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Evapotranspiration and Quantitative Partitioning of Spring Maize with Drip Irrigation under Mulch in an Arid Region of Northwestern China

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Abstract: To examine evapotranspiration (ET_c), soil evaporation (E_s), and transpiration (T_r), and partitioning of ET_c, a two-year field experiment was carried out in a maize field with drip irrigation under mulch in an arid region of northwestern China in 2017 and 2018. In the experiment we designed two treatments with full irrigation (T1) and growth stage-based strategic regulated deficit irrigation (T2). The applied irrigation of T2 was 40% of the T1 during both late vegetative and reproductive growth stages. Based on the measurements of soil water content (SWC) and T_r, a dual crop coefficient model (SIMDualK$_c$) was calibrated and validated, and daily ET_c, E_s, and T_r were estimated. The model can simulate well the dynamic variations of SWC and T_r. The calibrated basic crop coefficient at the initial, mid-season, and end growth stages was 0.2, 1.15, and 0.75, respectively. The ET_c was 507.9 and 519.1 mm for the T1 treatment, and 428.9 and 430.9 mm for the T2 treatment. The ratios of T_r to ET_c were higher for the two treatments, ~90%, for two years. Collectively, both drip irrigation under mulch and strategic deficit irrigation after canopy covering of the ground can significantly reduce the ineffective proportion of ET_c and E_s.

Keywords: evapotranspiration; transpiration; maize; drip irrigation under mulch; strategic deficit irrigation

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1. Introduction

Crop evapotranspiration (ET_c) is one of the key indicators of field water management, crop irrigation scheduling, and planning and design of farmland water conservancy projects [1]. ET_c is divided into two parts, soil evaporation (E_s) and plant transpiration (T_r). Among them, E_s, known as ineffective water consumption for crop growth and yield, can be decreased by ground coverage or proper irrigation management [2,3]. T_r, associated with photosynthetic carbon fixation through leaf pores, directly decides crop growth and the final yield [4]. However, as two water consumption processes in the farmland, T_r and E_s occur simultaneously, so it is difficult to carry out quantitative partitioning. Therefore, accurate determination of crop evapotranspiration and its components is of great significance for guiding field irrigation and improving the water use efficiency.

The FAO-56 dual crop coefficient approach is widely used because it can be used to accurately estimate crop evapotranspiration and realize quantitative partitioning of daily E_s and T_r [5]. Fan and Cai [6] and Lu et al. [7] demonstrated that ET_c can be accurately estimated by the dual crop coefficient approach. A micro-lysimeter can be used to measure E_s, but owing to the limited measuring accuracy of the instrument, the accuracy can merely be controlled within 15–20% [8]. Rosa et al. [9] developed a dual crop coefficient model (SIMDualK$_c$) based on the dual crop coefficient approach, making it easier to partition ET_c. Many studies showed that the model has a highly accurate estimation of ET_c and its components for wheat, maize, forage, tomato, chili, pea, cucumber, etc., in Brazil, Uruguay, Portugal, Spain, and North China [10–17].

Agricultural irrigation is a large water user in arid regions of Northwest China, which is short of water resources, so the use of a new effective water-saving irrigation technology is of great strategic significance for ensuring the water resources security and ecological safety of Northwest China [18]. Drip irrigation under mulch, which is a new type of water-saving technology integrating the advantages of the mulch film, such as soil temperature conservation, soil moisture conservation, yield increase, and the water-saving advantage of drip irrigation, can be used to decrease E_s and increase water use efficiency utilization during the initial stage of crop growth [19]. Thus, it has been widely used in arid regions of Northwest China. Previous studies have indicated that E_s was reduced by ~50% with plastic film mulch over the whole growing season [20–22]. Fan et al. [23] indicated that plastic mulch decreases the available energy and ET_c of maize in an arid region of northwest China, and thus the crop coefficient (K_c). Ding et al. [20] introduced a ground-mulching factor to modify the original soil evaporation coefficient in order to account for the reduction of the evaporation area by plastic film mulch. Zhang et al. [24] found that maize ET_c with drip irrigation under mulch was reduced by 2.8–5.2%, with reduced soil evaporation by 45.2% and increased transpiration by 8.9% in Northeastern China. However, there remain very few studies on ET_c and its components related to the use of drip irrigation under mulch in arid regions of Northwest China.

Crop regulated deficit irrigation (RDI) is a water-saving and high-yield irrigation technology based on the relationship between crops and water. Moderate water deficit in the growth stage of crops can reduce crop water consumption but has a small impact on the final grain yield, thereby improving water use efficiency [25]. RDI reduces crop water consumption mainly by reducing crop growth and leaf area or canopy coverage, but a reduction in canopy coverage will increase the area of bare soil and increase soil evaporation. For example, water deficit in the seedling or early growth period would delay crop growth and canopy cover time, increasing the proportion of ineffective soil evaporation [26]. After the canopy covers the ground (or the leaf area index is greater than 3.0 m^2 m^{-2}), the implementation of the strategic stage of deficit adjustment can ensure the reduction of crop water consumption without increasing the proportion of soil evaporation [27]. Therefore, the timing of RDI is very important to reduce crop water consumption without increasing ineffective soil evaporation.

In this study, a two-year field experiment of maize with drip irrigation under mulch was carried out, and two water treatments were set up, namely full irrigation (T1) and strategic stage regulated deficit irrigation in the late growth and reproductive periods (T2). The SIMDualK$_c$ model was used to estimate the ET_c and E_s and T_r of maize during the whole growth period. The objectives were: (1) to quantify the proportion of ET_c and E_s and T_r of maize with drip irrigation under mulch, and (2) to compare the differences in water use between the two treatments. These results provide a novel approach for efficient water management by strategic growth stage-based RDI in field maize.

2. Materials and Methods

2.1. Experimental Area

The experiment was conducted at the Shiyanghe Experiment Station, China Agricultural University in 2017 and 2018. The station is located in Liangzhou District, Wuwei, Gansu Province, northwest China (37°51′ N, 102°52′ E, at an altitude of 1581 m). The area has a typical continental temperate climate (arid inland desert climate) and abounds in photothermal resources. The annual sunshine duration exceeds 3000 h; the frost-free season lasts for more than 150 d; the annual average temperature is 8 °C and accumulated temperature above 0 °C is higher than 3550 °C; the multi-year average wind speed is 1.3 m s^{-1}; the multi-year average precipitation is 164 mm; the groundwater depth is greater than 30 m. The soil in the experimental area is light sandy loam. The average dry bulk density in the 100 cm soil layer of the root zone is 1.38 g cm^{-3}, with an average field capacity (θ_{FC}) of 0.32 cm^3 cm^{-3} and permanent wilting point (θ_{WP}) of 0.13 cm^3 cm^{-3}.

2.2. Experiment Design

A randomized block experiment was used, with two irrigation treatments, i.e., full irrigation (T1) and regulated deficit irrigation (T2). Each treatment had three replicates, and there were six plots in total. Each plot had a size of 7 × 4.5 m, and the plots stayed unchanged in terms of size and treatment location in the two years. The planting crop was spring maize (Xianyu 335), which was sown on 29 April 2017, and the harvest date was 24 September, and the growth period was 148 days; in 2018, the planting was carried out on 26 April, the harvest date was 24 September, and the length of the growth period was 151 days. We used drip irrigation under the film, and each plot was laid with three white transparent films (Figure 1). The film width was 1.4 m, and each film had three drip irrigation tapes. The seeds were sown on one side of the drip irrigation tapes under the mulch, with a pore diameter of 5 cm, row spacing of 50 cm, and plant spacing of 25 cm. The film coverage rate was one minus the sum of the bare soil area per unit area and the film hole area, which was about 80%. The dripper flow rate was 2.5 L h^{-1}, the dripper spacing was 30 cm, and the working pressure was 0.1 MPa. Nitrogen fertilizer of 250 kg ha^{-1}, phosphate fertilizer of 60 kg ha^{-1}, and potassium fertilizer of 139 kg ha^{-1} were applied during the whole growth period. Nitrogen fertilizer of 60 kg ha^{-1} was applied before sowing, and the remaining nitrogen fertilizer was applied four times. Other agronomic measures were consistent with local field management.

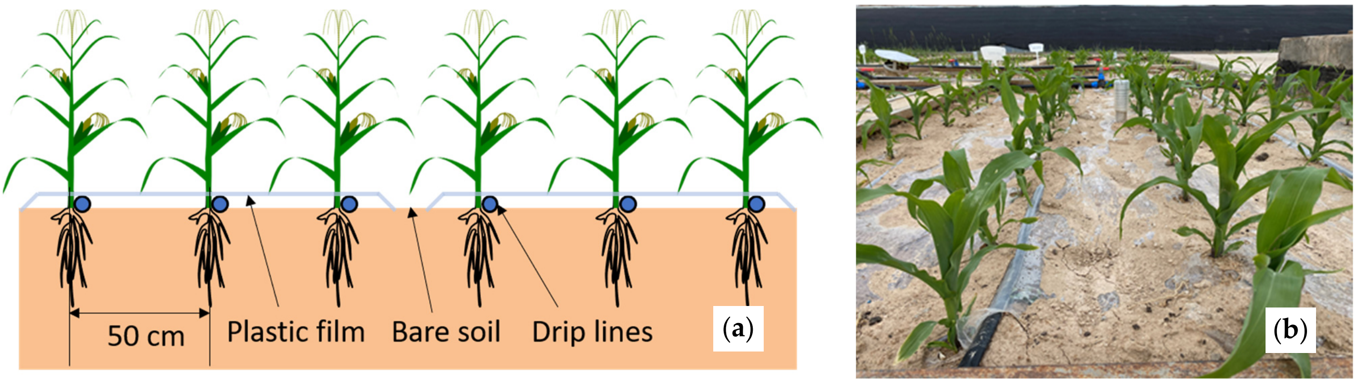

Figure 1. Schematic diagram of maize planting with drip irrigation under mulch (**a**) and photo (**b**).

2.3. Irrigation Management

For the T1 treatment, irrigation scheduling was designed based on both the water requirements of the crop estimated by the FAO-56 approach and on the measured soil water content. The irrigation amount was set to 100% ET_c or θ_{FC}. The water amount for the T2 treatment was 40% of that for T1 during both the late vegetative and reproductive growth stages and irrigated to θ_{FC} both at the seedling stage and the filling stage. For T1 treatment, unified irrigation was performed before the soil water content decreased below the level of readily available water (RAW). ET_c was determined according to the reference evapotranspiration (ET_0) and crop coefficient (K_c), while K_c was determined by canopy cover (f_c) calculation. Table 1 shows the irrigation time and amount for T1 and T2 in 2017 and 2018. The total irrigation amount for T1 and T2 was 433 and 337 mm in 2017, and 382 and 347 mm in 2018, respectively.

Table 1. Irrigation scheduling for maize with drip irrigation under mulch for two water treatments (T1 and T2) during the whole growth period of maize in 2017 and 2018.

Years	Dates	Irrigation Depth (mm)	
		T1	T2
2017	5/3	30	30
	5/31	17	16
	6/18–6/19	40	41
	6/30–7/1	55	22
	7/10–7/11	53	21
	7/22–7/24	120	120
	8/8	43	57
	8/31	75	30
2018	4/27	30	30
	5/9	21	21
	6/10	50	51
	6/23	60	25
	6/30	41	17
	7/9	37	16
	7/18–7/19	68	100
	8/15–8/16	75	87

2.4. Data Measurements

The meteorological data were measured by a 2 m-high automatic weather station (Hobo, Onset Computer Corporation, Cape Cod, MA, USA) at the Experimental Station. The data included solar radiation (R_s), air temperature (T_a), relative humidity (RH), 2 m wind speed (u_2), and precipitation (P) recorded every 15 min. ET_0 was calculated using the FAO-56 Penman–Monteith equation [5]. The average wind speed during the growth period was 0.7 m s^{-1} in 2017 and 0.66 m s^{-1} in 2018. The average R_s during the growth period was 223.54 W m^{-2} in 2017 and 213.4 W m^{-2} in 2018. Figure 2 shows the ET_0, P, and maximum and minimum T_a (T_{max}, and T_{min}) in 2017 and 2018.

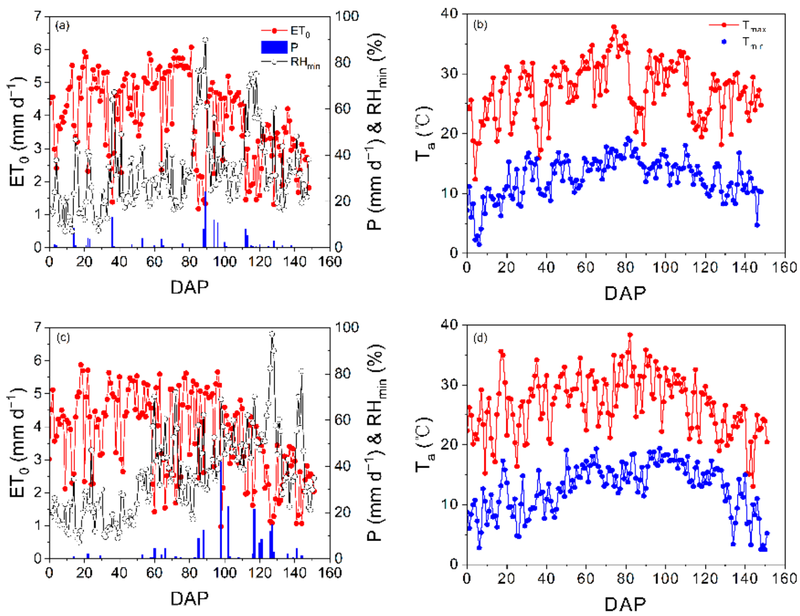

Figure 2. Daily variations of reference evapotranspiration (ET_0), precipitation (P), daily minimum relative humidity (RH_{min}), and maximum and minimum air temperature (T_{max} and T_{min}) with days after planting (DAP) during the whole growth period of maize in 2017 (**a**,**b**) and 2018 (**c**,**d**).

The volumetric soil water content (SWC, $cm^3\ cm^{-3}$) was measured in 10 cm increments in depths of 0–200 cm using a neutron probe (CPN-503 Hydroprobe, InstroTek, San Francisco, CA, USA). One neutron tube was installed at the center of each plot. SWC was measured every 7–10 d, and an additional measurement was made before and after irrigation and after rain. The soil drying method was used for calibration.

Maize transpiration was measured by the wrapped sap flowmeter Flow32-1k (Dynamax Inc., Houston, TX, USA). Three uniformly growing maize plants in each plot were selected for wrapping. Before wrapping, the stem diameter of maize at the wrapping site was measured with a vernier caliper with an accuracy of 0.01 mm. An average value was used to calculate the cross-sectional area of the maize stalk and then the cross-sectional area was converted into the transpiration of the plot based on the leaf area index as follows:

$$T_r = \frac{1}{N}\sum_{i=1}^{n}\frac{Q_{di}}{LA_i}LAI \tag{1}$$

where T_r is the transpiration rate of the plot ($mm\ d^{-1}$); Q_{di} is the sap flow per plant of the i-th plant ($L\ d^{-1}$); LA_i is the leaf area of the i-th plant (m^2); LAI is the leaf area index ($m^2\ m^{-2}$).

The crop height (h_c) was measured with a ruler every 10–15 d. The canopy coverage (f_c) was measured by photographing above the crop perpendicular to the ground. The ratio of the green area to the total area in the photo was equal to f_c. The root zone depth (Z_r) was measured at each growth stage by root drilling.

2.5. Quantitative Partitioning of ET_c Using the SIMDualKc Model

The SIMDualKc model calculates daily crop ET_c by considering both E_s and T_r based on the soil water balance and dual K_c method [9,28]. In the model, actual crop ET_c is computed as follows:

$$ET_c = (K_s \cdot K_{cb} + K_e)ET_0 \tag{2}$$

where K_{cb} is the basal crop coefficient, K_e is the soil evaporation coefficient, K_s is the water stress coefficient [0, 1], and ET_0 is the reference evapotranspiration. The SIMDualK_c model was used to calculate ET_c and its components by simulating the dynamic variations of SWC in the root zone. The input data of the model included soil data (field water holding capacity, withering coefficient, saturated moisture content), meteorological data, crop growth data (start and end dates of each growth stage, root depth, plant height, canopy coverage), and irrigation data (irrigation amount and date). The model also considers the effects of mulching film coverage, groundwater recharge, surface runoff, and deep percolation on T_r. Before running the model, the total evaporable water (TEW), readily evaporable water (REW), depth of evaporation layer (Z_e), basic crop coefficient (K_{cb}), and soil water depletion fraction (p) were calibrated.

To calibrate the model parameters, according to the FAO-56 method [5,28], the whole growth period of maize was divided into the initial stage (from seed sowing to f_c = 10%), development stage (10% < f_c < 80%), mid-season stage (from f_c = 80% to maturing) and late-season stage (from maturing to harvest). The average growth indicators of maize in 2017 and 2018 are shown in Table 2 for each treatment. The parameters were calibrated by the trial-and-error method. The simulated soil water content was compared with the measured value. When the error between the simulated and the measured values reached a minimum, the parameter calibration process ended [28,29]. In this study, the measured SWC of 2017 was used for parameter calibration while the data of 2018 were used for verification. The initial values of TEW, REW, Z_e, K_{cb}, and p were set to be equal to the values recommended by Allen et al. [5] and corrected according to the local meteorological conditions and crop factors. Because drip irrigation under mulch was used, the irrigation water–soil wetting ratio (f_w) was 0.4 and the film mulching rate was 0.6. The irrigation amount did not exceed the water capacity of the root layer, so deep-water seepage or deep percolation was not taken into consideration. Surface runoffs were not detected in the two years. A simulation was performed using the given K_{cb} and p. Since the T2 treatment caused some limitations on the growth of maize, the f_c of the T2 treatment decreased somewhat at the mid-season and late-season stages compared with T1. Therefore, K_{cb} was adjusted according to the mid-and late-season stages' measured values of f_c.

Table 2. Growth traits for two water treatments (T1 and T2) during the whole growth period of maize in 2017 and 2018.

Traits	Years	Treatments	Growth Stages				
			Initial	Development	Mid-Season	Late-Season	Whole Season
Growth length (d)	2017	T1	27	27	64	30	148
		T2	28	29	58	33	148
	2018	T1	32	25	64	30	151
		T2	32	28	59	32	151
Plant height (m)	2017	T1	0.3	1.5	2.9	3.1	—
		T2	0.29	1.5	2.4	2.4	
	2018	T1	0.4	1.4	2.9	3.1	
		T2	0.4	1.2	2.7	2.7	
Root depth (m)	2017	T1	0.1	0.4	0.74	0.74	—
		T2	0.2	0.5	0.65	0.65	
	2018	T1	0.2	0.44	0.7	0.7	
		T2	0.25	0.5	0.7	0.7	
Canopy cover	2017	T1	0.1	0.97	0.93	0.6	—
		T2	0.1	0.9	0.85	0.56	
	2018	T1	0.1	0.95	0.9	0.6	
		T2	0.1	0.88	0.85	0.55	

Model performance was assessed using the regression coefficient (b), determination coefficient (R^2), root mean square error (RMSE), maximum absolute error (E_{max}), average absolute error (AAE), Willmott index of agreement (d_{IA}), and Nash and Sutcliffe modeling efficiency (EF) between the simulated value and the measured value [13,30–33]. Among them, b, R^2, d_{IA}, and EF were closer to 1.0, and RMSE, E_{max}, and AAE were closer to 0, indicating that the fitting effect was better.

3. Results and Discussion

Table 3 shows the initial and calibration values of the main model parameters. After calibration, the K_{cb} of maize with drip irrigation under mulch at the initial stage ($K_{cb\text{-}ini}$), mid-season stage ($K_{cb\text{-}mid}$), and late season stage ($K_{cb\text{-}end}$) were equal to 0.2, 1.15, and 0.55, respectively. The values of K_{cb} obtained in this study were similar to those in the existing studies and sit within the reviewed and updated range of K_{cb} for field maize based on accurate crop ETc measurement and FAO56 method by Pereira et al. [34]. Chauhdary et al. [35] presented $K_{cb\text{-}mid}$ = 0.93, $K_{cb\text{-}end}$ = 0.47 for dripped maize with high grain moisture; they used the SALTMED model and gravimetric SWC measurements in Faisalabad, Pakistan. The experimental results achieved by Gimenez et al. [11] in western Uruguay showed that $K_{cb\text{-}ini}$ = 0.15, $K_{cb\text{-}mid}$ = 1.05, and $K_{cb\text{-}end}$ = 0.3. Martins et al. [36] studied maize with sprinkling irrigation and drip irrigation under organic film in southern Brazil and showed that $K_{cb\text{-}ini}$ = 0.2, $K_{cb\text{-}mid}$ = 1.12, and $K_{cb\text{-}end}$ = 0.2. Rodrigues et al. [37] conducted a study on maize under full irrigation and deficit drip irrigation in Portugal and found that $K_{cb\text{-}ini}$ = 0.15, $K_{cb\text{-}mid}$ = 1.15, and $K_{cb\text{-}end}$ = 0.4. Paredes et al. [38], in Portugal, showed by using the AquaCrop model that $K_{cTr,x}$ = 1.18. Paredes et al. [12] in 2014 showed that $K_{cb\text{-}ini}$ = 0.15, $K_{cb\text{-}mid}$ = 1.15, and $K_{cb\text{-}end}$ = 0.3. Yan et al. [39] studied summer maize under different drip irrigation conditions using the SIMDualK_c model in Yangling, Shaanxi, concluding that $K_{cb\text{-}ini}$ = 0.15, $K_{cb\text{-}mid}$ = 1.13, and $K_{cb\text{-}end}$ = 0.2. Zhao et al. [40] studied summer maize in Beijing, concluding that $K_{cb\text{-}ini}$ = 0.2, $K_{cb\text{-}mid}$ = 1.1, and $K_{cb\text{-}end}$ = 0.45. Li et al. [25] studied maize by drip irrigation under mulch in northeastern Inner Mongolia, concluding that $K_{cb\text{-}ini}$ = 0.15, $K_{cb\text{-}mid}$ = 1.05, and $K_{cb\text{-}end}$ = 0.4. The slightly higher $K_{cb\text{-}end}$ might be due to the incomplete senescence of maize.

Table 3. Initial and calibrated values of key parameters for the SIMDualKc model.

Parameters	Initial Values	Calibrated
Crop parameters		
$K_{cb\text{-}ini}$	0.15	**0.2**
$K_{cb\text{-}mid}$	1.15	1.15
$K_{cb\text{-}end}$	0.50	**0.55**
p_{ini}	0.55	0.55
p_{mid}	0.55	0.55
p_{end}	0.55	0.55
Soil parameters		
REW (mm)	10	**12**
TEW (mm)	30	30
Z_e (m)	0.12	**0.15**

Note: K_{cb} and p are the maize basal crop coefficient and the soil–water depletion fraction, respectively, for no stress at the initial (ini), mid-season (mid) and late-season (end) stages; REW and TEW are readily and total evaporable water, respectively; and Z_e is the depth of the soil evaporation layer. The emboldened values are calibrated parameters that are different from the initial ones.

The measured and simulated SWC in the root zone of the two treatments in 2017 and 2018 are shown in Figure 3. The goodness-of-fit statistic of calibration and verification are shown in Table 4. The simulated value and measured SWC fit well. The simulated SWC can capture a dynamic process in which the SWC increased in a short period with irrigation or rainfall, and then gradually decreased due to ET_c. The regression coefficient b was 0.96–1.07, R^2 was 0.84–0.95, RMSE was 0.005–0.008 $cm^3\ cm^{-3}$, AAE 0.01 was $cm^3\ cm^{-3}$, E_{max} 0.025 was $cm^3\ cm^{-3}$, and d_{IA} reached up to 0.96, which was better than the results of the study of rain-fed maize in Inner Mongolia by Wu et al. [41]. These results were slightly lower than those found by Zhao et al. [39] on summer maize in Beijing (b = 0.91–1.01, R^2 = 0.87–0.93), but the relative error of SWC in this study was lower than 10%, suggesting that the SIMDualK_c model was accurately able to calculate SWC and can be used to calculate ET_c of maize and its partitioning [9].

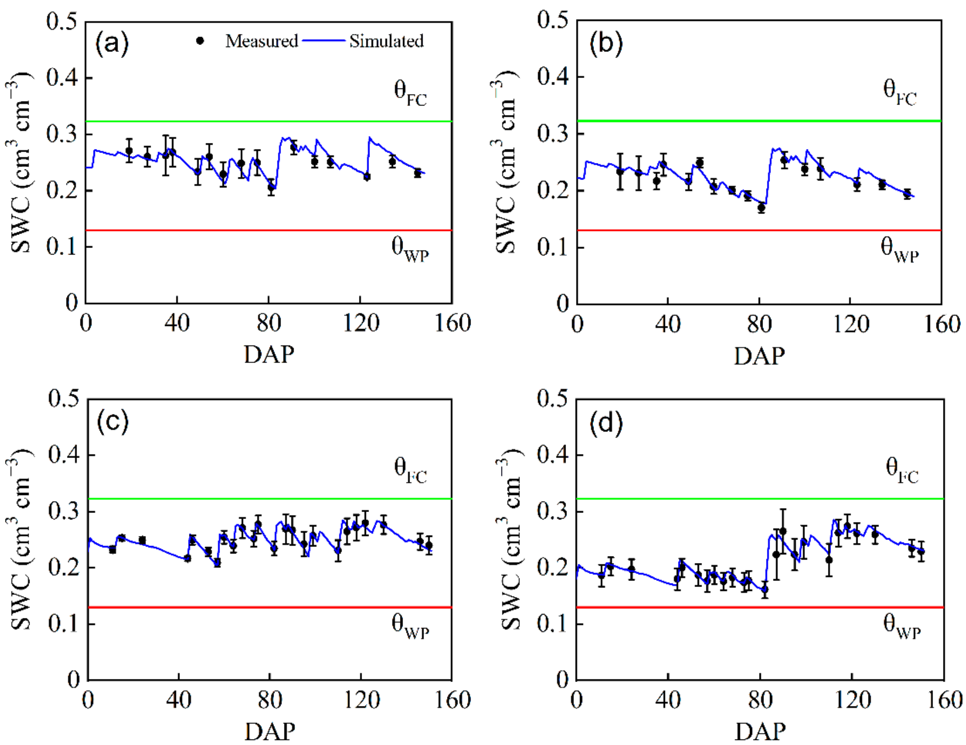

Figure 3. Measured and simulated seasonal soil water content (SWC) for two water treatments (T1 and T2) with days after planting (DAP) during the whole growth period of maize in 2017 (**a**,**b**) and 2018 (**c**,**d**).

Table 4. Statistical indicators of goodness-of-fit between measured and simulated seasonal soil water content (SWC) for the two treatments (T1 and T2) in 2017 and 2018.

Years	Treatments	b	R^2	RMSE ($cm^3 \cdot cm^{-3}$)	AAE ($cm^3 \cdot cm^{-3}$)	E_{max} ($cm^3 \cdot cm^{-3}$)	d_{IA}	EF
2017	T1	0.98	0.84	0.008	0.006	0.013	0.96	0.82
	T2	0.96	0.90	0.008	0.006	0.022	0.97	0.89
2018	T1	1.07	0.95	0.005	0.004	0.010	0.99	0.94
	T2	1.00	0.95	0.008	0.006	0.025	0.99	0.94

Note: b, linear regression coefficient; R^2, coefficient of determination; RMSE, root mean square error; AAE, average absolute error; E_{max}, maximum absolute error; d_{IA}, Willmott index of agreement; and EF, the Nash and Sutcliffe modeling efficiency.

The E_s, T_r, and ET_c of maize were estimated using the calibrated and verified SIMDualK$_c$ model. Daily K_e, K_{cb}, and K_{cbadj}, as well as E_s, T_r, and ET_c, and measured T_r for T1 and T2 in 2017 and 2018 are shown in Figures 4 and 5, respectively. The goodness-of-fit statistics of the measured and simulated T_r are presented in Table 5. The simulated and measured T_r had the same changing trend during the growth period. The b was 0.91–1.04, R^2 was 0.91–0.97, RMSE was 0.366–0.389 mm d^{-1}, AAE < 0.5 mm d^{-1}, E_{max} was 1.163 mm d^{-1}, d_{IA} > 0.95, and EF 0.80–0.91. Although T_r was only verified during the mid-to-late growth period, we concluded that the model can estimate T_r throughout the growth period since it accurately simulated SWC throughout the growth period. Qiu et al. [42] compared tomato ET_c measured by a lysimeter with SIMDualK$_c$ simulations and found that b was 0.91–1.13 and R^2 was 0.55–0.82. Yan et al. [17] compared measured T_r values of greenhouse cucumber with simulations and demonstrated that the R^2 was 0.89–0.92 and RMSE was 0.36–0.51 mm d^{-1}. Our results were similar to those of previous studies. Overall, after being calibrated, the SIMDualK$_c$ model can better simulate the changes in ET_c of maize with drip irrigation under mulch during the growth period.

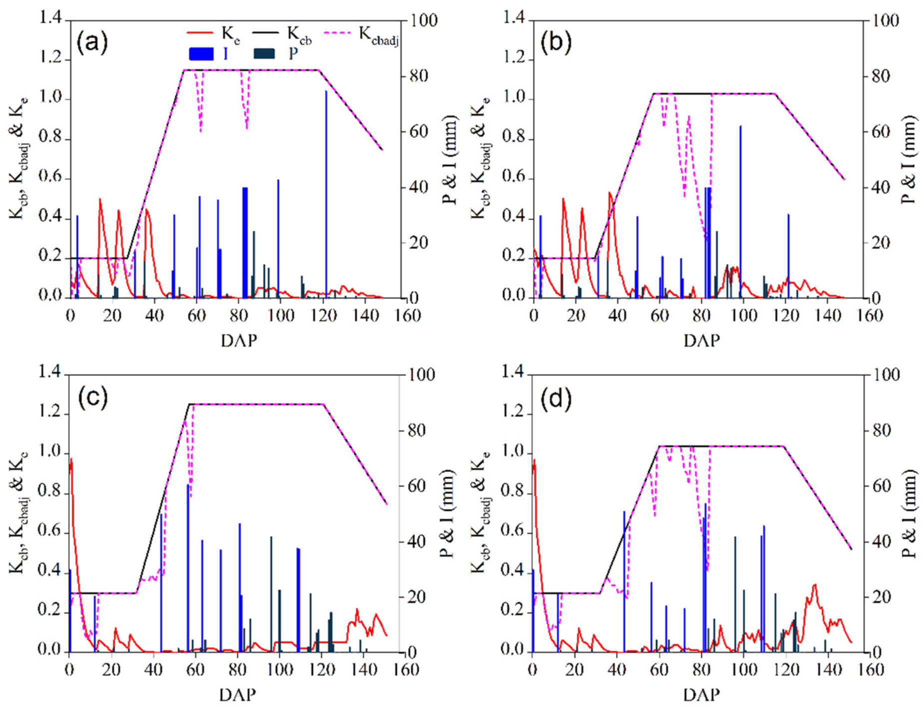

Figure 4. Dynamic variations of basic crop coefficient (K_{cb}), actual adjustment K_{cb} (K_{cbadj}) and soil evaporation coefficient (K_e) for two water treatments (T1 and T2) with days after planting (DAP) during the whole growth period of maize in (**a**,**b**) and 2018 (**c**,**d**).

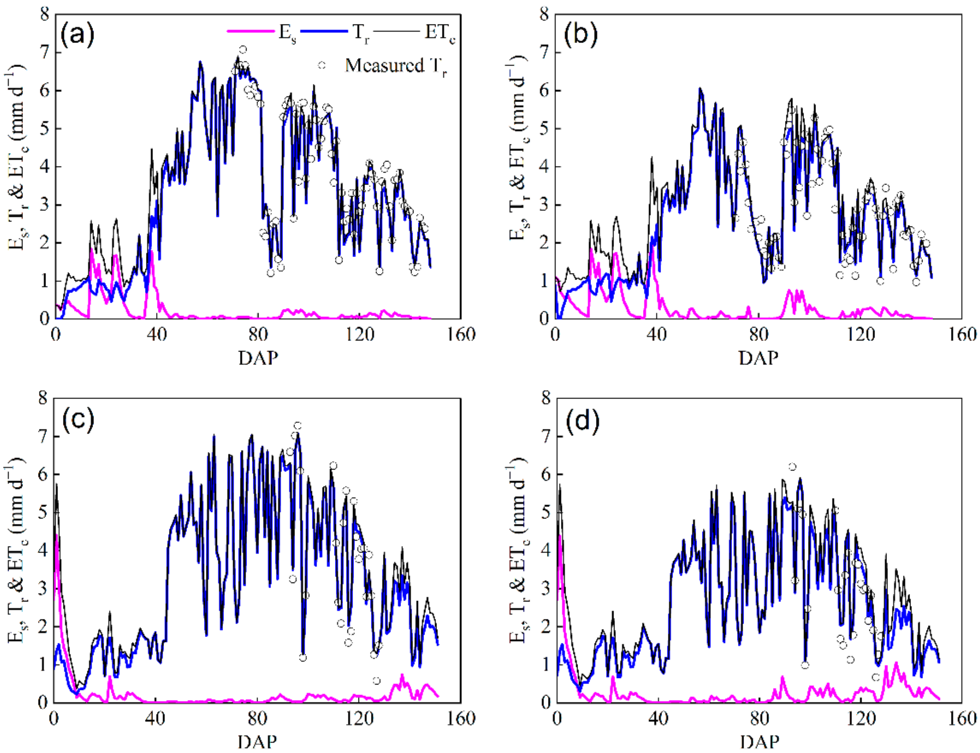

Figure 5. Seasonal variations of simulated evapotranspiration (ET_c), transpiration (T_r), and soil evaporation (E_s), and measured T_r for two water treatments (T1 and T2) with days after planting (DAP) during the whole growth period of maize in (**a**,**b**) and 2018 (**c**,**d**).

Table 5. Statistical indicators of goodness-of-fit between measured and simulated seasonal plant transpiration (T_r) for the two treatments (T1 and T2) in 2017 and 2018.

Years	Treatments	b	R^2	RMSE (mm·d^{-1})	AAE (mm·d^{-1})	E_{max} (mm·d^{-1})	d_{IA}	EF
2017	T1	0.99	0.95	0.366	0.294	1.060	0.97	0.88
	T2	1.00	0.91	0.379	0.293	1.163	0.95	0.80
2018	T1	0.91	0.97	0.367	0.310	0.709	0.98	0.91
	T2	1.04	0.95	0.389	0.346	0.649	0.96	0.82

Note: b, linear regression coefficient; R^2, coefficient of determination; RMSE, root mean square error; AAE, average absolute error; E_{max}, maximum absolute error; d_{IA}, Willmott index of agreement; and EF, the Nash and Sutcliffe modeling efficiency.

E_s and T_r values and their ratios to ET_c in different growth stages of maize are shown in Table 6. In 2017, the ET_c for T1 and T2 was 507.9 and 428.9 mm, E_s was 32.0 and 43.6 mm, and T_r was 476.0 and 385.3 mm, respectively during the whole growth period of maize. In 2018, the ET_c for T1 and T2 was 519.1 and 430.9 mm, E_s was 35.2 and 43.4 mm, and T_r was 484.0 and 387.5 mm, respectively during the whole growth period of maize. There were large differences in ET_c, E_s, and T_r between T1 and T2. In particular, there was a difference of 90.7–96.5 mm in T_r, which occurred in the middle growth period. The pattern was similar for two years, which suggests that drip irrigation with film mulching can significantly reduce soil evaporation regardless of whether full or regulated deficit irrigation are used.

T_r was the major component of ET_c, with the T_r/ET_c ratio of 93.7% and 89.8% for T1 and T2 in 2017, and 93.2% and 89.9% in 2018, respectively. Although T_r and ET_c decreased for T2, the T_r/ET_c ratio did not decrease significantly, suggesting that the growth-based RDI strategy maintains a higher percentage of crop effective transpiration. The E_s/ET_c ratio obtained for T1 in the two years was 6.3% and 6.8%, while it was 10.1% and 10.2% for T2, respectively. T2 caused higher evaporation than T1 for the reason that T2 restricted the growth of maize and the f_c for T2 was lower than that for T1 at the mid-season stage and late-season stage, causing an increase in the exposed soil area, thus increasing the E_s. In the early stage of growth, the f_c of maize was very low, with E_s as the major active component, and the E_s/ET_c ratio was highest, in the range of 39–49.4%. At the development stage, the evaporation ratio was 9.9–12.2% in 2017 and 1–1.6% in 2018. Such a large difference was due to a decrease of 18.4 mm in rainfall and a decrease in irrigation volume of 7.2 mm in the same period in 2018. The E_s in the mid-growth period in 2017 was smaller than that in the late-growth period, and the opposite was true in 2018. This was because the rainfall in the mid-growth period in 2018 was 140.2 mm, which was 57.6 mm more than in 2017, which led to an increase in soil evaporation. These results indicated that soil evaporation is greatly affected by the degree and coefficient of soil surface moisture and canopy coverage. For efficient crop water management practices, inefficient water consumption can be minimized by covering the ground with the canopy as soon as possible before performing deficit irrigation.

Table 6. Soil evaporation (E_s), transpiration (T_r), evapotranspiration (ET_c) and ratios of evaporation and transpiration to evapotranspiration for the two treatments (T1 and T2) at different growth stages of maize in 2017 and 2018.

Growth Stages	Years	E_s (mm)		T_r (mm)		ET_c (mm)		E_s/ET_c (%)		T_r/ET_c (%)	
		T1	T2	T1	T2	T1	T2	T1	T2	T1	T2
Initial	2017	17.8	21.5	18.3	22.0	36.2	43.6	49.3	49.4	50.7	50.6
	2018	21.0	21.0	31.9	32.9	52.9	54.0	39.7	39.0	60.3	61.0
Development	2017	7.8	10.0	70.5	71.8	78.3	81.8	9.9	12.2	90.1	87.8
	2018	0.8	1.2	77.3	73.3	78.1	74.5	1.0	1.6	99.0	98.4
Mid-season	2017	3.9	7.9	302.9	214.2	306.9	222.1	1.3	3.5	98.7	96.5
	2018	5.5	8.6	306.4	218.3	311.9	226.9	1.8	3.8	98.2	96.2
Late-season	2017	2.4	4.2	84.2	77.2	86.6	81.4	2.8	5.2	97.2	94.8
	2018	7.9	12.6	68.3	62.9	76.3	75.5	10.4	16.7	89.6	83.3
Whole season	2017	32.0	43.6	476.0	385.3	507.9	428.9	6.3	10.2	93.7	89.8
	2018	35.2	43.4	484.0	387.5	519.1	430.9	6.8	10.1	93.2	89.9

Previous studies have shown that drip irrigation under mulch can effectively reduce soil evaporation, thus improving the effective water use efficiency of crops or increasing T_r/ET_c, thereby promoting the growth of biomass and yield [23]. Ding et al. [20] found that for maize for seed under film conditions (f_m = 0.7) in arid regions of Northwest China, E_s decreased by 55.7% compared to film-free conditions, while T_r was higher. Martins et al. [36] found that the E_s/ET_c ratio in a maize field was 8–9% under drip irrigation with straw mulch. Li et al. [19] found that that the maize E_s/ET_c ratio was 19.85–20.29% with film-mulched treatment but 26.15–27.23% without mulch in northeastern Inner Mongolia. Kang et al. [43] studied irrigated maize without mulch in the Guanzhong area, concluding that the E_s/ET_c ratio was 26%. In this study, the E_s/ET_c ratio of the two treatments under the condition of mulching drip irrigation were 6.3–10.2%, which is lower than the results of previous studies, indicating that drip irrigation under mulching mainly increases the effective transpiration rate of crops by reducing soil evaporation to save water and increase yield.

The E_s/ET_c ratios were 10.1% and 10.2% for T2 for the two years, respectively, which is slightly higher than those of T1, at 6.3–6.8%. We started to implement water deficits in the late growth period after the canopy covered the ground, which might cause leaf curling, reduce the canopy coverage, and increase the area of bare soil and evaporated surface. Comas et al. also found that in addition to reducing crop growth and leaf area, water deficit also increased the proportion of rolled leaves, thereby reducing canopy coverage [27]. In this study, due to the use of drip irrigation under the mulch, the area of irrigated wetness and bare soil was small. Even though RDI reduced the canopy coverage and increased the bare soil area, the actual wet soil evaporation area did not increase, so there was no significant increase in E_s. These results indicate that in the practices of efficient water management for crops, sufficient irrigation in the early stage of growth can be used to quickly cover the ground in the canopy and then implement the strategic stage of RDI. At the same time, combined with high-efficiency water-saving irrigation methods such as drip irrigation under mulch, it can reduce water use but does not increase the proportion of effectless water.

Although our study area is arid and cold with an annual average temperature of 8 °C, our methods and result patterns can be extended to other areas. The purpose of our study was to estimate ET_c and its components to support irrigation scheduling using the SIMDualKc model based on daily soil water balance. The estimation accuracy can be improved if ones take into account soil water infiltration together with the root water uptake [44–46]. Further work will be needed to incorporate the two processes into dynamic soil water equations, e.g., using the Richards equation, for accurate partitioning of ET_c and soil water flow.

4. Conclusions

A two-year experiment of full irrigation and regulated deficit irrigation of maize with drip irrigation under mulch was conducted in an arid region of Northwest China. The daily evapotranspiration (ET_c), soil evaporation (E_s), and transpiration (T_r) of maize during its whole growth period and their ratios were calculated using the calibrated dual crop coefficient model SIMDualK_c. Then, the differences in ET_c and its components between the two treatments were analyzed, drawing the following conclusions: (1) The SIMDualK_c model can well simulate the dynamic variations of soil water content and plant transpiration in the maize field with drip irrigation under mulch, and can be used to calculate the evapotranspiration, soil evaporation, and transpiration of maize during its whole growth period; (2) a local basic crop coefficient was obtained for maize with drip irrigation under mulch in an arid region of Northwest China; (3) drip irrigation under mulch can significantly reduce the proportion of soil evaporation, and increase the proportion of plant transpiration that is effective for crop production. Growth-based strategic RDI can reduce crop water use without significantly increasing the proportion of ineffective soil evaporation.

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