under multiple climate conditions (i.e., wet-warm, dry-warm, 30-year average climate). Additionally, our study aims to determine the optimal plant AWC threshold to trigger irrigation in this region under these potential future conditions in which minimal irrigation is required to obtain a substantial increase in maize yield and reduction in nitrogen leaching. We focused on answering the following questions for maize: (1) If irrigation is applied at an optimal plant AWC threshold, how is yield impacted? (2) How will nitrate leaching respond to increased irrigation under warmer and wetter or drier conditions? (3) Which regions in the Midwest are most likely to benefit from irrigation under these potential future climate conditions?

2. Material and methods

2.1. Model simulations

An agroecosystem model, Agro-IBIS (Kucharik, 2003; Kucharik and Brye, 2003), was used to simulate maize yields under various weather conditions and irrigation thresholds across the Midwest US. Agro-IBIS, a derivative of the IBIS model (Foley et al., 1996; Kucharik et al., 2000), is a physically based model that simulates both biogeochemical and biophysical processes and accounts for the exchange of water, carbon, energy, and nitrogen between the soil, plant, and atmosphere. Leaf-level interactions, including photosynthesis and stomatal conductance, are initially calculated at an hourly temporal resolution (Collatz et al., 1991; Farquhar et al., 1980). These variables are then scaled up to the canopy level and updated at daily to yearly timescales (Thompson and Pollard, 1995a, 1995b). The biophysical processes within the canopy are driven by hourly solar radiation, water availability, stomatal conductance, and evapotranspiration (ET) (Kucharik et al., 2000; Thompson and Pollard, 1995b, 1995a). Total ET from the land surface is the sum of three fluxes: evaporation from the soil surface, evaporation of canopy-intercepted water, and canopy transpiration. Transpiration rates are linked to photosynthetic rates through the modeling of stomatal conductance (Collatz et al., 1991; Farquhar et al., 1980; Kucharik et al., 2000). Agro-IBIS simulates soil temperature, soil moisture, and soil ice content for each soil layer (i.e., 11 layers to a total depth of 2.5 m) as a function of the soil water flux vertical gradient by using Richard's equation and Darcy's law, which is dependent on soil texture properties (Clapp and Hornberger, 1978; Foley et al., 1996). This model, along with the various inputs required to run this version and resolution, have been well documented and validated in previous studies (Dong et al., 2020; Ferin et al., 2023; Kucharik et al., 2013; Motew and Kucharik, 2013). Agro-IBIS has also previously been thoroughly calibrated and evaluated for crop yields in many locations across the Midwest US as well as nitrate leaching and downstream nutrient transport in multiple watershed basins of different spatial scales (Donner and Kucharik, 2008; Ferin et al., 2023; Kucharik, 2003; Kucharik and Brye, 2003; Kucharik and Twine, 2007; Motew et al., 2017; Soylu et al., 2014). Our simulations utilize the version of code from Kucharik and Twine (2007) and implemented minor adjustments to the rate of carboxylation for photosynthesis (Vcmax), maize hybrid growing degree day requirements, and the fraction of carbon allocated to grain to reflect the annual increases in maize yield reported by USDA NASS. In this study, we further compared maize yields and nitrate leaching output with observational data from USDA NASS and Shrestha et al. (2023), respectively (Section S3 of the Supplementary Materials).

This study uses model input data previously described in Liu et al. (2023). This model was driven by the ZedX Inc. (Bellefonte, PA) observation-based daily weather dataset which is at the 5 arcmin spatial resolution for the entire CONUS. Soil texture data was obtained from the USDA State Soil Geographic Database (STATSGO) (Miller and White, 1998) and previously described in Kucharik et al. (2013) (Fig. S1). Maize yields across the Midwest US were simulated under weather conditions from 1978 to 2007. Maize received broadcast inorganic nitrogen fertilizer and manure at planting by using rates consistent with previous datasets from Donner and Kucharik (2008) for 1978 to 1989 and EarthStat fertilizer and manure rates from 1990 to 2007 (available at http://www.earthstat.org/; Fig. S2). Simulated maize yields for both rainfed and irrigated conditions were evaluated against recent NASS county average yields (Section S3 of the Supplementary Materials). Model simulations were conducted without irrigation (i.e., rainfed only) and with irrigation triggered across a range of plant available water thresholds, described in detail below.

The focus of this study is on the Midwest US states contributing to the majority of US maize production including North Dakota, South Dakota, Nebraska, Kansas, Minnesota, Iowa, Missouri, Wisconsin, Illinois, Michigan, Indiana, and Ohio. A mask identifying areas of maize production was generated by aggregating 2016 Cropland Data Layer data from 30 m resolution to 10 km. This mask was used to isolate grid points where maize production occurs within the Midwest and to exclude areas where maize is not typically in production.

2.2. Irrigation and water stress in Agro-IBIS

Irrigation simulated within Agro-IBIS requires several conditions to be met. These conditions include the following: (1) a crop must be planted and living, (2) minimum daily temperatures >5 °C, (3) 5-day running mean temperature >10 °C, and (4) the actual soil water content in the top 60 cm of soil is less than or equal to the irrigation threshold multiplied by the maximum value at field capacity. The irrigation threshold parameter is the ratio of current soil plant AWC to maximum plant AWC in the root zone (defined as the top 60 cm of soil) at field capacity, referred to as the fraction of maximum plant AWC. The fraction of maximum plant AWC thresholds used to trigger irrigation events in this study are as follows: 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, and 0.8. Irrigation was applied at a consistent rate during a nominal 6-h event and added an amount that brought the current plant AWC to the maximum (field capacity) value, but with the constraint that the maximum daily amount that could be applied was 50 mm. Agro-IBIS does not simulate water withdrawal from aquifers, wells, or surface water bodies; therefore, the water applied through irrigation does not reduce water storage or influence drainage at the bottom of the soil profile (250 cm).

The simulated effects of water stress within Agro-IBIS play an important role in the modeling results of this study and are based on methodology presented in Campbell and Norman (1998). The water stress factor (zwilt) is a factor of AWC and is plotted in Fig. S3. In the model, AWC for zwilt is calculated as follows:

$$AWC = \frac{(wsoi^*(1 - wisoi)) - swilt}{sfield - swilt}$$

Where *wsoi* is the fraction of soil pore space containing liquid, *wisoi* is the fraction of soil pore space containing ice, *swilt* is the plant permanent wilting point soil moisture value (fraction of pore space), and *sfield* is the field capacity soil moisture value (fraction of pore space). This value is then used in the water stress factor equation:

$$zwilt = 1 - \frac{log\left(1 + 799^*e^{(-12^*AWC)}\right)}{log(800)}$$

This water stress fraction is calculated at each time step and is used to reduce the maximum rate of carboxylation (Vcmax) and stomatal conductance in the leaf-level photosynthesis calculations for maize. When stomatal conductance is reduced, both photosynthesis and transpiration are therefore reduced. By reducing Vcmax when water stress occurs, the productivity of the plant will be reduced and can result in a reduction of biomass accumulation along with total yield at the end of the growing season. Water stress may be alleviated when irrigation is applied due to the additional water increasing AWC and therefore reducing zwilt.

2.3. Weather classifications and conditions

Following methods from Balboa et al. (2019), weather years from 1978 to 2007 were categorized by wet-warm ($n = 7$), wet-cool ($n = 8$), dry-warm ($n = 10$), and dry-cool ($n = 5$) which were determined by the 30-year average growing season (April through October) total precipitation (547 mm) and daily maximum temperature (23.9 °C; Fig. S4) across the study region. A portion of our analysis focused on maize grown under the wet-warm and dry-warm weather years as these conditions are most likely to occur with continued climate change (Seneviratne et al., 2021).

Total precipitation for the growing season months of April through

October were averaged over the 1978 to 2007 weather years across all twelve states in the Midwest (Fig. S5a). This data shows the highest precipitation in the southern regions of the Midwest and the lowest precipitation in the far western portion of the Midwest. Growing season total precipitation patterns across the Midwest are noticeably different for the wet-warm and dry-warm years (Fig. S6). The average growing season precipitation for the wet-warm years shows totals of 700 to 800 mm across most of Iowa and into portions of Missouri, Wisconsin, Indiana, and eastern portions of Nebraska and Kansas (Fig. S6a). The dry-warm weather years show growing season total precipitation between 500 and 600 mm for most of the middle to eastern Midwest with totals decreasing towards the eastern portion of the Midwest (Fig. S6b).

Daily maximum temperature was also averaged over the growing season for the 30-year period across all states in the Midwest (Fig. S5b). The warmest average daily maximum temperatures were between 27.5 and 29.4 °C in the most southern portion of the Midwest and the coolest average daily maximum temperatures of 18.8 to 21.3 °C were found in the northernmost portion of the Midwest. When weather years were separated by wet-warm and dry-warm conditions, daily maximum temperature spatial patterns were very similar to one another (Fig. S7), with slight differences observed when compared to the 30-year average (Fig. S5b).

2.4. Model output and analysis

Data used in this analysis includes 30 years of annual growing season average maximum daily temperature and total precipitation, maize yield, irrigation rates, and nitrate leaching rates. Water use efficiency (WUE; kg-C m-H_2O^{-3}) was calculated using Agro-IBIS simulated yield divided by model simulated ET. Irrigated water use efficiency for irrigated maize (IWUE) was calculated using the difference between simulated irrigation and rainfed maize yield divided by the total applied irrigation (kg-C m-H_2O^{-3}) (Howell, 2001). This output was analyzed using R (R Core Team, 2022) and visualized using ArcPro (ESRI, 2022). Our analysis includes state average tables and spatial maps of the Midwest for variables separated by 30-year average, wet-warm, and dry-warm climate conditions along with percent change for irrigation relative to rainfed. Four single grid points were also selected for the 30-year weather average that encompass a wide range of total annual precipitation and soil texture across the Midwest region to further assess the relationship between yield and irrigation threshold relative to irrigation amount, nitrogen leaching, WUE, and IWUE.

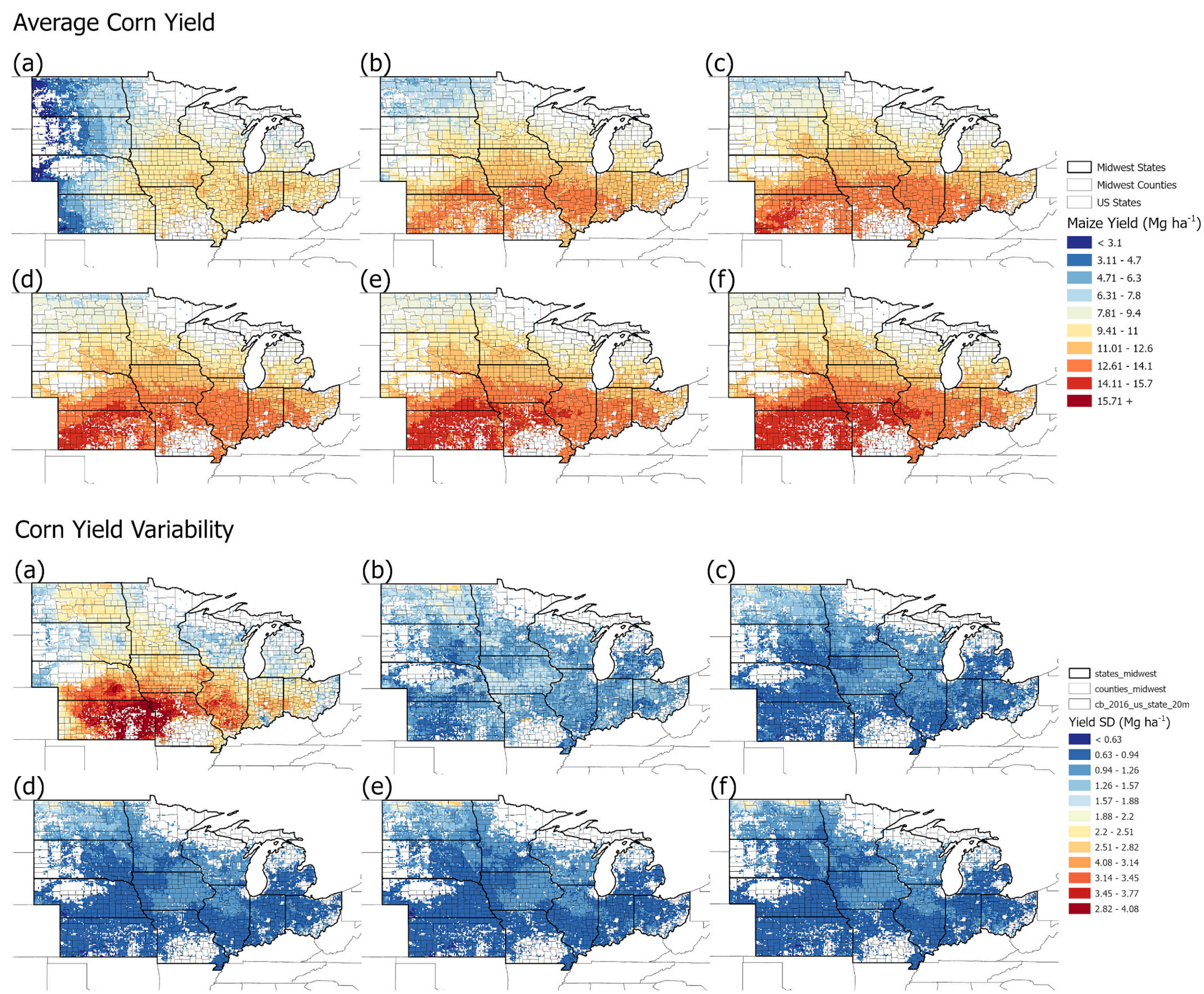


Fig. 1. 30-year average maize yield and maize yield variability (standard deviation, SD) for (a) no irrigation (rainfed only) and irrigation triggered at the (b) 0.2, (c) 0.3, (d) 0.4, (e) 0.5, and (f) 0.8 plant AWC threshold.

3. Results

3.1. Maize yield

3.1.1. 30-year yield averages and variability

Modeled maize yield averages for the 30 years were calculated across the Midwest under rainfed only and under irrigation for multiple ranges of plant AWC thresholds (Fig. 1). Rainfed yields were greatest in the Iowa, Illinois, Indiana, and Ohio regions of the Midwest. Yields across the entire region increased when irrigation was introduced into the model, even when irrigation was triggered at the 0.2 plant AWC threshold. Increases in plant AWC thresholds coincided with increases in yield across the entire region. Mean simulated rainfed and irrigated yields for the eastern portion of the Midwest were comparable to NASS county average yields, and the magnitude of spatial variability (and extremes) were also similar (Section S3 of the Supplementary Materials). On average across the Midwest under the 30-year average weather conditions, maize yield increased by 0.4 Mg ha^{-1} for every 10 mm of irrigation applied relative to rainfed conditions (Fig. S8a).

Interannual yield variability (standard deviation) was the greatest in the southwest portion of the Midwest with values >3.8 Mg ha^{-1} (Fig. 1). The average Midwest yield variability over the 30 years was 2.5 Mg ha^{-1}. The introduction of irrigation substantially reduced the Midwest yield variability across 30 years of weather conditions by 1.2 to 1.6 Mg ha^{-1} depending on the plant AWC threshold used to trigger irrigation. As plant AWC thresholds increased, yield variability continued to decrease.

3.1.2. Yield under wet-warm and dry-warm conditions

On average across the Midwest, maize yield under wet-warm and dry-warm conditions showed significant increases when irrigation was applied relative to rainfed conditions (Fig. S9). Maize yield increased on average by 2.0 Mg ha^{-1} under wet-warm conditions and 3.1 Mg ha^{-1} under dry-warm conditions when irrigation is triggered at the plant AWC threshold of 0.2 relative to rainfed. A maximum average yield increase of 3.2 Mg ha^{-1} for wet-warm and 4.6 Mg ha^{-1} for dry-warm conditions occurred with irrigation triggered at a plant AWC threshold of 0.5. Average yields for both conditions plateaued as irrigation thresholds were >0.5 plant AWC (Fig. S9).

Simulated rainfed maize yields were the lowest in both the wet-warm and dry-warm climate conditions relative to all irrigation treatments (Table S1). When the 0.2 plant AWC threshold was implemented for

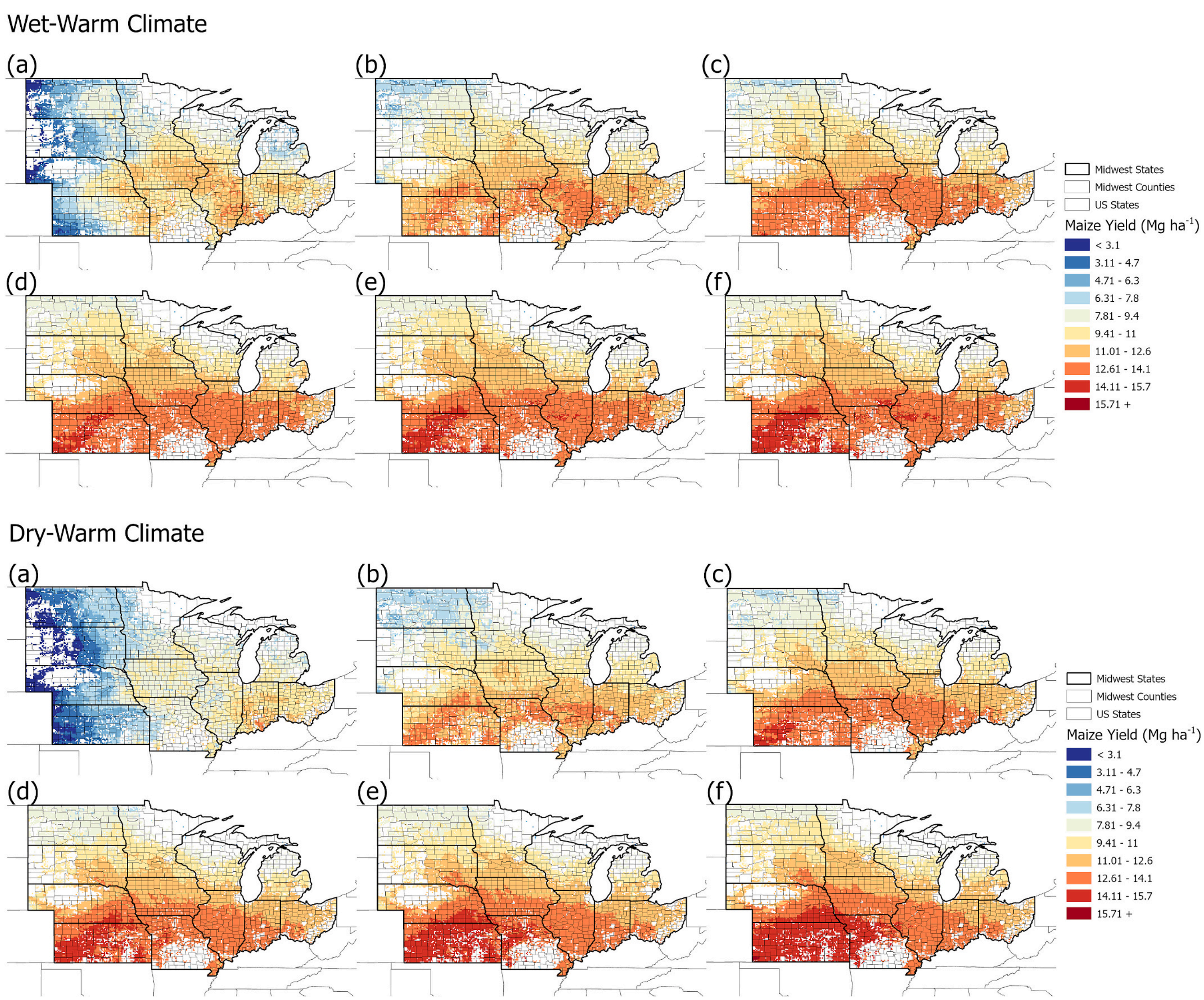


Fig. 2. Average maize yields under wet-warm and dry-warm conditions for (a) no irrigation (rainfed only) and irrigation triggered at the (b) 0.2, (c) 0.3, (d) 0.4, (e) 0.5, and (f) 0.8 plant AWC threshold.

irrigation, maize yields across the entire Midwest increased by 4–57% and 8–145% under wet-warm and dry-warm conditions, respectively, relative to rainfed yields (Fig. S10; Table S2). Increases in yield were also observed when plant AWC thresholds of 0.3 (wet-warm = 6–68%; dry-warm = 12–169%) and 0.4 (wet-warm = 7–75%; dry-warm = 15–181%) were induced, relative to rainfed conditions (Fig. S10; Table S2). Irrigation triggered at plant AWC thresholds of 0.4, 0.5, and 0.8 all resulted in similar spatial patterns and yield increases relative to the rainfed yields (Fig. 2, S10; Tables S1 and S2). The highest increase in yields under irrigated conditions were observed in the western Midwest states (i.e., South Dakota, Kansas, Nebraska) while the lower end of the yield increase was in Wisconsin, Ohio, Indiana, Minnesota, and Michigan. However, there were regions across the rainfed portion of the Midwest (i.e., eastern Iowa, southwest Wisconsin, and portions of Minnesota) that had a very slight yield decline under plant AWC thresholds of 0.2 and 0.3 relative to rainfed yields under the wet-warm conditions (Fig. S10).

3.2. Irrigation applied and associated yield increases

On average across the Midwest, maize yield grown under wet-warm conditions increased by 0.3 Mg ha^{-1} for every 10 mm of irrigation applied relative to rainfed conditions (Fig. S8b). When maize was grown under dry-warm conditions, yield increased by 0.4 Mg ha^{-1} for every 10 mm of irrigation applied (Fig. S8c). The plant AWC threshold of 0.2 resulted in irrigation application rates much lower than all other plant AWC thresholds (Fig. 3; Table S3). Irrigation application rates for this plant AWC threshold ranged between 13.7 and 43.3 mm yr^{-1} in states outside of the Great Plains region and 37.8 to 114.2 mm yr^{-1} in the Great Plains states on average (i.e., North and South Dakota, Nebraska, Kansas) under the wet-warm conditions, resulting in a 4–14% and 23–57% increase in yield, respectively (Tables S2 and S3). Irrigation rates increased from 20.6 to 82.5 mm yr^{-1} east of the Great Plains and 57.6 to 191.5 mm yr^{-1} in the Great Plains states under the dry-warm conditions, leading to an 8–38% and 47–145% increase in yield (Tables S2 and S3).

As plant AWC thresholds increased from 0.3 and 0.4, the rates of irrigation previously described continued to increase in both weather condition scenarios, with dry-warm conditions nearly doubling the amount of irrigation applied in the majority of the states compared to wet-warm conditions (Fig. 3; Table S3). The maximum simulated irrigation application rate for plant AWC threshold of 0.3 was 114.8 mm yr^{-1} in states outside of the Great Plains region and 231.8 mm yr^{-1} in the Great Plains, resulting in a maximum of 48% and 169% increase in

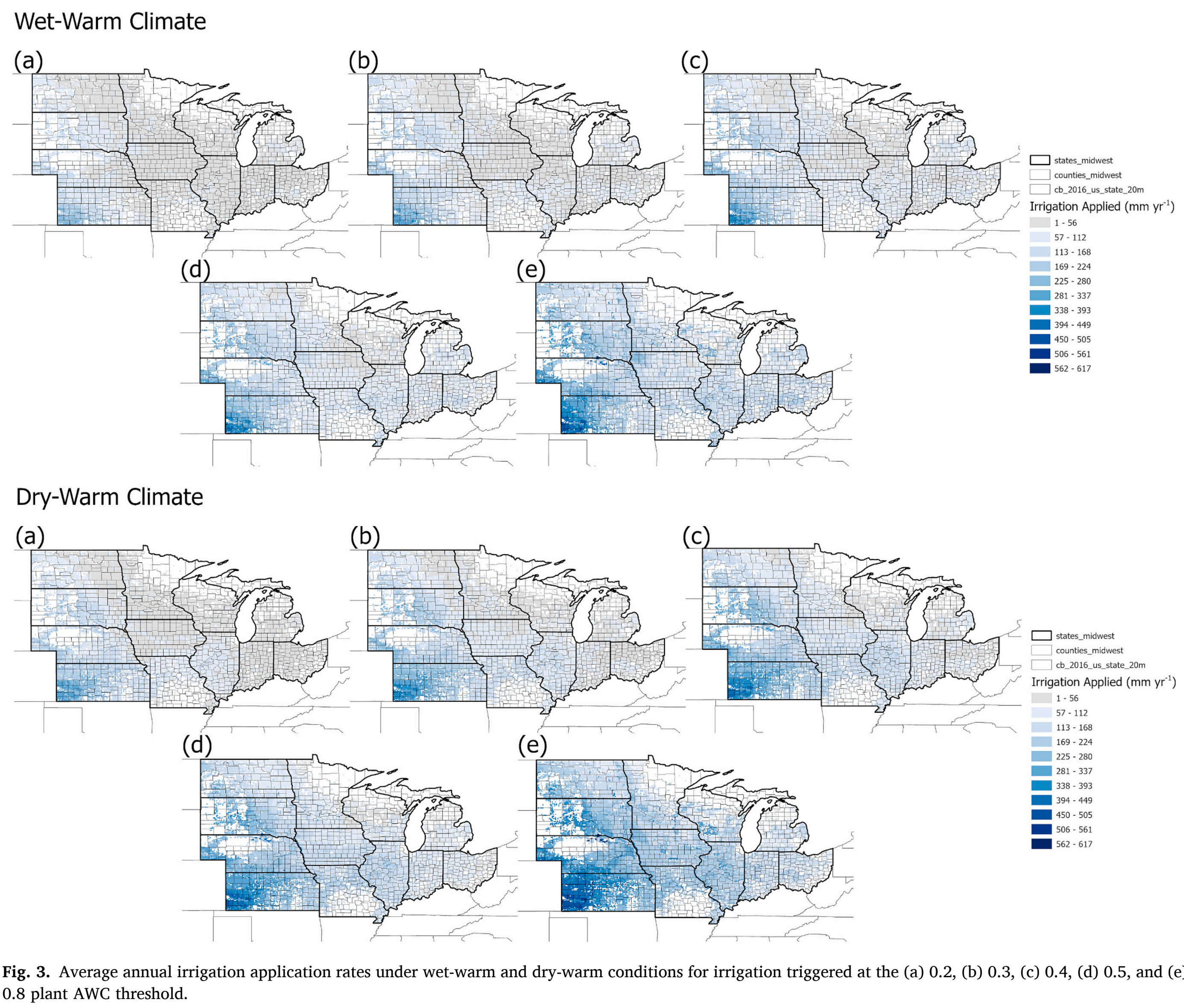


Fig. 3. Average annual irrigation application rates under wet-warm and dry-warm conditions for irrigation triggered at the (a) 0.2, (b) 0.3, (c) 0.4, (d) 0.5, and (e) 0.8 plant AWC threshold.

yield, respectively, relative to no irrigation in the dry-warm conditions (Tables S2 and S3). When the plant AWC threshold increased to 0.4, maximum simulated irrigation rates of 139.7 mm yr^{-1} led to a 54% increase in yield outside of the Great Plains states, and 261.3 mm yr^{-1} resulted in a 181% increase in yield within the Great Plains states relative to no irrigation (Tables S2 and S3). Irrigation rates for plant AWC thresholds >0.4 continued to increase but no significant increases in yield were attained.

Average yield for the four grid cells across the Midwest simulated under 30 years of weather conditions for the range of plant AWC thresholds resulted in a similar pattern and plateau near 0.3 to 0.5, however, irrigation applications continued to increase linearly. Irrigation and yields were greatest for the grid cells located in Nebraska (clay loam) and Illinois (silty loam; Fig. 4a). The sandy soils location in central Wisconsin had the lowest yield compared to the other locations as well as the lowest irrigation amounts applied.

3.3. Nitrate leaching

Nitrate leaching rates were greatest under the rainfed, wet-warm conditions for the entire Midwest region with average rates ranging from 49.2 to 101.3 kg-N ha^{-1} (Fig. 5; Table S4). Leaching rates under the rainfed dry-warm conditions were much lower with a range of 27.5 to 78.7 kg-N ha^{-1}. Regions of higher nitrate leaching rates are found in counties that coincide with greater fertilizer and manure nitrogen application rates relative to the surrounding areas for the Midwest (Fig. S2). This observation is consistent across both the wet-warm and dry-warm climate and for rainfed and irrigated conditions.

When irrigation was applied (for all plant AWC thresholds), nitrate leaching rates significantly decreased by 7–77% under wet-warm and 10–78% under dry-warm conditions relative to rainfed leaching rates (Fig. S11; Table S5). The largest reductions in nitrate leaching under all irrigation thresholds and climate conditions relative to rainfed were in the Great Plains states of North Dakota, South Dakota, Nebraska, and Kansas and ranged between 41% to 69% (Table S5). Counties that had the highest rates of nitrate leaching in rainfed conditions showed a significant reduction when irrigation was introduced (Figs. 5 and S11).

On average, most states irrigated under the 0.8 plant AWC threshold resulted in a slight increase in nitrate leaching rates (approx. 1–3%) relative to the 0.5 plant AWC threshold and under both wet-warm and dry-warm conditions (Tables S4 and S5). Additionally, there were a few locations in the Central Sands region of Wisconsin that showed minimal reduction in nitrate leaching (maximum of −4%) and even locations with an increase in leaching by 6–15% (Fig. S11). This increase was observed for the 0.8 plant AWC threshold for irrigation relative to the rainfed conditions.

Average nitrogen leaching rates for four grid cells across the Midwest simulated under 30 years of weather conditions for the range of plant AWC thresholds resulted in a similar response to the wet-warm and dry-warm climate conditions (Fig. 4b). Nitrogen leaching rates typically

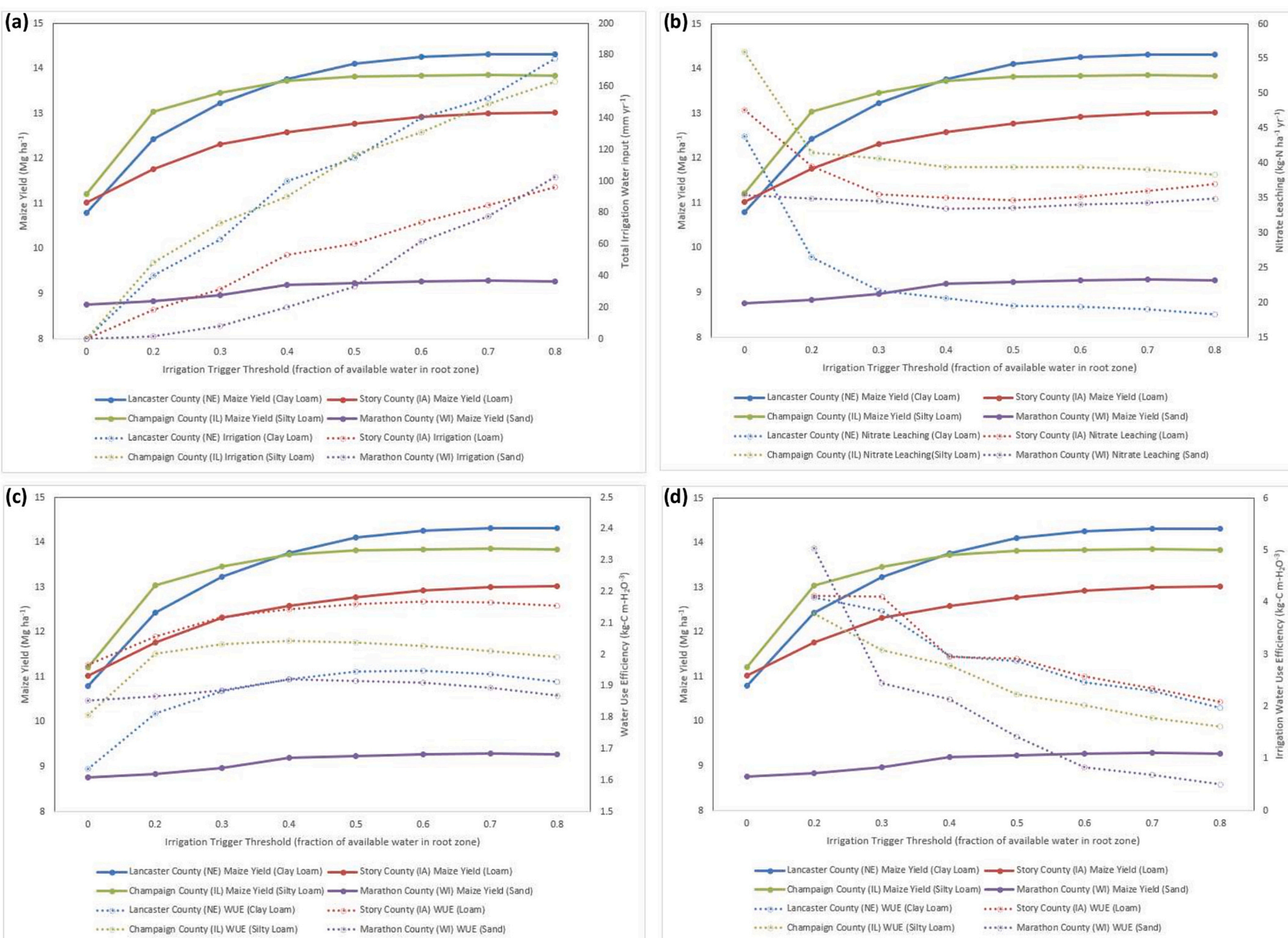


Fig. 4. Relationships between 30-year average Agro-IBIS simulated continuous maize yield with (a) irrigation application rates, (b) nitrogen leaching rates, (c) water use efficiency (WUE), and (d) irrigation water use efficiency (IWUE) for four grid cells across the Midwest for a range of plant available water content (AWC) irrigation thresholds. These grid cells were selected to encompass a range of annual growing season precipitation totals and soil texture classifications.

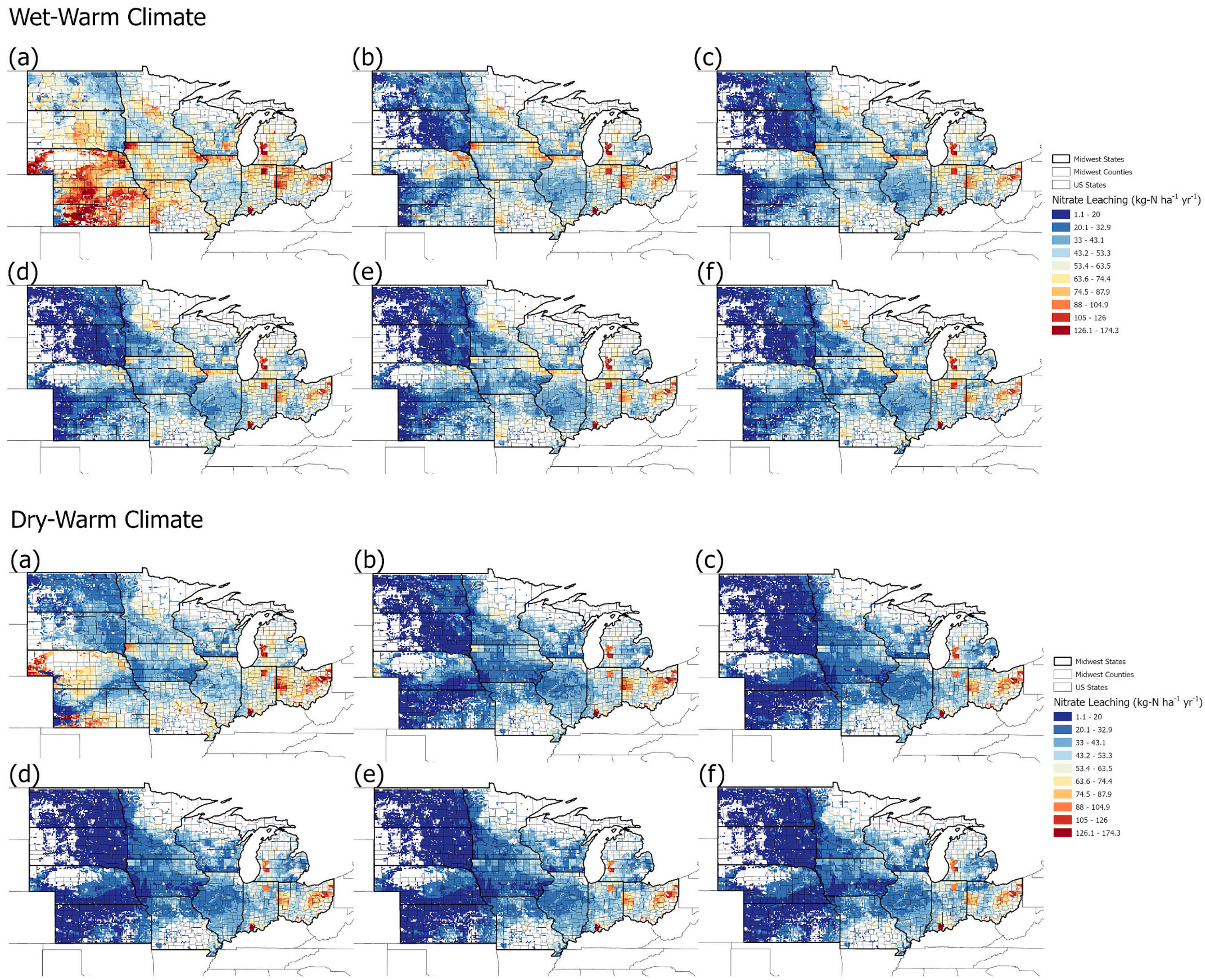


Fig. 5. Average nitrate leaching rates under wet-warm and dry-warm conditions for (a) no irrigation (rainfed only) and irrigation triggered at the (b) 0.2, (c) 0.3, (d) 0.4, (e) 0.5, and (f) 0.8 plant AWC threshold.

decreased and became more constant as plant AWC thresholds increased. Greater yields generally coincided with lower nitrogen leaching rates for plant AWC thresholds of 0.2 to 0.4 (Fig. 4b). Unlike the grid cells selected for Nebraska and Illinois, both Iowa and Wisconsin had slight increases in nitrogen leaching rates as the plant AWC threshold increased above 0.5 (Fig. 4b).

3.4. Water use efficiency and irrigation water use efficiency

WUE in rainfed maize ranged between 0.47 and 2.34 kg-C m-H_2O^{-3} under wet-warm conditions and between 0.38 and 2.50 kg-C m-H_2O^{-3} under dry-warm conditions (Fig. 6). This was much lower in regions with less growing season precipitation (i.e., Great Plains states). WUE was maximized across the region when irrigation was triggered near the plant AWC threshold of 0.3 under both climate conditions. Under both climate conditions, WUE plateaued as plant AWC thresholds increased past 0.3 and 0.4 (Fig. 6). Looking specifically at four grid cells across the Midwest which represent different soil textures and growing season precipitation totals, WUE for the 30-year average climate was very similar to WUE under the wet-warm and dry-warm conditions (Fig. 4c). WUE was lower for the sand and clay loam soils of Wisconsin and Nebraska relative to the loam and silty loam soils of Iowa and Illinois, respectively.

When irrigation was applied to maize, IWUE was typically greater at lower plant AWC thresholds for both climate conditions (Fig. 7). As plant AWC thresholds increased, IWUE decreased across the Midwest under both climate conditions. Dry-warm climate conditions resulted in greater IWUE relative to wet-warm for irrigated maize. Under the dry-warm climate, plant AWC thresholds between 0.2 and 0.4 resulted in consistently high IWUE compared to plant AWC thresholds of 0.5 and 0.8 for the entire Midwest (Fig. 7). For these conditions, the eastern portion of the Midwest had much lower IWUE than the west. Under the wet-warm climate conditions for the plant AWC thresholds of 0.2 and 0.3, IWUE was lowest in portions of northeastern Iowa, southcentral Wisconsin, and southern Illinois (Fig. 7). These patterns became more prominent as plant AWC increased above the 0.3 threshold. Overall, similar patterns of decreasing IWUE with increasing irrigation threshold were observed for these four single grid cells under the 30-year average weather conditions (Fig. 4d). While the response of IWUE to increasing thresholds for Nebraska, Iowa, and Illinois were nearly identical, IWUE calculated on maize grown on the sandy soils of Wisconsin declined at a much quicker rate as plant AWC threshold increased and was generally much lower than the other locations as this threshold surpassed 0.3.

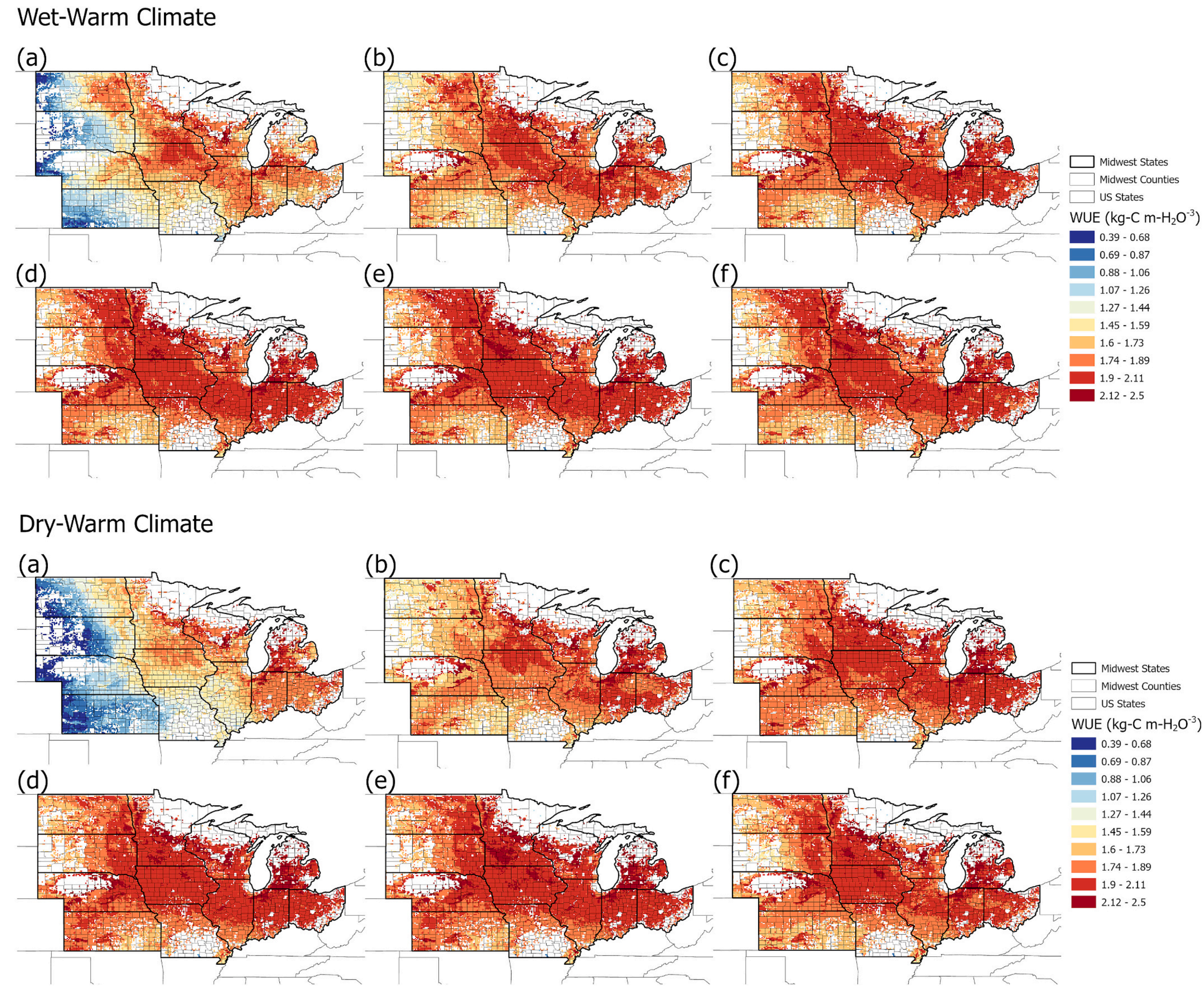


Fig. 6. Average water use efficiency under wet-warm and dry-warm conditions for (a) no irrigation (rainfed only) and irrigation with (b) 20%, (c) 30%, (d) 40%, (e) 50%, and (f) 80% soil moisture threshold trigger.

4. Discussion

4.1. Irrigation expansion has the potential to increase maize yield across the Midwest

Irrigating maize in dry regions of the Midwest has shown significant potential regarding increasing yields and reducing yield gaps, especially under potential future climate conditions (Balboa et al., 2019; DeLucia et al., 2019; Lobell et al., 2009; Nandan et al., 2021). Our study shows that maize yields across the Midwest have the potential to increase when irrigation is applied, even when triggered at the lowest plant AWC threshold of 0.2 resulting in the lowest rate of irrigation relative to other plant AWC thresholds. Additionally, any amount of irrigation applied to the Midwest significantly reduced variability in maize yield under the 30-year average weather conditions (Fig. 1), which was consistent with previous studies (Baker et al., 2012; Irmak et al., 2022; Kucharik et al., 2020; Troy et al., 2015). All regions of the Midwest benefited from irrigation, with the highest irrigation rates aligning with regions where growing season total precipitation was below 500 mm (Fig. S6) and in soil texture classifications with the lowest water holding capacity (i.e., sandy loam, loamy sand, and sand; Fig. S1). Coinciding with previous studies (Huang et al., 2021; Luan et al., 2021), our study showed that maize yields grown under warm-dry climate conditions had a greater potential for increased yield and reduced sensitivity to low precipitation when irrigated than in warm-wet conditions. However, future simulations will need to include a wider range of likely precipitation extremes for a changing climate to capture this yield response and further our understanding of the implications of using irrigation in these conditions.

The benefits of irrigation increased as plant AWC threshold increased from 0.2 to 0.4 but began to diminish as the threshold reached 0.5 to 0.8. A slight yield increase was obtained with a plant AWC threshold >0.4, however, a large amount of irrigation was required to achieve these results. For instance, the 0.8 plant AWC threshold resulted in an average of 3–4% increase in yield relative to 0.4 plant AWC, but at the cost of 77–83% (61.8–74.0 mm) increase in irrigation rates for all weather conditions. Even when plant AWC threshold increased from 0.4 to 0.5, an average of 2% increase in yield across the region for all weather conditions was reached but required a 21–23% (17.5–20.5 mm) increase in irrigation relative to the 0.4 plant AWC threshold. Our results align with findings from Gehl et al. (2005) which conclude that additional irrigation above the requirement to replenish crop water use does not provide any significant maize yield increase.

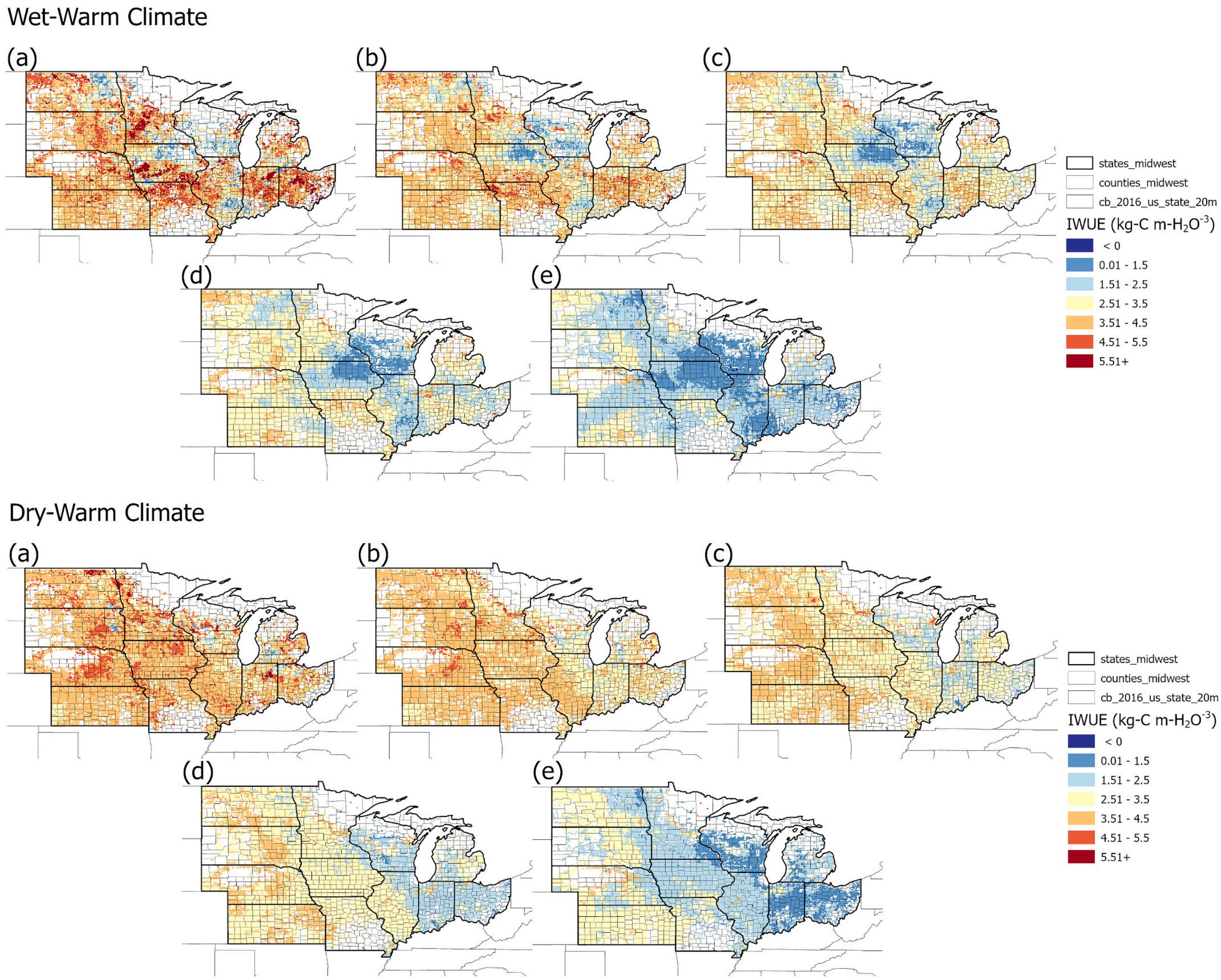


Fig. 7. Average irrigation water use efficiency (IWUE) under wet-warm and dry-warm conditions for irrigation triggered at the (a) 0.2, (b) 0.3, (c) 0.4, (d) 0.5, and (e) 0.8 plant AWC threshold.

Our analysis showed that on average across the region one could obtain between 0.3 and 0.4 Mg ha^{-1} yield increase for every 10 mm of irrigation applied (Fig. S8), implying that all regions could potentially benefit from minimal irrigation amounts. Therefore, the continuation of irrigation in the Great Plains regions of the Midwest will be necessary with continued climate warming to maintain current increasing yield trends. This region showed to have the greatest increase in yield even under the lowest plant AWC threshold but also resulted in the highest rates of irrigation relative to other states in the Midwest in this scenario. Similar to our results, DeLucia et al. (2019) show in one of many scenarios that if precipitation were to remain at historical rates while vapor pressure deficit increases (creating dryer, more stressful conditions), it would take a significant increase in irrigation (approx. 180–260 mm yr^{-1}) for states with lower annual precipitation totals to achieve similar yields from 2013 to 2016. While some regions of the Midwest that have greater growing season precipitation may not require as much supplemental irrigation under the wet-warm climate conditions, irrigation will likely be required as precipitation variability increases under future climate projections (Seneviratne et al., 2021). Our study shows that other states in the core of the Corn Belt (i.e., Iowa, Illinois, Indiana) will also benefit from irrigation under the dry-warm and wet-warm climate conditions. These states have the potential to increase yields by 17–41% with irrigation rates of 71.6 to 120.6 mm yr^{-1} when irrigation is triggered by the 0.4 plant AWC threshold under the dry-warm conditions.

Climate change may result in shifts in irrigated areas, technological advances in irrigation methods, and shifts in the sources for irrigation water supply (i.e., recycled or reclaimed water) (Hejase et al., 2022; Hrozencik and Aillery, 2021; Nandan et al., 2021; Willison et al., 2021). However, the expansion of supplemental irrigation may not be feasible everywhere due to limitations on water resources and associated costs (Partridge et al., 2023). Partridge et al. (2023) found that irrigation could increase maize yields across the Midwest states under future climate conditions, but the benefit of increased yields may not outweigh the costs of equipment and groundwater pumping. Their study assumed that the plant AWC threshold to trigger irrigation was fixed at 0.4 and that 10 mm of water was applied each day this condition was met, which differs from the methodology in our study. Future work should conduct similar cost-benefit analyses but include a wider range of irrigation application strategies to better assess these tradeoffs under future conditions.

4.2. Nitrate leaching losses from maize can be reduced with lower optimal irrigation thresholds

Our study shows that irrigating maize has significant potential to reduce nitrate leaching relative to rainfed conditions, which is consistent with previous findings (Baker et al., 2012; Quemada et al., 2013). One example of this can be found in a meta-analysis conducted by Quemada et al. (2013) which found management practices that adjust water application (i.e., irrigation to crop needs, improved irrigation schedule) could reduce nitrogen leaching by up to 78% without reducing crop yields. The reduction in nitrate leaching observed in both our study and the previous studies may be attributed to an increase in crop productivity under irrigated conditions (i.e., no water stress) leading to an increase in nitrogen uptake.

A reduction in nitrate leaching was observed under all plant AWC thresholds for irrigation relative to rainfed conditions. However, under the highest plant AWC threshold (0.8) nitrate leaching rates slightly increased relative to the rates under 0.5 plant AWC (Figs. 4b and S11). Since maize productivity was sustainability maximized with irrigation rates under the 0.4 plant AWC threshold as discussed above, additional available nitrate in the soil was then leached due to the extra flux of water from irrigation that was not used by the crops. A similar response has been observed throughout the literature across the Midwest (Chatterjee, 2020; Gehl et al., 2005; Irmak et al., 2023; Singh et al., 2023).

Fertilizing maize with optimal nitrogen rates may be sufficient for increasing crop productivity when optimum irrigation rates are used across the Midwest (Baker et al., 2012; Gehl et al., 2005; Quemada et al., 2013; Zhou and Butterbach-Bahl, 2014). A meta-analysis conducted by Zhou and Butterbach-Bahl (2014) showed slightly suboptimal fertilization rates resulted in the lowest nitrate leaching rates and corresponded with 90% of maximum maize yields, which was consistent with our findings despite their analysis not separating the observations by water management type (i.e., rainfed vs irrigated). This boost in productivity and reduction in nitrogen loss observed when maize is irrigated may help aid in the reduction of nitrogen export to regions like the Gulf of Mexico under future climate conditions if nitrogen fertilizer is not applied in excess. One example of this can be found in Ferin et al. (2023) in which modeled nitrogen leaching and downstream nitrogen export increased under rainfed maize and soybean in future climate conditions but was significantly reduced when maize productivity increased due to increasing the thermal time accumulation threshold to reach maturity under the same future climate conditions. While this study did not include irrigation, it shows that an increase in crop productivity may lead to increased nitrogen uptake and therefore has the potential to reduce nitrogen leaching. However, it is important to note that the predicted increase in the frequency of future extreme precipitation events may hinder this potential improvement in water quality and will need to be further investigated under an array of management and climate conditions.

Many other biophysical and environmental factors play a role in determining the fate of nitrogen from these fields (Shrestha et al., 2023). One example of this is that coarser soil textures are likely to increase nitrogen leaching under wetter climates and plant AWC conditions (Huang and Hartemink, 2020; Shrestha et al., 2023). This was observed in our model results over the Central Sands region of Wisconsin when irrigation triggered at 0.8 plant AWC was applied under the wet-warm and 30-year average climate conditions (Figs. 4a, S1, and S11e). Another key factor that has been shown to affect the potential for nitrogen leaching in agriculture fields is applying above the optimum rate of fertilizer (Scanlon et al., 2007; Shrestha et al., 2023). These are all factors that should be further explored in future work to better understand the implications that supplemental irrigation and a changing climate may have on the fate of nitrogen if above-optimal fertilizer rates are used.

4.3. Water use efficiency can aid in determining the optimal threshold for irrigation

In this study, both WUE and IWUE were used to aid in the determination of the optimal plant AWC threshold for irrigation to ensure that near maximum maize yields were attained but with the lowest possible irrigation amounts and the largest potential for nitrogen leaching reductions across the Midwest. Our results showed that WUE for irrigated maize was always greater than rainfed maize, coinciding with results from previous studies (Huang and Hartemink, 2020; Irmak and Sharma, 2015). This was more prominent in regions of the Great Plains where growing season total precipitations are low, but this pattern was also observed across the entire Midwest. The largest increase in WUE occurred when comparing rainfed to irrigated maize that was triggered by the 0.2 and 0.3 plant AWC thresholds. Our model results showed that as this irrigation threshold increased past 0.4 plant AWC, WUE began to plateau. As previously discussed, our simulations showed that the increase in maize yields due to increasing irrigation typically began to plateau around this same plant AWC threshold. The plateau of both yield and WUE as plant AWC thresholds got closer to 0.8 implies that ET is no longer increasing as more water is applied to the system and drainage and/or runoff are increasing. At these thresholds, the plant is no longer benefiting from the additional water through irrigation resulting in increased drainage and nitrogen leaching relative to plant AWC thresholds of 0.3 to 0.4, which is similar to previous findings (Gehl et al., 2005).

We used IWUE to identify the plant AWC threshold that best balances yield, irrigation, and nitrogen leaching under potential future climate conditions. Our results showed that IWUE decreased as plant AWC thresholds increased. This decrease in IWUE was due to a significant increase in irrigation coinciding with little to no yield gain as plant AWC thresholds increased. This rate of decline was more evident under the wet-warm climate conditions, implying that most rainfed regions of the Midwest could suffice with small amounts of applied irrigation under these climate conditions (i.e., the 0.2 plant AWC threshold). States with lower growing season precipitation are likely to always benefit from irrigation triggered at a higher plant AWC threshold under the wet-warm climate conditions, but this may not always be needed for states with soils that have higher water-holding capacities and greater growing season precipitation. IWUE in portions of Iowa, Illinois, and Wisconsin were much lower than in other portions of the Midwest (Fig. 7). Even though irrigation triggered at the lowest thresholds resulted in a very slight yield increase in these regions, this coincided with a reduction in nitrogen leaching (Figs. 3 and 5). Other portions outside of these specified regions however did see a greater increase in both yield and nitrogen leaching reductions when plant AWC threshold was near 0.3 to 0.4 without over-applying irrigation.

Under the dry-warm climate conditions, irrigation triggered at the 0.3 to 0.4 plant AWC threshold may become more beneficial for all regions of the Midwest. IWUE did decline as thresholds increased but at a much lower rate compared to wet-warm conditions (Fig. 4). Not only does irrigation provide a greater yield increase at the 0.3 to 0.4 threshold under these conditions but the reduction in nitrogen leaching is also substantially greater (Figs. 3 and 5). The regions of Iowa, Illinois, and Wisconsin that were previously mentioned in the wet-warm conditions benefit more from additional irrigation under the dry-warm conditions (Fig. 7). Both yield and nitrogen leaching reductions increase when irrigation is applied under these conditions at the plant AWC threshold of 0.3 to 0.4 (Figs. 3 and 5), implying that the optimal plant AWC threshold to trigger irrigation will be dependent on the climate conditions of that growing season.

This analysis may be useful in providing evidence to show the importance of irrigation under likely future climate conditions to achieve maximum yield increases without wasting water resources. However, we realize that not all land managers may be able to trigger irrigation at these specific plant AWC thresholds. For instance, economic decisions may drive farmers to apply even more irrigation especially if they are not responsible for the costs which may result in over-application beyond the optimal demand of the crop. Additionally, increasing irrigation rates is not the only way to increase WUE under future conditions. For instance, WUE may increase under future climates due to the indirect water savings from elevated carbon dioxide concentrations driven by the carbon dioxide fertilization effect and this should be included in future simulations that focus on the effects of crop productivity under a changing climate (Bagley et al., 2015; DeLucia et al., 2019; Ort and Long, 2014).

4.4. Limitations of this modeling framework

There are many limitations of the irrigation framework within Agro-IBIS which may impact the results of this study. For instance, irrigation in this model does not simulate water withdrawal from ground or surface water and therefore does not reduce water storage or drainage at the bottom of the soil profile. Additionally, Agro-IBIS does not consider plant ability to access ground water and achieve a subsidy in dry conditions. Irrigation in the model was applied to every grid cell and the duration of each irrigation event was the same. The model does not account for varied irrigation efficiency of different practices or how weather conditions may impact that value. This irrigation approach does not take into consideration potential limitations to water availability or capacity of farmers within each grid cell to invest in such management. Furthermore, we did not include an economic analysis component to this study and therefore limitations to associated costs of irrigation expansion and water availability were not considered but should be a focal point in future related studies.

Our study did not explore multiple ranges of fertilizer and manure application amounts beyond the dataset used in Donner and Kucharik (2008) and the EarthStat dataset. This may result in our modeling study predicting more optimistic reductions in nitrogen loss. Additionally, this study assumes nitrogen inputs are applied via a single broadcast event at planting and does not account for the additional nitrate that may be available in the irrigation water or through the practice of fertigation throughout a growing season which could potentially affect fertilizer application rates and the rate of nitrogen loss in these systems.

Simulations in this study focused on categorizing historical weather data from the past 30 years in which we selected the wet-warm and dry-warm conditions to act as future conditions. By not including future Global Climate Model (GCM) projections, our study may not be encompassing a full range of potential future conditions which may result in different modeling outcomes for irrigation amounts, maize yield, and nitrogen leaching.

5. Conclusions

By conducting multiple simulations using an agroecosystem model to simulate maize growth under both rainfed and irrigated conditions triggered by a range of plant AWC thresholds across the Midwest US, this study was able to assess the effects of irrigation expansion on maize yield and nitrogen leaching for multiple weather conditions (i.e., wet-warm, dry-warm, 30-year average climate). Key findings from this analysis show that the optimal plant AWC threshold to trigger irrigation across the Midwest under an array of climate conditions is likely between 0.3 and 0.4, which may result in increased yield and reduced nitrogen leaching if irrigation is expanded across the entire Midwest. Future work should focus on modeling under an array of future climate conditions from multiple GCM projections while including the representation of reproductive heat stress to better represent changes in crop productivity (Ferin, 2020; Heinicke et al., 2022; Siebert et al., 2014; Webber et al., 2018), conducting simulations for above-optimal fertilizer rates to better understand the potential implications of irrigation expansion on nitrogen leaching in future conditions, and including in-depth economic analyses to assess the associated costs in regards to different methods of irrigation that take water resource limitations into consideration (i.e., recycled or reclaimed water) (Hejase et al., 2022; Willison et al., 2021). As climate continues to change and weather variability increases, farmers will likely face challenges in adapting sustainable farm management practices to meet the increasing demands of future crop production while also achieving water quality improvement goals. While these challenges are likely beyond their control, this work along with future studies will help to make more informed decisions on the landscape.

CRediT authorship contribution statement

Kelsie M. Ferin: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Christopher J. Kucharik:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Christopher J. Kucharik reports financial support was provided by National Science Foundation.

Data availability

Data will be made available on request.

Acknowledgments

This work was supported by the National Science Foundation (NSF) Innovations at the Nexus of Food, Energy, and Water Systems (INFEWS) program [grant numbers 1855996; 1855937].

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2024.104055.

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