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Co-regulation of temperature and moisture in the irrigated agricultural ecosystem productivity

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ABSTRACT

Agroecosystem photosynthesis is key to coping with global climate change. In farmland where human activities are highly involved, the interaction between environmental factors and their influences on gross primary productivity (GPP) are insufficiently understood. Particularly, the irrigation and mulching in water-saving agriculture can alter the crop responses to environmental change. Based on eddy covariance measurements of maize fields under mulched drip irrigation (DM) and mulched border irrigation (BM) in arid areas of Northwest China from 2014 to 2018, we systematically studied the interaction between multiple environmental factors and their independent effects on GPP using structural equation modeling, partial correlation coefficient and decoupling analysis by bins. The top three factors exerting the largest total effects on the GPP were soil temperature (Ts), canopy temperature (Tc) and vapor pressure deficit (VPD), among which Ts (0.75) and Tc (0.66) had the largest total effect on GPP under DM and BM, respectively. The independent effects of Ts, soil water content (SWC) and VPD on GPP were different under the two irrigation methods. SWC after excluding the influence of Ts showed a negative effect on GPP under DM (−1.24 g $Cm^{-2}d^{-1}$), while a positive effect under BM (0.02 g $Cm^{-2}d^{-1}$). By contrast, SWC after excluding the influence of VPD showed a positive effect on GPP under DM (0.59 g $Cm^{-2}d^{-1}$), while a negative effect under BM (−0.05 g $Cm^{-2}d^{-1}$). Interestingly, higher Ts, lower SWC and higher VPD had the potential to increase GPP under the two irrigation methods. We also found that the total effects of irrigation and VPD as well as the indirect effects of environmental factors on GPP should not be ignored. Our study will provide important reference for dealing with the effect of high temperature and drought stress on agro-ecosystem GPP and evaluating the response of vegetation to environmental factors.

1. Introduction

CO_2 is the most important greenhouse gas that exacerbates global climate, while vegetation photosynthesis is an effective way to absorb CO_2. Farmland ecosystems account for a large proportion of land areas, and so that their CO_2 exchange plays an important role in the total CO_2 budget in terrestrial ecosystems (Li et al., 2018). Irrigation is an important practice in agricultural management to guarantee grain production in arid regions (Döll and Siebert, 2002; Kang et al., 2017; Yang et al., 2018). Mulched drip irrigation (DM) and mulched border irrigation (BM) are typical water-saving irrigation methods in the arid areas of Northwest China (Qin et al., 2018).

In recent decades, as water shortages is worsened increasingly, the promotion of DM has become a national water-saving strategy, and a large area of traditional BM will be replaced by DM (Guo et al., 2021). Compared with BM, DM changes the infiltration mode of irrigation water, reduces the deep drainage, and significantly affects the field water, energy and microclimate environment (He et al., 2018; Zotarelli et al., 2009), which will regulate crop growth and affect the absorption of CO_2 flux. Therefore, studying how biophysical conditions control farmland CO_2 fluxes under different mulching irrigation management practices has will have profound implications for agriculture irrigation

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strategies in arid regions across the world.

Many studies have pointed out that irrigation (I), precipitation (P), soil water content (SWC), soil temperature (Ts), canopy temperature (Tc), and vapor pressure deficit (VPD) affect gross primary productivity (GPP) (Gimenez et al., 2019; Hu et al., 2019; Li et al., 2019a). Different environmental factors interact with each other, thus further complicating the impact of environmental factors on GPP, especially in ecosystems having human interference. Therefore, studies on the influencing factors of plant CO_2 uptake mainly focus on the grassland ecosystem and forest ecosystem rather than the farmland ecosystem with agricultural management measures (Fonseca et al., 2019; Quan et al., 2019; Reich et al., 2018). Most of the existing studies on influencing factors of carbon flux in farmland ecosystems only analyzed the correlation between a single factor and GPP, but few studies separated the direct and indirect effects on GPP from the synergistic changes of different environmental factors (Li et al., 2006; Qin et al., 2018).

With more and more attention paid to global warming, despite many studies try to reveal the feedback direction of carbon flux under temperature rise, no final conclusion has been reached so far (Crowther et al., 2016; Dorangeville et al., 2016; Zhang et al., 2017). Some studies have pointed out the important contribution of temperature to GPP (Dang et al., 2022; Nemani et al., 2003), but others have concluded that SWC plays an important role in GPP (Green et al., 2019; Liu et al., 2020). Higher temperature can promote plant photosynthesis, while lower SWC will reduce the rate of CO_2 assimilation (Reich et al., 2018). However, higher temperature often corresponds to lower SWC (Koster et al., 2006; Seneviratne et al., 2010). Therefore, it is important to separate the relative importance of Ts and SWC for GPP. A large number of studies have shown that SWC plays a regulatory role in the feedback of carbon flux to temperature rise (Quan et al., 2019; Schindlbacher et al., 2012), especially in forests and meadows (Dorangeville et al., 2016; Quan et al., 2019; Reich et al., 2018). However, in different ecosystems and vegetation types, the relative importance of Ts and SWC to GPP varied (Dang et al., 2022). In particular, the relationship between Ts and SWC becomes complicated in farmland ecosystems under mulching and irrigation management. In this case, the independent effects of Ts and SWC on GPP in irrigated and mulched fields haven't been fully analyzed.

Climate warming can lead to drought, including soil drought and atmospheric drought, which can have an impact on plant photosynthesis (Madadgar et al., 2017; Novick et al., 2016; Reichstein et al., 2002; Sulman et al., 2016). Studies have shown that high VPD could limit plant photosynthesis (Liu et al., 2020; Markow, 1979; Sulman et al., 2016; Williams et al., 2012), and that low SWC can also affect plant photosynthesis (Reich et al., 2015), but negative effects of VPD on GPP may be moderated by SWC (Kimm et al., 2020; Sulman et al., 2016). Some studies even suggested that VPD may have a greater effect on carbon flux than SWC (Sulman et al., 2016; Wong et al., 1979). The individual effects of SWC and VPD on GPP remain unclear due to their coupling effect (Liu et al., 2020; Novick et al., 2016). However, disentangling the relative importance of VPD and SWC on GPP in agricultural production will have important implications for managing drought risks in agricultural practices (Liu et al., 2020).

Therefore, in this study, we obtained detailed measurements of water, heat, and carbon fluxes in the maize fields under DM and BM in Northwest China from 2014 to 2018. We first evaluated the direct and indirect effects of environmental factors on GPP using structural equation models, and further quantified independent effects of Ts vs. SWC and SWC vs. VPD on GPP. Specifically, we address the following questions: (1) is there a contrasting pattern for these effects between two irrigation management? (2) what are direct and indirect effects of environmental factors on GPP under DM and BM? (3) what is the relative importance of Ts vs. SWC and VPD vs. SWC on GPP under DM and BM?

2. Materials and methods

2.1. Experimental site description

The experiments on maize fields were carried out from 2014 to 2018 in the National Field Scientific Observation and Research Station on Efficient Water Use of Oasis Agriculture (37°52'N, 102°50'E, 1581 m) in Wuwei City, Gansu Province, Northwest China. The experimental fields were located in the region with typical continental temperate climate, characterized with abundant light and heat resources, high evaporation and low rainfall (Qin et al., 2018; Wang et al., 2020b). Such an environmental condition provides good living environment for maize production (He et al., 2018).

Experimental study on two irrigation methods (i.e., DM and BM) was carried out, applying the style of cropping of "one film, and four rows of maize". The ratio of film mulching was 0.74. The ratio of female parents to male parents was 6:1. Seeding, film mulching, laying drip irrigation belts and harvest were mechanized. Under the DM treatment, two drip irrigation belts were laid under a plastic film and the irrigation water flowed out from the dripper in the form of point source and directly poured near the maize root. From 2014 to 2018, the irrigation methods with less amount and more frequency were used under DM, and the irrigation times were 7, 8, 8, 7 and 8, respectively. Under the BM treatment, irrigation water in the maize field penetrated into soil from bottom to top in the form of non-point source. From 2014 to 2018, the irrigation methods with more amount and less frequency were used under BM, and the irrigation times were 4, 5, 4, 6, and 5, respectively. The irrigation times were slightly adjusted according to the weather and crop growth conditions of the year under two irrigation methods.

Two eddy covariance (EC) systems were set up in maize fields with DM and BM to continuously observe water, heat and carbon fluxes. A 2-meter-high automatic weather station was installed near the experimental field. Meteorological measurements such as precipitation (P)

Table 1
List of observation items and instruments in maize fields under DM and BM.

No	Measurement variables	Instruments	Frequency	Treatment
1	Three dimensional wind speed	3d ultrasonic anemometer (CSAT3, USA)	0.1 s	DM (2014–2018) BM (2014–2018)
2	Water and carbon density	Open-path infrared gas analyzer (EC150, USA)	0.1 s	DM (2014–2018) BM (2015–2018)
3	Water vapor deficit	Air temperature and humidity sensor (HMP155A, Finland)	10 min	DM (2014–2018) BM (2014–2018)
4	Canopy temperature	Infrared temperature sensor (SI-111, USA)	10 min	DM (2016–2018) BM (2016–2018)
5	Soil temperature	Soil temperature sensor (109 L, USA)	10 min	DM (2014–2018) BM (2014–2018)
6	Soil water content	Soil water sensor (CS616, USA)	10 min	DM (2014–2018) BM (2014–2018)
7	Irrigation	Water meter		DM (2014–2018) BM (2014–2018)
8	Precipitation	Automatic weather station (H21001, USA)	15 min	DM (2014–2018) BM (2014–2018)

were recorded by the weather station. The specific measurement variables and corresponding instruments were shown in Table 1. Growth seasons of maize under DM and BM from 2014 to 2018 were shown in Appendix 1. The meteorological data during the growth period of maize under DM and BM from 2014 to 2018 were shown in Table 2.

2.2. EC flux data processing

The EC flux data was processed with Eddy Pro 4.0 software. For the purpose of data processing, we used the linear interpolation method for missing data from fewer than four points, but the MDV (mean diurnal variation) method otherwise (Falge et al., 2001). Gross primary productivity (GPP) was calculated as the difference between ecosystem respiration (ER) and net ecosystem exchange (NEE). GPP at night was assumed as 0 since no photosynthesis happened. The calculation of daytime GPP required daytime ER, which was obtained with the fitted model after applying the nighttime ER data to the respiratory model. Finally, NEE and ER were used to calculate GPP. Here we choose the commonly used Van't Hoff model to obtain the ER value. The Van't Hoff model is calculated by the following formula (Collatz, 1991):

$$ER = ER_{ref} \times exp\left[B(T - T_{ref})\right] \tag{1}$$

where ER_{ref} (g Cm^{-2}) is the reference ER (g Cm^{-2}) at 10 °C, B is the regression parameter, T is the surface temperature (°C) and T_{ref} is the reference surface temperature at 10 °C.

The estimation of parameters applied the short-term temperature-dependent method proposed by Reichstein et al. (2005), which was mainly divided into two steps. In the first step, nighttime CO_2 flux data was divided into a 15-day window and sliding at an interval of 5 days. B was used to fit each set of data, and the reciprocal of standard error was used as a weighting factor to average all fitted B to obtain the final B value. Second, fix the B value obtained in the first step, used ER_{ref} to fit each group of data, then got the ER_{ref} value of each group of data, and then got the daily ER_{ref} value through linear interpolation fitting.

2.3. Crop growth data

Eight representative plants were selected from the experimental field every 7–10 days in the whole growth period. The SPAD value represents the relative content of chlorophyll in leaves, which can indirectly reflect the content of nitrogen in leaves. We used a portable chlorophyll meter (SPAD-502 PLUS, Konica Minolta, Japan) to measure the SPAD values of all the leaves of each maize plant sampled each time, to obtain the average as the relative chlorophyll content of that plant. When the canopy coverage (CC) of maize reached 80%, the surface temperature data taken by the infrared temperature sensor in the farmland could be considered as the canopy temperature (Tc) of maize (DeJonge et al., 2015). Therefore, to obtain Tc, we segmented the surface temperature with the canopy cover (CC). In this study, canopy cover was transformed by LAI. LAI (m^2 m^{-2}) (Guo et al., 2019) and CC(%) (Hsiao et al., 2009) were calculated using the following formula:

$$LAI = 0.74 \times \frac{\left(\sum_{i=1}^{n} L_i \times W_i\right)}{D \times S} \tag{2}$$

$$CC = 1.005(1 - e^{-0.6LAI})^{1.2} \times 100\% \tag{3}$$

where *0.74* is an empirical constant, *Li* (m) is the length of the leaf, *Wi* (m) is the width of the leaf, and *D* (m) and *S* (m) are the distance between two rows and the space between two plants, respectively. In this experiment, *D* and *S* are 0.25 m and 0.22 m, respectively.

Since the infrared temperature sensor was installed in 2016, the Tc was only available from 2016 to 2018. The surface temperature of the whole growth period under DM and BM during 2016–2018 was shown in Table 2. The seasonal variation of Tc under DM and BM from 2016 to 2018 were shown in Fig. 1.

Table 2
Meteorological data during the growth period of maize under DM and BM from 2014 to 2018.

Treatment	Year	Irrigation mm	Precipitation mm	Wind speed $m\ s^{-1}$	Surface temperature °C
DM	2014	350.00	195.40	1.72	
	2015	400.00	119.40	1.79	
	2016	426.82	115.40	1.87	19.63
	2017	368.28	134.00	1.70	20.36
	2018	421.92	156.40	1.54	20.29
	Mean	393.40	144.12	1.72	20.09
BM	2014	360.00	201.20	1.68	
	2015	550.00	150.60	1.42	
	2016	480.00	118.80	1.59	19.17
	2017	600.00	132.80	1.54	19.07
	2018	525.00	156.40	1.55	19.28
	Mean	503.00	151.96	1.56	19.17

2.4. Statistical analysis

2.4.1. Significance analysis and structural equation model

Significance analysis between data groups was performed using SPSS for Windows Software (Version 21.0, SPSS Inc., Chicago, IL, USA). The structural equation models (SEM) were output by the AMOS model (Version IBM SPSS Amos 22.0). AMOS model is a graphical modeling software, which can determine the relationship between variables in an intuitive path diagram and analyze the degree of correlation between variables. Considering some data might be missing over a long period, we selected the data from 2016 to 2018 available for all factors for analysis. The causal networks of SEM are based on existing knowledge and only consider the significant effects among factors. We chose Comparative Fit Index (CFI) and Tuck-Lewis Index (TLI) for model evaluation. The specific calculation method could be found in Hu and Bentler (1999). When CFI was greater than 0.95 and TLI was greater than 0.90, the results of the model were satisfactory (Fan et al., 2016).

2.4.2. Partial correlation coefficient

In this study, we applied the partial correlation coefficient to calculate the independent linear influence of each parameter on GPP under SWC and Ts combination and under SWC and VPD combination, respectively. R (Ts, GPP|SWC) represents the correlation between Ts and GPP excluding the influence of SWC. Likewise, we also calculated the R (SWC, GPP|Ts), R (VPD, GPP|SWC), and R (SWC, GPP|VPD). The calculation formula is as follows (Dang et al., 2022):

$$R\quad(1,\ 2|3) = \frac{R_{12} - R_{13} \times R_{23}}{\sqrt{1 - R_{13}^2} \times \sqrt{1 - R_{23}^2}} \tag{4}$$

where *R (1, 2|3)* is the partial correlation coefficient between variable 1 and variable 2 after controlling for the linear effect of variable 3; R_{12}, R_{13}, and R_{23} are correlation coefficients between variable 1 and variable 2, variable 1 and variable 3, and variable 2 and variable 3, respectively.

2.4.3. Decoupling analysis by bins

The method of decoupling by separate bins will not change the relative influence of factors on GPP, and can better compare the relative influence of factors after separation (Dang et al., 2022; Liu et al., 2020). The data was divided into 8 equal numbers of bin by the ascending order of Ts, and determined the boundary points of each bin. The same rule was applied to SWC. After that, we would make segmentation according to the boundary point of SWC in each Ts bin, sum the differences in GPP from high SWC to low SWC at each segmentation and then divide by the number of SWC segments in this Ts bin. Hence, the SWC influence on

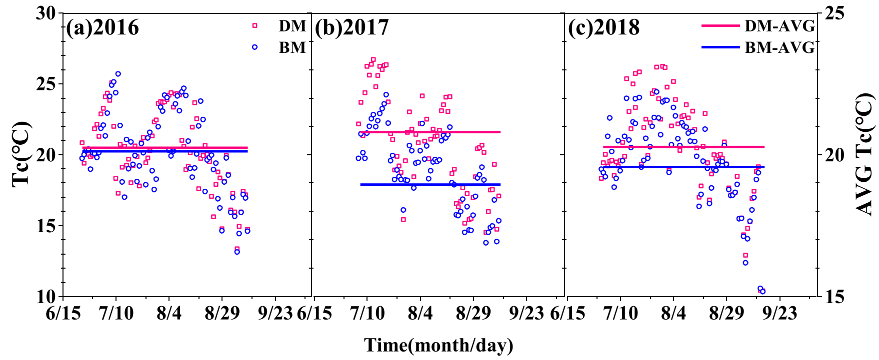

Fig. 1. The seasonal variation of Tc under DM and BM from 2016 to 2018. The red and blue dots represent the Tc under DM and BM, respectively, and the red and blue lines represent the average Tc (AVG Tc) under DM (DM-AVG) and BM (BM-AVG), respectively.

GPP considering Ts and SWC decoupling was obtained in each Ts bin (denoted as ΔGPP (SWC|Ts)). The data from fewer 5 groups after segmentation were eliminated and binning and segmentation would not change the corresponding relationship between Ts, SWC and GPP. The calculation formula is as follows (Dang et al., 2022; Liu et al., 2020):

$$\Delta GPP\ (SWC|, Ts) = \frac{1}{I}\sum_{i=1}^{I}\left(GPP_{i,n_{i,max}} - GPP_{i,n_{i,min}}\right) \quad (5)$$

where I is the number of SWC segmentations in Ts bin, i is the specific SWC segmentation number, $n_{i,max}$ and $n_{i,min}$ is the maximum and minimum of SWC, respectively. Equally, we also calculated ΔGPP (Ts|SWC), ΔGPP (SWC|VPD) and ΔGPP (VPD|SWC).

3. Results

3.1. Inter-annual variability of Ts, SWC and VPD

The annual mean Ts (0–20 cm), SWC (0–20 cm) and VPD of maize fields under DM and BM from 2014 to 2018 were shown in Fig. 2. During 2015–2018, the annual mean Ts under DM was higher than that under BM, while in 2014, the annual mean Ts under DM was lower than that under BM (Fig. 2(a)), possibly due to the disturbance of the soil where the probe was located by the agronomic management measures in 2014. From 2014 to 2018, there were significant differences in daily Ts between DM and BM ($p < 0.05$), and the annual mean Ts under DM was 20.35 ℃, which was significantly higher than that under BM (19.58 ℃) ($p < 0.05$).

The annual mean SWC under DM and BM from 2014 to 2018 was shown in Fig. 2(b). DM had a higher irrigation frequency but a smaller irrigation amount than BM, so it saw a smaller fluctuation in SWC accordingly. Since soil temperature and soil moisture sensors were installed at the same position, the annual mean SWC under DM in 2014 was 0.17 $cm^3\ cm^{-3}$, slightly lower than that under BM (0.18 $cm^3\ cm^{-3}$). From 2015 to 2018, the annual mean SWC of maize field during the growth period under DM was significantly higher than that under BM ($p < 0.05$). Although the irrigation amount of BM was larger, there were more deep drainage. Therefore, the 5-year mean SWC was 0.22 $cm^3\ cm^{-3}$ under DM, which was higher than 0.20 $cm^3\ cm^{-3}$ under BM.

The annual mean VPD under DM and BM from 2014 to 2018 was shown in Fig. 2(c). Due to failure of the instruments, some data were missing for the whole growth period of 2016 in the maize field under BM. Therefore, VPD in 2016 only showed data that existed simultaneously on the same day after sowing under both irrigation methods. VPD of the whole growth period of maize in 2018 under DM was slightly lower than BM, but not significantly ($p > 0.05$). From 2014 to 2018, the annual mean VPD under DM (1.46 KPa) was significantly higher than that under BM (1.38 KPa) ($p < 0.05$).

3.2. Relationships between environmental factors and GPP

The seasonal variation of GPP in the growth period of maize under DM and BM were shown in Fig. 3. We found that the maximum value of GPP appeared in the middle growth stage of maize under both irrigation methods. The difference in GPP between the two irrigation methods mainly happened in the late seedling stage and the jointing stage. During the two stages, the growth status of maize under DM was better than that under BM, and the photosynthetic capacity of maize under DM was higher than that under BM. The GPP saw little difference at the later growth stage of maize under DM and BM. The mean GPP under DM and BM during the whole growth period of maize was 1351.44 g Cm^{-2} and 1323.03 g Cm^{-2}, respectively.

The changes of daily GPP with Ts, SWC and VPD during the growth period of maize under the two irrigation methods were shown in Fig. 4. The larger value of GPP appeared in company with higher Ts, while no

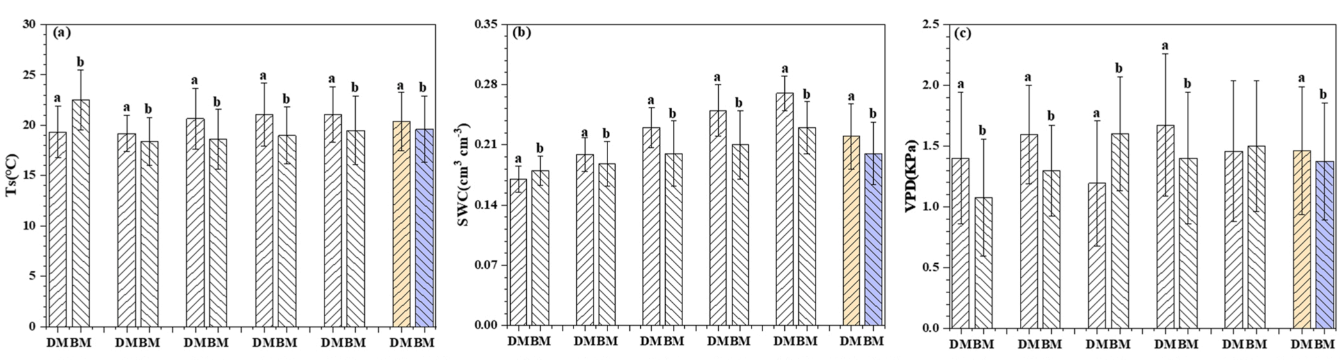

Fig. 2. The annual mean Ts, SWC and VPD under DM and BM from 2014 to 2018. The letters a and b above error bars represent significant differences between DM and BM in the same year for the daily scale data ($P < 0.05$). The error bar represents the standard deviation of daily data for each year.

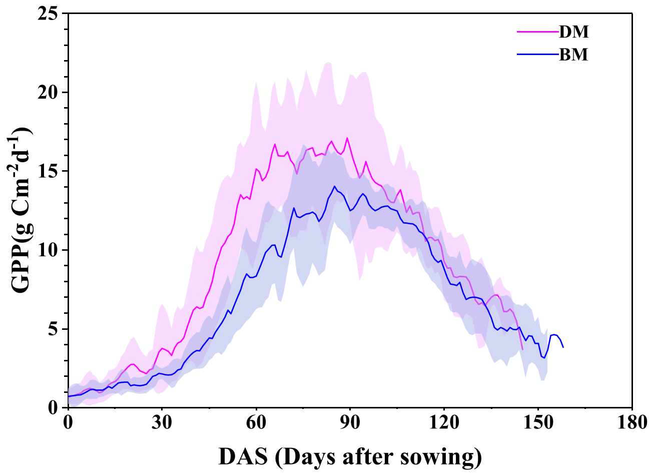

Fig. 3. The seasonal variation of GPP in the growth period of maize under DM and BM. The pink line is the mean of the smoothed GPP and the pink shade is the standard deviation range under DM from 2014 to 2018. The blue line is the mean of the smoothed GPP and the blue shade is the standard deviation range under BM from 2015 to 2018.

obvious change was observed in SWC, possibly due to the effect of mulching film on Ts and SWC under both water-saving irrigation measures. Both irrigation methods adopted full irrigation, so that GPP did not show the limiting effect in the case of high VPD. The distribution of GPP and VPD were similar in the whole growth period of maize under the two irrigation methods. Ts and SWC under DM were more found in the range of higher values that those under BM.

3.3. *Direct and indirect effects from environmental factors*

We used SEM to analyze the effects of irrigation (I), precipitation (P), SWC, Ts, Tc and VPD on GPP, and the constructed SEM were shown in Fig. 5. We selected the time when each factor co-existed and analyzed 242 and 231 groups of samples from DM and BM during 2016–2018, respectively. On the prerequisite of ensuring the number of samples, the effects of environmental factors on GPP were analyzed under DM and BM, and the results were shown in Fig. 6.

Ts, Tc and VPD had greater influence on the total GPP than other variables under DM and BM. The total effects of Ts, Tc and VPD on GPP under DM were 0.75, 0.32 and 0.17, respectively, and those under BM were 0.53, 0.66 and 0.17, respectively. I, P, Ts, SWC and Tc had an indirect effect of 0.11, − 0.05, 0.27, 0.05 and 0.11, respectively on GPP under DM, while I, P, Ts and Tc had an indirect effect of 0.11, − 0.07, 0.53 and 0.08, respectively on GPP under BM. The analyzed influencing factors could explain the GPP of 0.61 and 0.47 for maize under DM and BM, respectively. Therefore, the irrigation method could change the interaction between environmental factors and their effects on GPP, and DM had more ability to promote crop photosynthesis than BM among the limited environmental factors we analyzed.

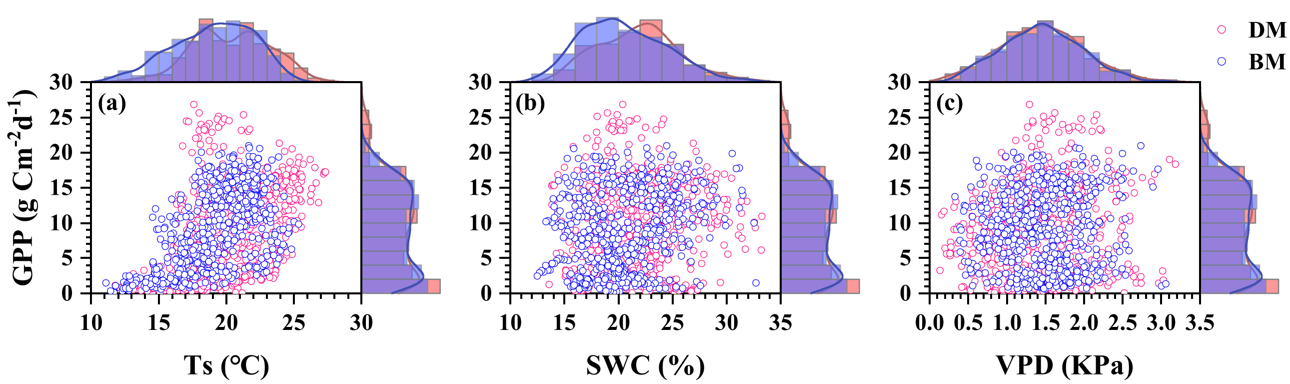

Fig. 4. The changes of daily GPP with Ts, SWC and VPD during the growing period of maize under DM and BM. The histograms at the top and right show the distribution of parameters in horizontal and vertical coordinates, and the fitting lines represent the distribution of kernel density. Red and blue represent DM and BM respectively.

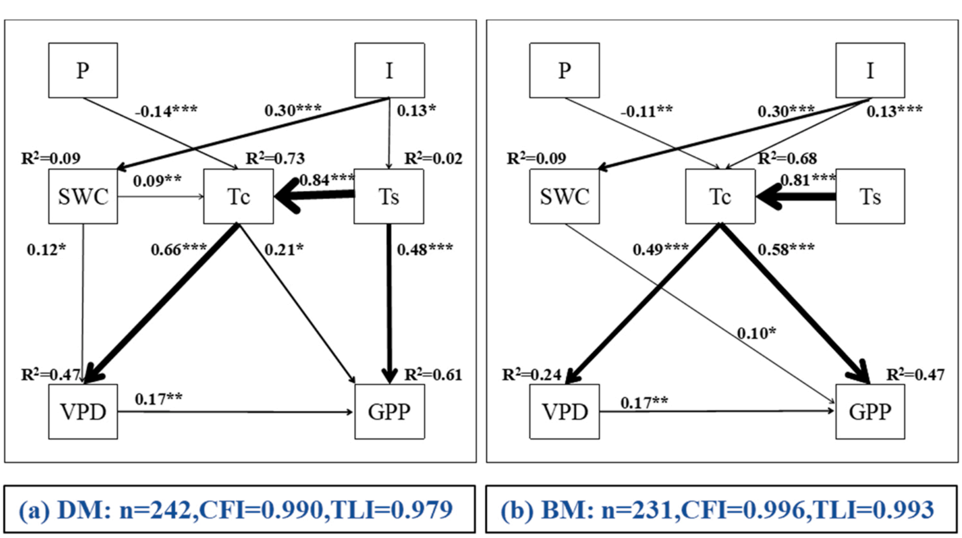

Fig. 5. The structural equation models (SEM) of the environmental factors of GPP under DM and BM. I: irrigation, P: precipitation, SWC: soil water content, Ts: soil temperature, Tc: canopy temperature, VPD: vapor pressure deficit, GPP: gross primary productivity. n is the number of data groups, and Comparative Fit Index (CFI) and Tuck-Lewis Index (TLI) as model evaluation indices. *Note: The larger the width of the arrow, the greater the direct effect of the two factors. The number on the arrow represents the direct influence between the two factors, and the number of asterisks represents the level of significance between the two factors. Only the significant influence between factors is considered in the model ($p < 0.05$).*

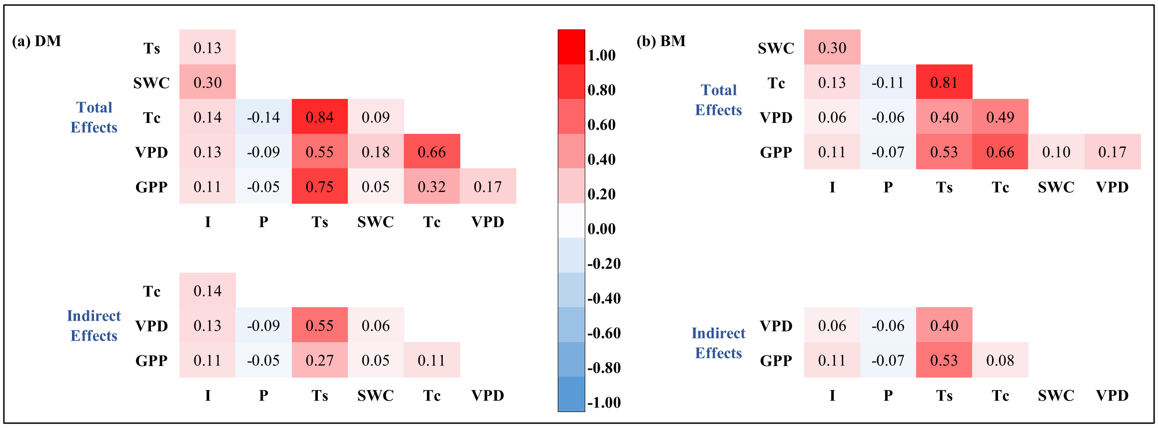

Fig. 6. Total and indirect effects of environmental factors on GPP under DM and BM. The color bar means the greater the effects, the darker the color.

3.4. Decoupling of Ts, SWC and VPD impacts on GPP

In order to better explain the independent influence of Ts, SWC and VPD on GPP, we calculated the partial correlation coefficients under DM and BM, and the results were shown in Table 3. R (VPD, GPP|SWC) and R (SWC, GPP|VPD) under DM were 0.15 and 0.10, respectively ($P < 0.05$). R (Ts, GPP|SWC) and R (SWC, GPP|Ts) under BM were 0.57 and 0.24, respectively ($P < 0.05$). R (Ts, GPP|SWC) under DM and R (SWC, GPP|VPD) under BM were 0.39 and 0.25, respectively ($P < 0.05$). However, the results for R (SWC, GPP|Ts) under DM and R (VPD, GPP|SWC) under BM were not credible ($P > 0.05$). Therefore, based on the partial correlation coefficients, VPD had a greater independent influence on GPP than SWC under DM, and Ts had a greater independent influence on GPP than SWC under BM.

We decoupled the effects of Ts vs. SWC and VPD vs. SWC on GPP by bins to more clearly reveal the nonlinear independent influence of parameters on GPP, and the results were shown in Fig. 7. Decomposed effects of Ts vs. SWC, and VPD vs. SWC on GPP for each bin were shown in Appendix 2. In both water-saving irrigation management measures, the median of ΔGPP (Ts|SWC) was greater than that of ΔGPP (SWC|Ts), and the median of ΔGPP (VPD|SWC) was greater than that of ΔGPP (SWC|VPD). However, the median of ΔGPP (Ts|SWC) under DM was 1.39 g $Cm^{-2}d^{-1}$ higher than 0.99 g $Cm^{-2}d^{-1}$ under BM. The median of ΔGPP (SWC|Ts) was negative under DM (−1.24 g $Cm^{-2}d^{-1}$), but a weak positive value under BM (0.02 g $Cm^{-2}d^{-1}$). The median of ΔGPP (VPD|SWC) was positive under both DM and BM (0.89 g $Cm^{-2}d^{-1}$ and 0.74 g $Cm^{-2}d^{-1}$, respectively). However, the median of ΔGPP (SWC|VPD) was positive under DM (0.59 g $Cm^{-2}d^{-1}$) while negative under BM (−0.05 g $Cm^{-2}d^{-1}$).

Table 3
The partial correlation coefficients of Ts, SWC and VPD to GPP under DM and BM, respectively.

Category		DM		BM	
		Partial correlation coefficient	P	Partial correlation coefficient	P
A	R (Ts, GPP|SWC)	0.39	0.000	0.57	0.000
	R (SWC, GPP|Ts)	-0.02	0.664	0.24	0.000
B	R (VPD, GPP|SWC)	0.15	0.000	0.05	0.292
	R (SWC, GPP|VPD)	0.10	0.013	0.25	0.000

4. Discussion

4.1. Major environmental factor controlling on GPP under different irrigation strategies

The influence of environmental factors on GPP was different under the two irrigation methods (Fig. 5). This indicated that irrigation methods could alter abiotic conditions and thereby affect the growth status and photosynthetic characteristics of crops (Abd El-Mageed et al., 2022; Ge et al., 2022; Wang et al., 2022). The important effect of temperature on GPP has been pointed out in many studies (Dold et al., 2017; Li et al., 2006; Qin et al., 2018). The main driving factor of GPP under DM and BM was Ts and Tc, respectively, in our study (Fig. 6). The main reasons for different influencing factors in the two irrigation methods could be: (1) DM provided a more suitable Ts for the growth of maize (Fig. 2), while BM had no significant effect on maize photosynthetic capacity, which was directly affected by Ts. Under DM, SPAD and LAI of maize were higher than those under BM (Appendix 3). SPAD, as a status indicator of nitrogen content (Li et al., 2019b; Yue et al., 2020), which could reflect that Ts under DM could promote root absorption of nitrogen and the growth of maize, to improve the photosynthetic capacity of maize as a result (Wang et al., 2021a). (2) Tc has been confirmed to act on GPP by affecting leaf stomata (Huang et al., 2019a; Lloyd and Farquhar, 2008; Park Williams et al., 2012). In our study, under both irrigation methods, Tc had a direct and significant effect on GPP, but it had a greater effect under BM. Tc under BM was lower than that under DM (Fig. 1), indicating that the plant water content was higher under BM, thus to promote photosynthesis (Prasad et al., 2011).

In addition, SWC indirectly affected GPP through influencing Tc and VPD under DM, while SWC acted directly on GPP under BM. Because the frequent wetting and drying of soil under DM would affect maize root uptake, which was reflected in Tc (Chaves et al., 2003), and also affect soil evaporation and thus have an impact on local VPD. However, BM had a lower irrigation frequency but more deep drainage (Deng et al., 2006; Wang et al., 2020a), so that SWC had no significant influence on Tc and VPD. SWC was less, and the response of crop growth to SWC was more significant under BM than those under DM (Fig. 6), possibly attributed to the fact that moderately low water level could promote photosynthesis in plants (Lu et al., 2022).

Tc had an indirect effect on GPP by influencing VPD under DM and BM (Figs. 5–6). This was because Tc affected the stomatal opening and closing of leaves (Fukuda et al., 2018; Tan, 1993), which changed canopy vapor pressure through affecting plant transpiration and thus had an impact on the VPD, which would also affect inflow and outflow of CO_2 flux in the plants (Olivo et al., 2009). Existing studies have shown that high VPD could reduce stomatal conductance and xylem conductance of plants, thus limiting plant photosynthesis (McDowell et al., 2008;

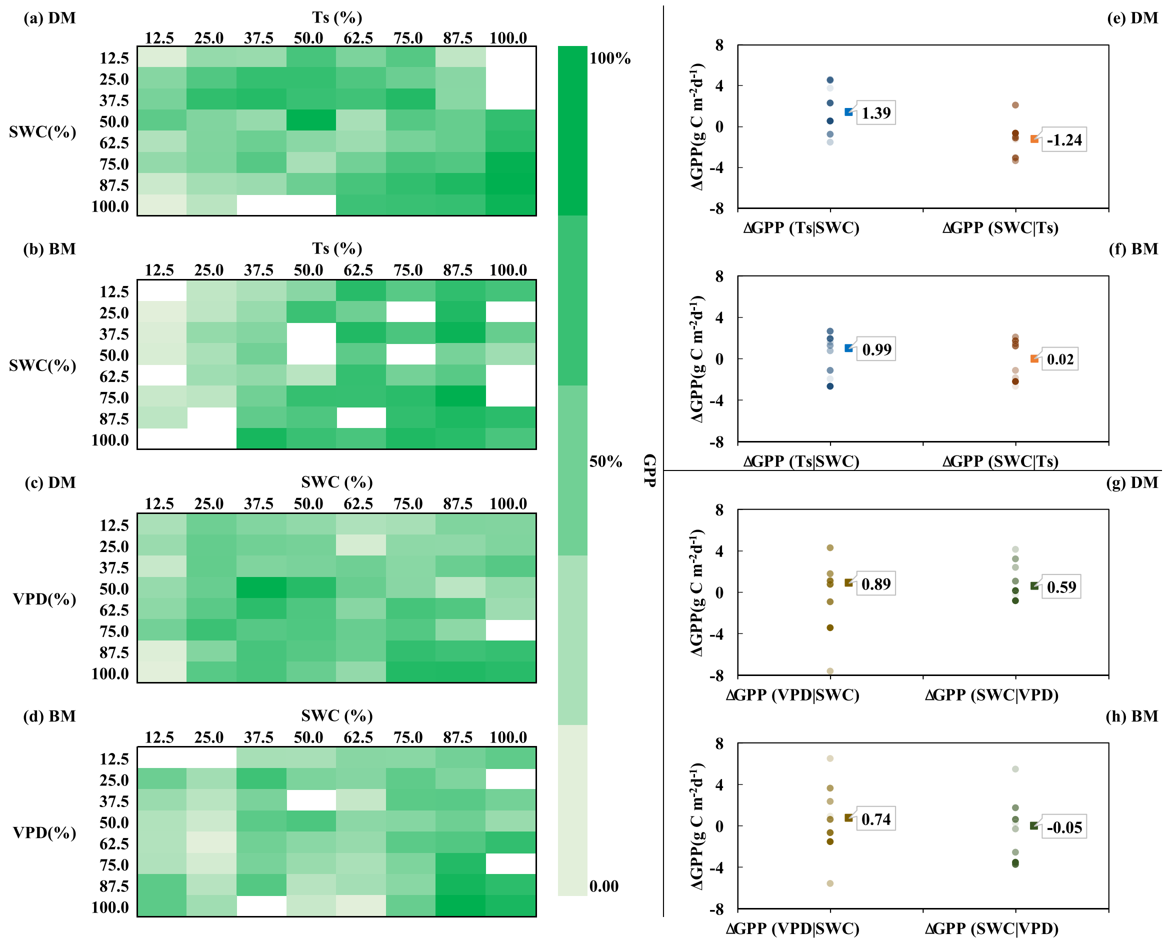

Fig. 7. Disentangling the effects of Ts vs. SWC and VPD vs. SWC on GPP. (a) and (b) are the mean GPP in each percentile bin of Ts and SWC under DM and BM, respectively. (c) and (d) are the mean GPP in each percentile bin of SWC and VPD under DM and BM, respectively. (e) and (f) are the distribution of ΔGPP (Ts|SWC) and ΔGPP (SWC|Ts) under DM and BM, respectively. (g) and (h) are the distribution of ΔGPP (VPD|SWC) and ΔGPP (SWC|VPD) under DM and BM, respectively. Circles denote the ΔGPP (Ts|SWC), ΔGPP (SWC|Ts), ΔGPP (VPD|SWC) and ΔGPP (SWC|VPD) in each bin and squares denote the corresponding median. *Note: the darker the color in a – d is, the greater the average GPP in that percentile bin and the darker the color in e – h is, the larger the percentile bin of the exclusion factor.*

Novick et al., 2016; Yuan et al., 2019a). However, both of our two irrigation methods applied full irrigation, which made VPD relatively low, so they both had a positive effect on GPP (0.17).

4.2. Disentangling the relative role of Ts, SWC and VPD on GPP under different irrigation strategies

The relative independent contributions of Ts, SWC and VPD to GPP in binning were consistent with the conclusions of partial correlation coefficients and SEM under DM and BM. Our study found that dominant effect of Ts on GPP was greater than that of SWC under the two irrigation methods, which was the same as conclusions at the global scale drawn by Dang et al. (2022). In our experiment, film mulching increased the mean Ts and reduced the damage of low Ts at night to crops, which might have expanded the promoting effect of Ts on crop growth. However, Dang et al. (2022) pointed out that SWC had a greater impact on GPP in arid and semi-arid areas, which was inconsistent with our conclusions, possibly because his study failed to consider irrigated fields with mulch could ensure sufficient SWC. Studies have shown that under high SWC availability, higher temperature could improve the net photosynthetic capacity of maize and other angiosperms (Korner, 2015; Reich et al., 2018).

VPD can greatly affect the carbon sequestration capacity of ecosystems (Pan et al., 2011), which was often ignored in research (Jin et al., 2018; Matheny et al., 2014). The conclusion that VPD had more influence on GPP than SWC was consistent with that of many other studies (Kimm et al., 2020; Sulman et al., 2016). This may be related to the fact that our irrigation method was full irrigation, which had a relatively small fluctuation of SWC and hence reduced the effect of SWC on GPP.

Some studies have shown that the ambient temperature, once having exceeded the optimum value, will limit photosynthesis (Chen et al., 2021; Medlyn et al., 2002), but the temperature couldn't maintain at an optimum value in most ecosystems (Dang et al., 2022; Huang et al., 2019b). In our study, the median of ΔGPP (Ts|SWC) under both irrigation methods was positive. At the same time, when Ts under DM was higher than that under BM, the promotion effect of Ts on GPP was also greater accordingly. Therefore, we believe that facing global warming, the two irrigation methods still have the potential to increase GPP.

Liu et al. (2020) pointed out that in most of the vegetation, Δ GPP (SWC|VPD) was negative, even in the semi-arid areas, and SWC restrictions on GPP were the most, but he failed to separate specific differences and effects under different irrigation methods. Our study further found that SWC under DM was higher than that under BM, and that the median of Δ GPP (SWC|Ts) under DM was negative, and under BM, weakly positive. This was perhaps because moderate soil water deficit could increase the activity of key enzymes in the process of carbon assimilation (Cui et al., 2015; Zhang et al., 2013), which was more conducive to photosynthesis (Lu et al., 2022). In a nutshell, the decrease of SWC could promote GPP under both DM and BM.

Under different conditions, the effects of VPD on photosynthesis were different (Kimm et al., 2020; Sulman et al., 2016). Plants closed stomata to limit GPP when VPD was high (McAdam and Brodribb, 2015; Yuan et al., 2019a). The value of VPD has not yet reached the threshold for limiting photosynthetic capacity of maize under these two irrigation methods. The VPD under DM was larger than that under BM (Fig. 2c), and had no negative effect on GPP of maize. Therefore, the continuous increase of VPD under the two water-saving irrigation methods may continue to promote GPP.

At present, our research on the leading role of Ts, SWC and VPD on GPP was mainly the study of laws and phenomena. More mechanistic study on canopy and leaf as well as stomatal level responses to water, temperature and nutrients is necessary to disentangle the physiological and phenological responses of crops to DM and BM. In the future, model simulation based on more experimental observation data may be carried out to make existing conclusions more convincing and further explain the underlying mechanisms.

4.3. Implications for agricultural microclimate and modeling research

Farmland management measures have an impact on microclimate conditions and even feedback to affect regional climate, but relevant researches are seldom found at present (Zhou et al., 2012). Although we only conducted a single point experiment on maize fields under DM and BM, we conducted a detailed comparative experimental design and data observations. The obvious difference between DM and BM was irrigation. According to the analysis, we found that irrigation had total effect on GPP (0.11) under DM and BM (Fig. 6). In the analysis of the results of mulched irrigation, Ming et al. (2021) found that irrigation would increase GPP, which was also confirmed in our study. Irrigation also had a certain degree of influence on VPD, varying among different under different irrigation methods (Fig. 6). Lo Valvo et al. (2018) pointed out that irrigation could effectively affect VPD in the study of 28 stations in Wisconsin Central Sands Region. Therefore, farmland management measures have an impact on microclimate. At present, many meteorological observations and climate models fail to fully consider the impact of irrigation, despite that fact that irrigation could have a certain impact on the climate system (Boucher et al., 2004; Harding and Snyder, 2012). With the expansion of irrigated agriculture, accuracy of the land-atmosphere coupling model of the earth could be greatly improved if taking account of the impact of irrigation on climate (Chen et al., 2017; Huang et al., 2013; Nocco et al., 2019).

VPD plays an important role in the carbon flux (McDowell et al., 2008; Novick et al., 2016; Olivo et al., 2009; Yuan et al., 2019a). The error of current global vegetation dynamic models in GPP simulation happened for failing to consider VPD (Rigden et al., 2020; Yuan et al., 2019b), and in our study, the relative contribution of VPD to GPP was even greater than that of SWC (Fig. 7). Interestingly, Novick et al. (2016) pointed out that atmospheric demand would have an increasing impact on vegetation function. Thus, we suggest that the influence of VPD should be fully considered in microclimate research and future model development.

In our study, we also found that I, P, Ts and Tc had indirect effects on GPP (Figs. 5–6). In previous analysis of SEM, it was not difficult to find that environmental factors were prone to have indirect effects on GPP, yet failing to arouse sufficient attention (Gui et al., 2021; Guo et al., 2021; Song et al., 2021; Wang et al., 2021b). Therefore, in analysis of the influence of the target parameters considering the mutual influence of each factor, only focusing on the direct influence and ignoring the indirect influence may misinterpret the effect of parameters. We suggest that the indirect effects of environmental factors on carbon fluxes and other parameters should be fully considered in both experimental analyses and climate models in future.

5. Conclusions

Based on the eddy covariance system, we measured water, heat, and carbon fluxes in maize fields under DM and BM during 2014–2018 in arid areas of Northwest China. The effects of environmental factors on GPP were quantified using the SEM and the relative importance of Ts vs. SWC and VPD vs. SWC to GPP were decoupled using the partial correlation coefficient and the binning method. The main research results are as follows:

1) The annual mean Ts, SWC, VPD and GPP in the whole growth period of the DM were higher than those under BM.
2) The top three factors having the largest total effects on GPP under the two irrigation methods were Ts, Tc and VPD, among which Ts had the largest total effect on GPP under DM and Tc had the largest total effect on GPP under BM.
3) Ts and VPD had greater relative contribution to GPP than SWC under DM and BM. Facing climate warming and increasing drought in the future, both irrigation methods have the possibility to further improve photosynthesis.
4) The effects of irrigation on farmland microclimate, VPD and the indirect effects of environmental factors on GPP should be highlighted in future experimental analyses and accounted for in the coupled Earth system models.

In general, we quantified the effects of environmental factors on GPP and separated the independent effects of temperature and drought on GPP under the two irrigation methods. However, in order to better clarify the physiological and phenological responses of crops to DM and BM, it is necessary to further study the response mechanism of canopy and leaf as well as stomatal level to water, temperature and nutrients and carry out corresponding model simulation research based on more detailed experimental data.

CRediT authorship contribution statement

Chunyu Wang was responsible for the data collection and paper writing. Sien Li and Mousong Wu made contributions to the construction of the paper framework, and revised the paper for important intellectual content. Wenxin Zhang provided instructional advice revised the paper for important intellectual content. Zhenyu Guo made contributions to the data processing of the paper. Siyu Huang and Danni Yang revised the paper.

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

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

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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.2022.108016.

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