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Evaluation of the Dual Crop Coefficient Approach in Estimating Evapotranspiration of Drip-Irrigated Summer Maize in Xinjiang, China

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Abstract: A dual crop coefficient approach was validated experimentally to estimate evapotranspiration of drip-irrigated summer maize with partial mulch and no mulch in an arid region in Aksu, Xinjiang, China, during 2016–2017. In this study, five treatments were established based on fixed or variable irrigation cycles. Summer maize transpiration and evapotranspiration were estimated by the dual crop coefficient approach. Evapotranspiration was validated, and a positive regression with those values was obtained using the water balance method, with a root mean square error (RMSE) of 10 mm. The estimated transpiration also had a positive regression with measurements obtained by the stable carbon isotope technique, with a RMSE of 20 mm. By analyzing the RMSE, regression coefficients, and concordance index, we suggest that the dual crop coefficient approach is an effective method to estimate and partition evapotranspiration. Across the entire growing season for partially mulched summer maize, the estimated crop transpiration accounted for 78.7% and 76% of the total evapotranspiration in 2016 and 2017, respectively. For non-mulched summer maize, the estimated crop transpiration accounted for 64.9% of the total evapotranspiration over the entire growing season, which implied that the soil evaporation was about 12% higher than that of the partially mulched treatments. Water consumption with partial mulching was reduced by about 10%, compared with non-mulching, which indicated that mulching improved the use of water during irrigation.

Keywords: summer maize; drip irrigation; evapotranspiration; crop transpiration; the stable carbon isotope technique

1. Introduction

Evapotranspiration (ET) includes soil evaporation (E) and crop transpiration (T). As an important term in both water and land surface energy balance equations [1], ET plays an important role in energy and water balance. The Food and Agricultural Organization (FAO) use the FAO-56 Penman-Monteith reference evapotranspiration (ET_0) and crop coefficient method to estimate cropland ET [2]. The crop coefficient method is a semi-empirical model recommended by the FAO. The crop coefficient (K_c) is multiplied by ET_0 to obtain ET. The crop coefficient approach consists of single and dual coefficient approaches. The dual crop coefficient approach can partition ET into E and T. It can also be used to estimate the effect of rainfall, irrigation, and use of mulch on soil water.

The dual crop coefficient approach has been used widely in many regions [3]. For example, Bodner et al. [4] found that the integration of stress compensation into the FAO crop coefficient approach provided reliable estimates of water losses under dry conditions. López-Urrea et al. [5] calculated the dual crop coefficient of irrigated sorghum biomass and found that the method aided in monitoring and estimating the spatially distributed water requirements of the sorghum biomass at field and regional scales. By investigating the crop water demands for winter wheat and summer maize, Liu et al. [6] found a good agreement between predictions from the dual crop coefficient approach and measurements from a lysimeter in the North China Plain. Zhao et al. [7] calculated the single crop coefficient and the dual crop coefficient of winter wheat and summer maize, respectively, and found the dual crop coefficient approach to be more precise than the single crop coefficient approach, particularly when the crops incompletely covered the ground. Shrestha et al. [8] investigated the basal crop coefficient (K_{cb}) values of mulched erect and vine crops in a sub-tropical region using the dual crop coefficient approach and they found that some K_{cb} values of watermelon and pepper recommended by FAO-56 were not applicable. Ding et al. [9] developed a modified dual crop coefficient approach to estimate and partition ET of mulched maize in the Shiyang River Basin of the Gansu Province and found that the modified dual crop coefficient approach had high precision for maize ET under mulching. The results suggested that the modified dual crop coefficient approach predicted E and T accurately. Tomomichi et al. [10] investigated the seasonal variation in the basal crop coefficient K_{cb} and the soil evaporation coefficient K_e of sorghum and quantified the relationship between crop coefficient and LAI (Leaf Area Index). Majnooni-Heris et al. [11] determined the crop coefficient and evapotranspiration ratio of canola using the dual crop coefficient approach. Current studies that estimate and partition crop ET using the dual crop coefficient approach are mostly carried out in wet and semi-humid regions, and these are validated by water balances derived using a large lysimeter and a stem flow meter under completely covered or bare ground conditions. However, in arid areas, the application of the dual crop coefficient approach under the partially mulched drip irrigation to estimate and partition crop ET are still limited, compared with the non-mulched condition.

The stable carbon isotope technique is a new approach in the study of plant physiology and ecology, and its reliability and stability have been shown in previous studies [12–14]. Anyia et al. [15] evaluated the application of carbon isotope discrimination as a selection criterion for improving water use efficiency (WUE) and productivity of barley (*Hordeum vulgare* L.) under field and drought stress conditions in a greenhouse. Chen et al. [16] validated the stability of a leaf carbon isotope discrimination as a measure of WUE across years and locations in Alberta, Canada, based on selected barley genotypes. Chen et al. [17] investigated WUE and water consumption in different growth stages of walnut-woad/semen cassia intercrop systems using the stable carbon isotope technique and a sap flow meter, and they found that the intercropping systems consumed less water than the mono-cropping systems. He et al. [18] measured the sap flow in walnut trees and the stable carbon isotope composition of different components of a walnut-wheat intercropping system and mono-cropped wheat, and they calculated WUE and water consumption. Total water consumption of mono-cropped wheat was higher than that of intercropped wheat. The stable carbon isotope technique is reliable and stable, but the employment of this technique to validate the dual crop coefficient approach is still limited.

Experiments were conducted in the Aksu, Xinjiang province during 2016–2017 to evaluate the FAO-56 dual crop coefficient approach for estimating evapotranspiration of summer maize with partial mulch and with no mulch. This study aimed to (1) establish a suitable dual crop coefficient model with the condition of partial mulch or non-mulch of summer maize in arid region, combining with the ecological environment of the experimental area and measured data to parameterize the dual crop coefficient model. (2) Using the water balance method to evaluate the estimated ET of the model. At the same time, the crop water consumption of summer maize was calculated by the method of a stable carbon isotope technique, and it was compared with T, predicted by the dual crop coefficient method. (3) The values of ET, E, and T, with the condition of partial mulch or non-mulch of summer maize, were simulated by the model in an arid region. The changes of ET, E, and T were analyzed in this paper. (4) Provide a scientific basis for improved water management on farmland in the region.

2. Materials and Methods

2.1. Study Site

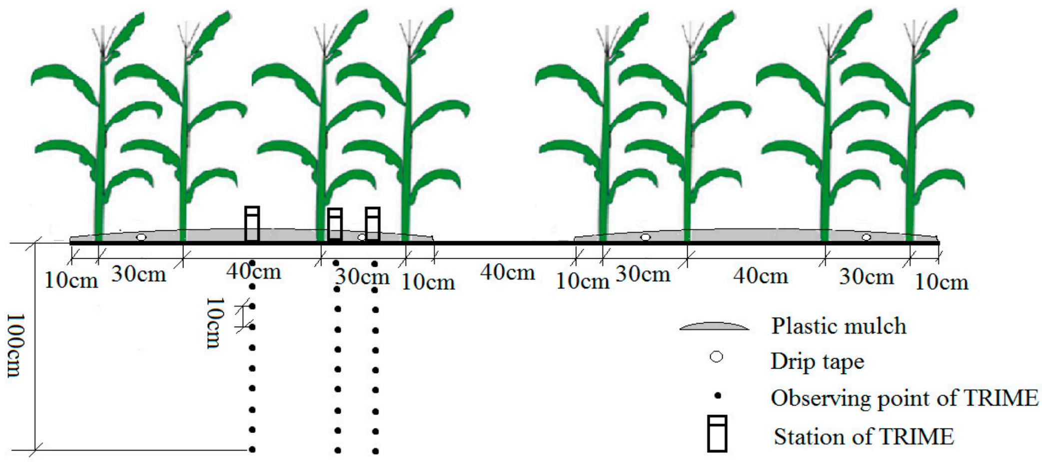
This study was conducted in 2016 and from June–October 2017, at the Xinjiang Agricultural University's Linguo Experimental Station, located in Hongqipo, Wensu County, Aksu Prefecture, China (41°16′ N, 80°20′ E). The site was warm and arid and had mean annual sunshine of 2800–3000 h and 200–220 frost-free days each year. The mean annual precipitation was 80.4 mm with large evaporation. During the growing season for summer maize, rainfall in 2016 was 75.9 mm and rainfall in 2017 was 64.8 mm. The groundwater depth was >10 m. The values of field capacity and permanent wilting point were 28% (volumetric water content) and 6% (volumetric water content), respectively. Soils were mostly sandy or silt loam (Table 1).

Table 1. Description of soils at the Xinjiang Agricultural University's Linguo Experimental Station in Hongqipo, Wensu County, Aksu Prefecture, China.

Depth cm	Bulk Density $g \cdot cm^{-3}$	Particle Size Distribution %				Soil Texture
		0–0.002 mm	0.002–0.05 mm	0.05–2 mm	>2 mm	
0–20	1.38	7.0	56.5	36.5	0	Silt loam
20–40	1.42	7.2	67.9	24.9	0	Silt loam
40–60	1.40	2.9	15.8	81.3	0	Sandy loam
60–80	1.38	0.1	1.7	98.2	0	Fine sand
80–100	1.35	0.2	8.0	91.8	0	Fine sand

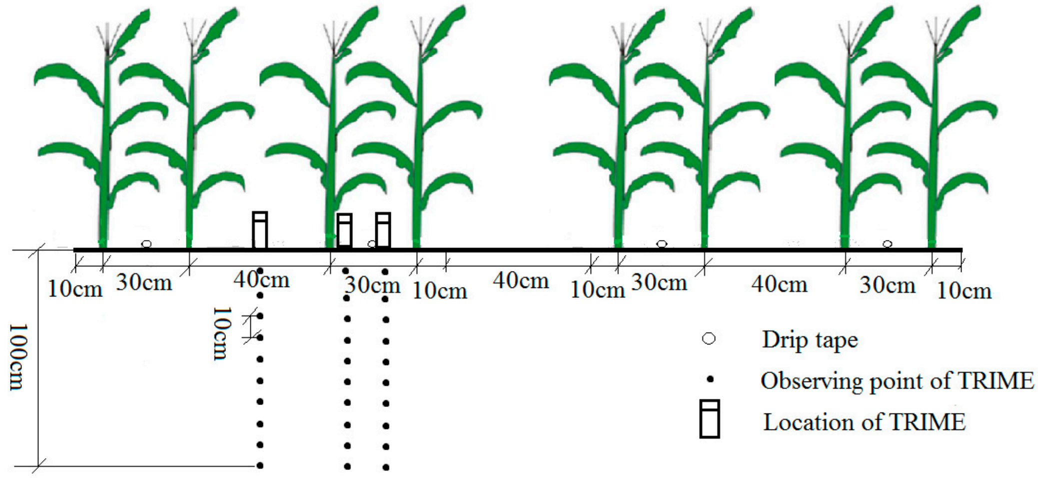
2.2. Experimental Design

The seeds of New Maize No. 9 were sown in 3 m × 2.2 m × 2 m plots. Each plot was spot-seeded manually with a plant spacing of 0.3 m, 0.4 m, 0.3 m, and 0.6 m in sequence, and 0.25 m between rows (Figure 1). The drip-irrigated treatment included a two-pipe and four-row system. The drip tube with 0.1 m emitter intervals was placed between two rows of maize, with a dripper discharge rate of 0.8 L h^{-1}. Each plot consisted of eight rows of maize (Figure 1). Water meters were installed in each plot to monitor the amount of irrigation water (measurement precision was 0.001 m^3).



(**a**) With partial mulch

Figure 1. *Cont.*



(**b**) With no mulch

Figure 1. Plot design for estimating evapotranspiration of drip-irrigated summer maize in Xinjiang, China. (**a**) With partial mulch; (**b**) With no mulch. (TRIME was the TRIME TDR system to determine the soil volumetric water content).

The experiments with partial mulch were conducted in 2016. In 2017, plots with partial mulch and without mulch were tested simultaneously. Five treatments were set up that included fixed irrigation cycles (W1, W2, and W3) and variable irrigation cycles (W4 and W5). Each treatment included three replicates. The fertilization and field management methods of each treatment were the same. To ensure seedling emergence, all the plots were irrigated once with approximately 125 mm water before sowing. The seeds were sown on 20 June (Table 2). The WUE values in Table 2 were calculated based on yields and water consumption.

Table 2. Description of experiments in 2016 and 2017 on mulched and non-mulched plots in Xinjiang, China.

Year	Treatment	Irrigation Cycle	Irrigation Amount/mm	WUE/kg·hm^{-2}·mm^{-1}
2016	W1	8 days (Y)	316 (Y)	41 (Y)
	W2	8 days (Y)	256 (Y)	41 (Y)
	W3	8 days (Y)	196 (Y)	44 (Y)
	W4	10 days (Y)	256 (Y)	47 (Y)
	W5	6 days (Y)	256 (Y)	47 (Y)
2017	W1	8 days (Y/N)	181 (Y/N)	38 (Y) 25 (N)
	W2	8 days (Y/N)	151 (Y/N)	35 (Y) 29 (N)
	W3	8 days (Y/N)	121 (Y/N)	35 (Y) 28 (N)
	W4	10 days (Y/N)	151 (Y/N)	39 (Y) 25 (N)
	W5	6 days (Y/N)	151 (Y/N)	42 (Y) 32 (N)

(Y) With partial mulch; (N) without mulch.

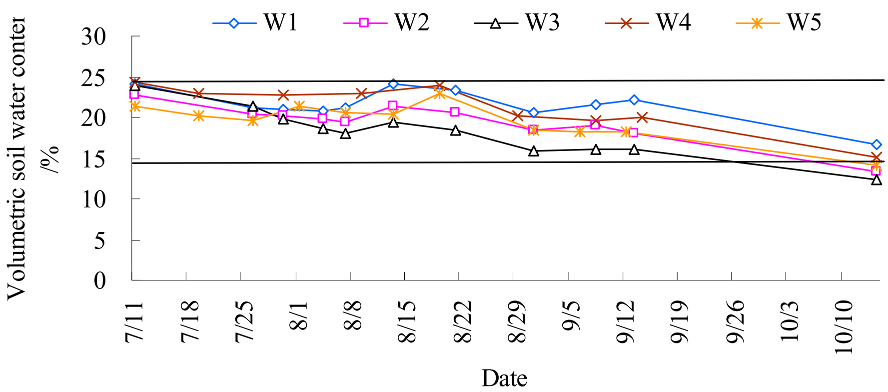
For the 2016 experiments with partial mulch, drip irrigation was started on 20 July and ended on 14 September. Maize was harvested on 14 October. The W1, W2, and W3 irrigation cycles were 8 d, with irrigation rates of 45, 37.5, and 30 mm, respectively, and total irrigation amounts of 316, 256, and 196 mm, respectively. The W4 and W5 irrigation cycles were 10 d and 6 d, respectively. The irrigation rates were 49.5 and 30 mm, respectively, and the total irrigation amount was 256 mm for both W4 and W5.

For the 2017 experiments with both partial mulch and no mulch, drip irrigation was started on 23 July and ended on 1 September, due to a pump failure. The maize was harvested on 3 October. The W1, W2, and W3 irrigation cycles were 8 d. The corresponding amount of water for irrigation was determined as 120% ET, 100% ET, and 80% ET for the W1, W2, and W3 irrigation cycles, which equated to 181, 151, and 121 mm, respectively. The ET in each irrigation cycle was calculated according to ET = $K_c \times ET_0$, and the crop coefficient (K_c) of each growth period, used values from Liang [19]. The irrigation cycles of W4 and W5 were 10 d and 6 d, respectively, and the irrigated water was determined as 100% ET, and the total irrigation amount was 151 mm. There were one or two fewer irrigation events for each treatment in 2017 compared with 2016, which resulted in a reduced amount of irrigation water in 2017 compared with 2016.

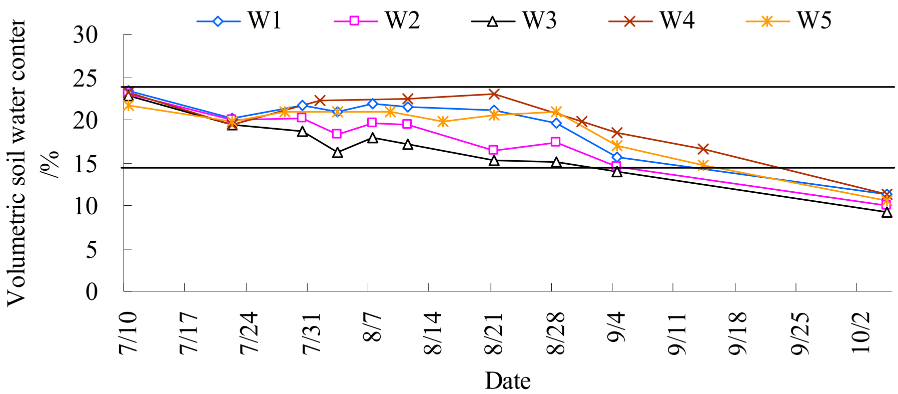
2.3. Measurements and Methods

2.3.1. Soil Water Content

The soil volumetric water content was determined by the TRIME TDR system [7,20]. Three TRIME tubes were placed in the middle of the two drip irrigation belts, next to the maize and between the rows in each plot. The data were recorded before each irrigation. The measured depth was 100 cm. The soil water content was collected at every 10 cm of depth for a total of 10 layers (Figure 2). Two lines in Figure 2 are 100% field capacity and 60% field capacity, respectively. In 2016 and 2017, the volumetric moisture content of soil declined with the whole growth period under partial mulched or non-mulched summer maize. The values of volumetric moisture content are almost between 60–100% field capacity. The volumetric moisture content of some treatments was lower than 60% field capacity at the beginning of September, in 2017. It was caused by drip irrigation was ended on 1 September.

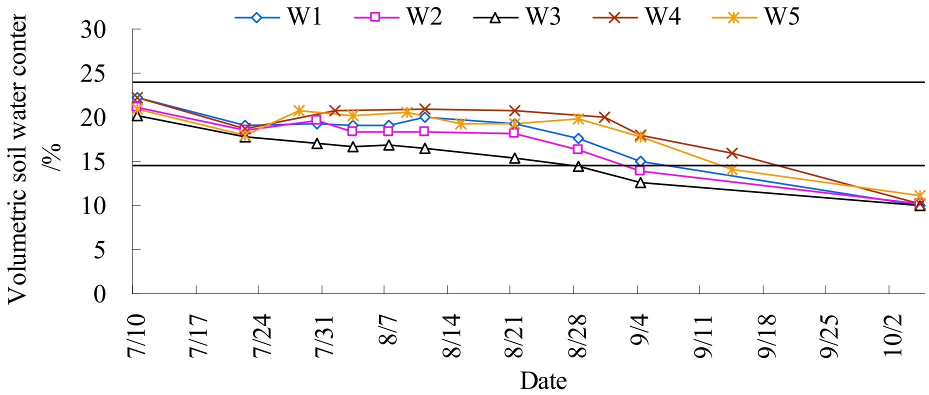


(**a**) Partial mulch in 2016



(**b**) Partial mulch in 2017

Figure 2. *Cont.*



(**c**) Non-mulch in 2017

Figure 2. Volumetric soil water content for W1–W5 treatments throughout the season for drip-irrigated summer maize in Xinjiang, China. (**a**) Partial mulch in 2016; (**b**) Partial mulch in 2017; (**c**) Non-mulch in 2017.

2.3.2. Calculation of Water Consumption

In this study, the water balance equation was used to calculate the evapotranspiration of partial mulched/non-mulched crops. The calculation of ET followed the equation below:

$$\mathrm{ET} = \mathrm{Pr} + \mathrm{I} + \mathrm{SWS} - \mathrm{R} - \mathrm{D} + \mathrm{K} \tag{1}$$

where ET (mm) is crop water consumption (evaporation transpiration), Pr (mm) is rainfall during the growth period, I (mm) is irrigation amount, SWS (mm) is the difference in soil water storage during sowing and harvesting, R (mm) is surface runoff, D (mm) is deep drainage, and K (mm) is groundwater recharge. Because the groundwater depth was at 10 m, R, D, and K were negligible and set to zero. Because the mulch intercepted effective rainfall, a factor of 0.25 was added to the effective rainfall for non-mulch treatments to calculate water consumption for the partially mulched summer maize, based on the percentage (25%) of the plots that were not mulched.

2.3.3. Meteorological Data

All meteorological data was obtained from a weather station (Watchdog) 300 m away from the experimental plots. Data included solar radiation, temperature, relative humidity, wind speed, atmospheric pressure, and rainfall. The data were recorded every 1 h.

2.3.4. Determination Water Use Based on the Stable Carbon Isotope Technique

The stable carbon isotope technique was used to calculate water use of summer maize. After the measurement of physiological index had been completed, the leaves in different treatments were sampled during the 6-leaf stage, 12-leaf stage, silking stage, filling stage, and mature stage, and healthy leaves (no pest or disease) were sampled at a similar height. In the laboratory, the leaf samples were dried in an oven at 70 °C for 48 h and sieved (80 mesh). The samples were sealed, stored, and sent to a laboratory (Department of Renewable Resources, Xinjiang Agricultural University, China) for determination of δ^{13}C values. The values of δ^{13}C of leaves were measured combining the Flash EA 2000 elemental analyzer (Thermo Electron, Waltham, MA, USA) with the Delta V Advantage isotope mass spectrometer (Thermo Finnigan, Bremen, German). The measurement error did not exceed 0.2‰. Observations were conducted to determine the actual water use of summer maize based on methods used as Farquhar and He et al. [12–16,21–24]. The calculation of WUE followed the equation below:

$$WUE = \frac{(1-\varphi)Ca(b-\delta a+\delta p)}{(b-a)1.6VPD} \tag{2}$$

where WUE (mmol C/mol H_2O) is the water use efficiency, a and b (empirical coefficient [18]) are isotopic shunt coefficients of CO_2 diffusion and carboxylation, respectively (a = 4.4‰, b = 30‰ [14]), Ca is the atmospheric CO_2 concentration, δa and δp [12] are values of $\delta^{13}C$ of air and plant material, and the carbon isotope composition of air was taken as −9‰ (Brugnoli and Farqhuar 2000). The the diffusion ratio of water vapor and CO_2 in air was 1.6, φ is the ratio of carbon consumed by nocturnal respiration of leaves and respiration of other organs during the entire growth period of a plant (φ = 0.3) [25], and VPD is the difference in vapor pressure between the inside and outside of the leaf blade. The VPD can be calculated according to the average daily meteorological data (air temperature, air humidity, etc.) on the day of sampling [26,27]

$$VPD = E - e$$

$$E = 0.611 \times 10^{17.502T/(240.97+T)}$$

$$RH = \frac{e}{E} \times 100\%$$

$$VPD = 0.611 \times 10^{17.502T/(240.97+T)} \times (1 - RH)\ (\text{kPa}) \tag{6}$$

where T is blade temperature, RH is the relative humidity of the atmosphere, 0.0611 is the saturated vapor pressure of the horizontal plane when T = 0 °C, e is the actual vapor pressure, and E is the saturated vapor pressure at the same temperature.

$$WUE = \frac{DW \times CC}{WU} \tag{7}$$

At the same time, WUE is the ratio between the total amount of carbon assimilated by plants and water use (WU, kg·m^{-2}) over a period of time, DW (g) is dry weight biomass of each organ, and CC (mg·g^{-1}) is carbon content.

2.3.5. Measurement of Physiological Indices

(1) Plant height: During the summer maize 6-leaf stage, 12-leaf stage, the silking stage, the filling stage, and the mature stage, three plants were selected at each stage for each treatment, and the plant height (cm) was measured with a ruler (1 mm).

(2) Dry mass: During the summer maize 6-leaf stage, 12-leaf stage, the silking stage, the filling stage, and the mature stage, three plants were selected at each stage for each treatment. The aboveground parts, including the leaves, stems, and ears, were dried at 105 °C initially, then dried at 80 °C until they reached a consistent weight.

2.4. Dual Crop Coefficient Approach

We calculated the evapotranspiration of summer maize in the experimental plots using the dual crop coefficient approach, according to the FAO-56 Equation as follows:

$$ET_c = (K_s K_{cb} + K_e)\ ET_0 \tag{8}$$

where ET_c (mm) is the actual crop evapotranspiration, ET_0 (mm) is the reference crop evapotranspiration that was calculated from the Penman-Monteith equation based on meteorological data [2], K_{cb} (-) is basal crop coefficient, and K_s (-) is the water stress coefficient. Both K_{cb} and K_s were calculated based on the K_e [2]. K_e (-) is the soil evaporation coefficient that was used to describe the soil evaporation component of crop evapotranspiration. Miao and Wen et al. [28,29] calculated K_e [2], which is generally calculated as

$$K_e = K_r\left(K_{c(\max)} - K_{cb}\right) \le f_{ew} K_{c(\max)} \tag{9}$$

where $K_{c(\max)}$ (-) is the maximum value of K_c after irrigation or rainfall, K_r (-) is the soil attenuation coefficient, and f_{ew} (-) is the percentage of exposed and wet parts of the soil surface. Detailed descriptions of the calculation of the parameters $K_{c(\max)}$ and K_r is available in FAO-56 [2].

This experiment included two treatments: Partial mulch and no mulch. The K_e of the no mulch treatments was calculated by Equation (9). The calculation of the soil evaporation coefficient for the partial mulch treatments consisted of two parts: Membrane hole evaporation and bare soil evaporation [29]. Based on the ratio of the area between covered and the bare soils in the partial mulch treatments, K_e was calculated as:

$$K_e = \frac{3}{4}K_{e_1} + \frac{1}{4}K_{e_2} \tag{10}$$

where K_{e_1} (-) and K_{e_2} are the membrane pore evaporation coefficient and the bare soil evaporation coefficient, respectively, which were calculated from Equation (9).

The f_{ew} [2] under the drip irrigation condition was calculated as follows:

$$f_{ew} = \min\left(1 - f_c, \left(1 - \frac{2}{3}f_c\right)f_w\right) \tag{11}$$

where f_c (-) is the proportion of vegetation cover to the surface soil area and f_w is the moisture ratio at the soil surface.

In the calculation of K_{e_1}, the f_w [29] in Equation (11) was calculated as:

$$f_w = \alpha N A_h / A_{total} \tag{12}$$

where α (-) is the membrane effective area factor, N (-) is the number of membrane holes, A_h (m^2) is the area of a single membrane hole, and.A_{total} (m^2) is the total area of the membrane.

In the calculation of K_{e_2}, f_w was set to 1.

2.5. Statistics

The regression coefficient (b) [30], coefficient of agreement (d) [30], and root mean square error (RMSE) [30] were used to evaluate the model's applicability. They were calculated as follows:

(1) The regression coefficient through the origin (b)

$$\mathrm{b} = \frac{\sum_{i=1}^{n} O_i \times P_i}{\sum_{i=1}^{n} O_i^2} \tag{13}$$

(2) The coefficient of agreement (d)

$$\mathrm{d} = 1 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} \left(\left|P_i - \overline{O}\right| + \left|O_i - \overline{O}\right|\right)^2} \tag{14}$$

(3) The root mean square error (RMSE)

$$\mathrm{RMSE} = \sqrt{\frac{1}{m}\sum_{i=1}^{m} (O_i - P_i)^2} \tag{15}$$

where O_i and P_i are the measured and estimated value of i, respectively, and $\overline{O}$ is the average of O_i (I = 1, 2, . . . , n).

The closer the values of b and d were to 1.0, the higher was the agreement between the estimates and the measurements. A lower RMSE value indicated a better fit.

3. Results

3.1. Parameterization of the Dual Crop Coefficient Approach

Using the parameters in Table 3, the dual crop coefficient approach was used to estimate the evapotranspiration of the partial mulched summer maize in 2016 and the non-mulched summer maize in 2017. Under mulching, the comparisons between evapotranspiration were estimated by the model and the practical crop evapotranspiration was calculated by the water balance method for the five treatments (Figure 3a). Under the non-mulched condition, the comparisons between the estimated evapotranspiration of W1, W3, and W5 by the model, and the practical crop evapotranspiration calculated by the water balance method, are shown in Figure 3b. The comparisons between measured and estimated ET are shown in Table 4.

Table 3. Parameters for the dual crop coefficient approach that was used to estimate evapotranspiration of summer maize on plots in Xinjiang, China.

Variables	Parameters	Range	Value	Sources
Basal crop coefficient (with/without mulch)	$Kcb_{(ini)}$ $Kcb_{(mid)}$ $Kcb_{(end)}$	0.15 1.15 0.50	0.15/0.15 1.20/1.12 0.87/0.50	calibration
Depth of the surface soil layer	*Ze*	0–0.15	0.10	FAO-56 [2]
Readily evaporable water	*REW*	8–11	9	calibration
Total evaporable water	*TEW*	18–25	20	calibration
Effective area coefficient of membrane hole	α	2–8	6	Wen et al. [29]

$Kcb_{(ini)}$, $Kcb_{(mid)}$, and $Kcb_{(end)}$ are basal crop coefficients in initial, middle, and late stages.

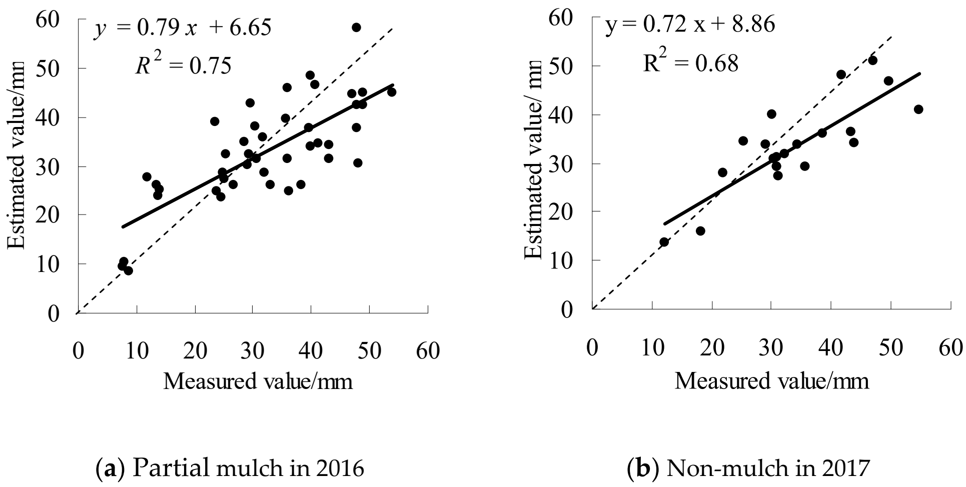


Figure 3. Regression between observed and estimated evapotranspiration in 2016 and 2017 on partial mulched and non-mulched plots in Xinjiang, China. (**a**) Partial mulch in 2016; (**b**) non-mulch in 2017.

The measured and estimated ET values under the partial mulching treatment in 2016 and the non-mulching treatment in 2017 were close to the 1:1 line, with determination coefficients (R^2) of 0.75 and 0.68, respectively (Figure 3a,b). The RMSE of the estimated ET values of mulched summer maize for the five treatments in 2016 ranged from 6.95 to 10.66 mm, and the regression coefficient (b) varied from 0.91 to 1.06 (Table 4). The concordance index (d) varied from 0.98 to 0.99. In 2017, the RMSE of estimated ET values of non-mulched summer maize for the three treatments (W1, W3, and W5) were similar to those of the mulched treatments and ranged from 7.71 to 10.43 mm. The regression coefficient (b) varied from 0.99 to 1.18, and (d) varied from 0.90 to 0.96, which indicated that there was a good fit between measurements and estimates.

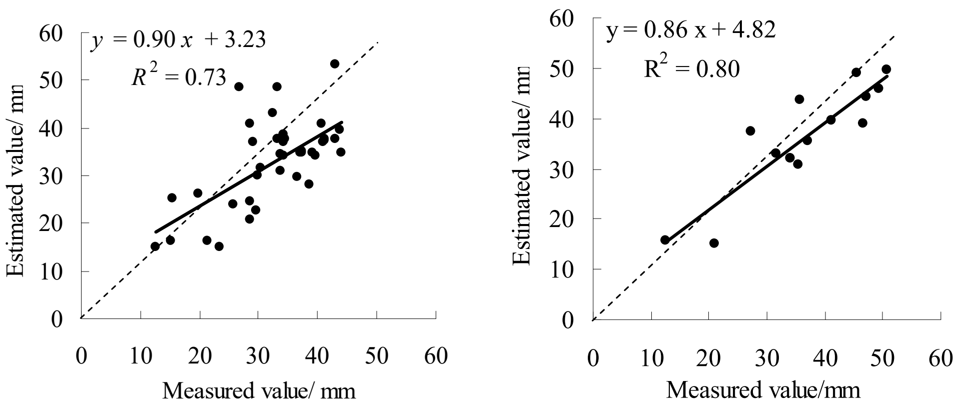
Table 4. Statistics of observed and estimated evapotranspiration in 2016 and 2017 on partial mulched and non-mulched plots in Xinjiang, China.

Year	Treatment	RMSE/mm	b	d
2016 With Partial Mulch	W1	8.12	0.93	0.99
	W2	7.52	0.91	0.99
	W3	7.59	0.92	0.99
	W4	6.95	0.99	0.99
	W5	10.66	1.06	0.98
2017 Without Mulch	W1	7.71	0.99	0.96
	W3	10.94	1.18	0.90
	W5	10.43	0.99	0.92

3.2. Model Evaluation

3.2.1. Model Evaluation Based on the Water Balance Method

The calibrated model parameters were put into the dual crop coefficient model to calculate crop ET for five treatments for different irrigation periods in 2017. We compared the model outputs with the measured ET. Figure 4a showed the relationship between the measured and estimated ET values of the five treatments in the mulched summer maize in 2017. Figure 4b demonstrated the relationship between the measured and estimated ET values of the two treatments (W2 and W4) in the non-mulched summer maize in 2017. The statistics are shown in Table 5.



(**a**) Partial mulch in 2017 (**b**) Non-mulch in 2017

Figure 4. Regression between observed and estimated evapotranspiration in 2017 on partial mulched and non-mulched plots in Xinjiang, China. (**a**) Partial mulch in 2017; (**b**) Non-mulch in 2017.

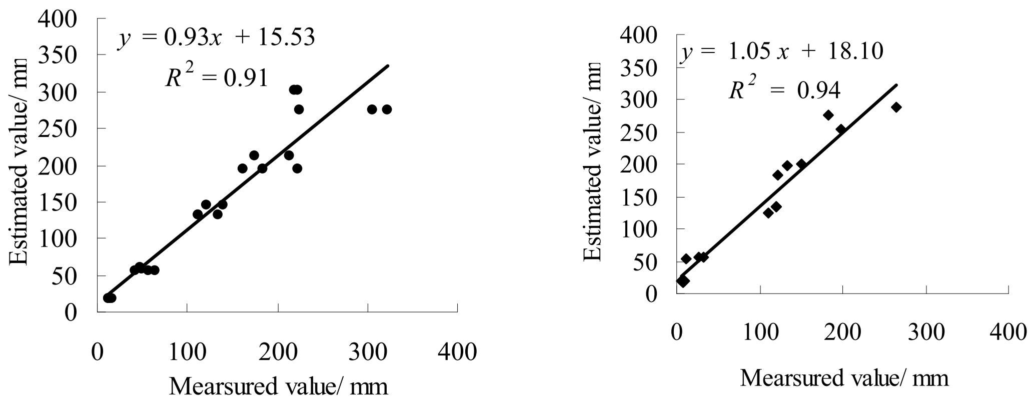
Compared with the measurements from the water balance method, the model accurately estimated ET of summer maize during the growing period in the experimental region. The measured and estimated ET values of the mulched summer maize in the growing season were close to the 1:1 line, with an R^2 of 0.73 (Figure 4a). The RMSE of the measured and estimated ET values in each treatment during the growing season ranged from 4.59 to 12.56 mm, with (b) of 1.03–1.12, and (d) of 0.86–1.00. The measured and estimated ET values of the non-mulched summer maize in the growing season were also close to the 1:1 line, with an R^2 of 0.80 (Figure 4b). The RMSE of the measured and estimated ET values of W2 and W4 treatments were 7.84 mm and 6.88 mm, with (b) of 1.04 and 0.98, and (d) of 0.96 and 0.95, respectively. Our results suggested that there were good agreements between predicted and measured ET for summer maize during the growing season after parameterizing the model correctly.

Table 5. Statistics of observed and estimated evapotranspiration in 2017 on partial mulched and non-mulched plots in Xinjiang, China.

Year	Treatment	RMSE/mm	b	d
2017 With Partial Mulch	W1	4.59	1.03	0.99
	W2	11.37	1.06	0.89
	W3	12.56	1.06	0.86
	W4	10.15	1.12	0.99
	W5	11.75	1.03	1.00
2017 Without Mulch	W2	7.84	1.04	0.96
	W4	6.88	0.98	0.95

3.2.2. Model evaluation based on stable carbon isotope techniques

Figure 5a showed the partial mulched regression between the measured and simulated crop transpiration (T) of summer maize with five treatments in 2017 using stable carbon isotope method. Since only non-mulched treatments, i.e., W1, W2 and W5, were used the stable carbon isotope technique to calculate crop transpiration, Figure 5b showed the regression between the measured and estimated crop T of the three treatments in summer maize during each growth periods. The statistics are shown in Table 6.



(**a**) Partial mulch (**b**) Without mulch

Figure 5. Regressions between observed and estimated transpiration in 2017 on mulched and non-mulched plots in Xinjiang, China. (**a**) Partial mulch; (**b**) without mulch.

Table 6. Statistics of observed and estimated transpiration for mulched and non-mulched plots in 2017 in Xinjiang, China.

Treatment	Partial Mulch	RMSE/mm	b	d
W1	Yes	17.83	1.14	0.98
	No	26.48	1.29	0.94
W2	Yes	22.62	1.23	0.97
	No	23.07	1.22	0.95
W3	Yes	14.21	1.14	0.98
W4	Yes	18.02	0.91	0.98
W5	Yes	25.44	0.82	0.97
	No	13.05	1.05	0.99

Compared with the measurements from stable carbon isotopes, the model accurately estimated summer maize crop transpiration (T) during the growing season. There was good agreement between the predicted and measured crop T during the growing season (Figure 5, Table 6). For the partial mulched and non-mulched treatments, the determination coefficients (R^2) were 0.91 and 0.94, respectively. The RMSE was in the range of 14.21–25.44 mm and 13.05–26.48 mm, with a coefficient (b) of 0.82–1.23 and 1.05–1.29, and (d) of 0.97–0.98 and 0.94–0.99 for partial mulched and non-mulched plots, respectively. The evaluations of the model suggested that after the model was calibrated, it accurately estimated summer maize change in T during the growing season. This further shows the effectiveness of the stable carbon isotope technique in quantifying the T of summer maize in arid regions.

3.3. Evapotranspiration Dynamics of Summer Maize

The measurements of five treatments under mulching conditions in 2016 suggested that the dual crop coefficient approach underestimated ET in the rapid growth and late growth stages of summer maize, but overestimated ET in the late growth stage (Table 7). The reason may be that the pump failure on 1 September 2017 led to early water emergence of summer maize, which resulted in a slight deviation between the measured ET and the simulated ET value. The highest water consumption of summer maize was in the middle growth stage, which accounted for about 40% of the total ET over the entire growing season. The second highest water consumption was during the rapid growth stage, which accounted for about 35% of the total ET over the entire growing season. Under the non-mulched condition, water consumption of summer maize during the rapid growth phase was larger than during other periods, which accounted for about 45% of the total ET, followed by the middle growth phase, where water consumption accounted for about 35% of the total ET. Compared with the two methods of partial mulch or no mulch, the proportion of ET differed in the different time periods. The reason is that summer maize under the mulching condition entered the middle growth stage earlier, which shortened the rapid growth stage and extended the crops middle growth stage. This conclusion is similar to that of Wen et al. [29].

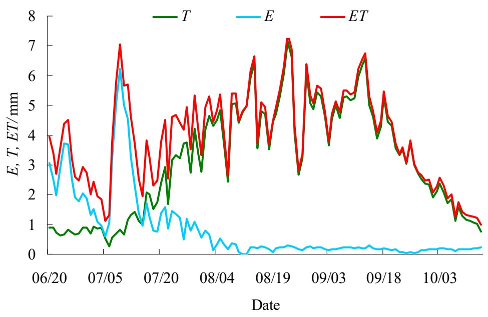
Table 7. Values of observed and estimated evapotranspiration at different growth stages of summer maize on partially mulched and non-mulched plots in Xinjiang, China.

Year	Growth Stage	W1		W2		W3		W4		W5	
		Observations (O)/mm	Estimations (E)/mm	O/mm	E/mm	O/mm	E/mm	O/mm	E/mm	O/mm	E/mm
2016 With PartialMulch	Initial	60.0	69.3	58.0	63.7	63.0	58.9	56.0	62.2	55.0	58.9
	Rapid	165.5	143.0	149.2	130.0	150.8	118.0	135.6	124.9	132.3	119.4
	Middle	183.4	219.2	176.4	199.2	152.0	179.2	167.8	188.9	129.6	179.2
	Late	58.4	31.2	50.5	28.9	39.9	25.5	40.8	26.9	67.6	25.5
	Whole	467.3	462.7	434.1	421.8	405.6	381.7	400.2	403.0	384.5	383.1
2017 With PartialMulch	Initial	69.5	70.0	62.6	67.1	55.7	63.0	56.0	68.5	65.6	63.0
	Rapid	129.5	132.5	146.0	131.2	146.1	120.5	132.5	123.7	116.6	120.5
	Middle	176.2	174.9	152.4	174.8	119.7	159.1	146.5	159.5	140.1	159.5
	Late	14.3	13.3	8.3	13.2	8.9	12.0	11.1	12.1	6.8	12.1
	Whole	389.6	390.7	369.2	386.3	330.4	354.7	346.1	363.7	329.0	355.0
2017 Without Mulch	Initial	81.5	68.4	81.2	67.6	63.0	66.2	71.0	53.6	76.2	53.6
	Rapid	191.9	192.9	169.3	186.6	154.1	175.9	164.8	169.1	143.9	173.2
	Middle	137.6	141.6	122.7	134.6	105.4	121.4	115.3	138.8	140.0	149.3
	Late	26.1	14.1	18.7	13.3	14.0	12.6	24.8	12.6	16.9	20.2
	Whole	437.1	417.0	392.0	402.1	336.5	376.0	375.9	374.1	377.0	396.3

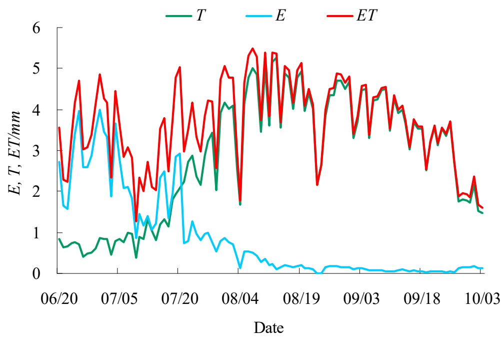
3.4. Partitioning of Evapotranspiration of Summer Maize

The temporal patterns of ET were similar under different treatments with the condition of partial mulched. For example, the estimated ET for W1 had similar patterns under partial mulching during the two growing seasons (Figure 6a,b). In the initial growth stage, ET values were small. As the crops grew, ET gradually increased in the middle growth stage and decreased gradually in the late stage.

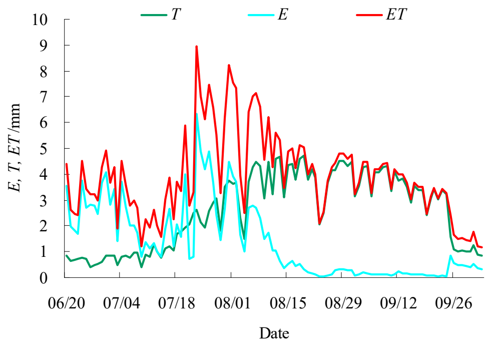
During the two growing seasons, the pattern of estimated T was consistent with ET. It was small at the initial stage, increased during the development stage, reached a maximum during the middle stage, and then decreased during the late stage. However, the E dynamics were the opposite of T; it was large at the initial stage, and decreased gradually as the crop grew during the middle and late stages. The dynamics of E changed little in the late growth stage compared with the middle growth stage.



(**a**) 2016—with partial mulch



(**b**) 2017—with partial mulch



(**c**) 2017—with no mulch

Figure 6. Seasonal variations in evapotranspiration (ET), evaporation (E), and transpiration (T) of summer maize for treatment W1 during the growing season on partially mulched and non-mulched plots in Xinjiang, China. (**a**) 2016—with partial mulch; (**b**) 2017—with partial mulch; (**c**) 2017—with no mulch.

ET with no mulching was high during the rapid growth stage because evaporation was high in this period (Figure 6c). T was low at the initial stage. During the rapid growth stage, T gradually increased and exhibited a relatively stable pattern during the middle stage. However, the E dynamics were the opposite of T. The E value in the initial and rapid growth stages were high, and it gradually became lower after the middle stage. The magnitude of the change was relatively stable.

The dual crop coefficient approach was used to estimate the evaporation (E) and leaf transpiration (T) under partially mulched and non-mulched conditions, and it was used to estimate the ratio of leaf transpiration to crop evapotranspiration (T/ET) and the ratio of evaporation to evapotranspiration (E/ET) during a crop's growing season (Table 8). In 2016 and 2017, under the partially mulched condition with summer maize, the estimated T/ET for 2016 and 2017 were 78.7% and 76.0%, respectively, and the E/ET were 21.3% and 24.0%, respectively. In 2017, under the non-mulched condition, the estimated T/ET was 64.89% over the entire growing season, which was about 12% lower than that of the partial mulched treatments. The E/ET was 35.11%, which was about 12% higher than that of the partial mulched treatments. This conclusion is different from the results of Ding et al. [10]. The reason may be that Ding et al. simulated the situation of complete film mulching, but in the current experiment, we used partial film mulching, which resulted in a higher evaporation.

Table 8. Variations in *T*, *E*, *T/ET*, and *E/ET* of summer maize on partial mulched and non-mulched plots during different growth periods in Xinjiang, China.

Stage	2016 With Partial Mulch				2017 With Partial Mulch				2017 With no Mulch			
	T/mm	E/mm	T/ET/%	E/ET/%	T/mm	E/mm	T/ET/%	E/ET/%	T/mm	E/mm	T/ET/%	E/ET/%
Initial	15.3	54.0	22.1	77.9	15.0	55.0	21.4	78.6	15.0	53.4	21.9	78.1
Rapid	109.4	33.6	76.5	23.5	99.2	33.4	74.8	25.2	109.6	83.3	56.8	43.2
Middle	211.0	8.2	96.3	3.7	170.6	4.3	97.6	2.4	136.3	5.3	96.2	3.8
Late	28.3	2.9	90.7	9.3	12.2	1.0	92.3	7.7	9.7	4.4	68.7	31.3
Whole	364.0	98.7	78.7	21.3	297.0	93.7	76.0	24.0	270.6	146.4	64.9	35.1

4. Conclusions

(1) The dual crop coefficient approach accurately estimated the ET during different summer maize growth periods. The RMSE was around 10 mm under the partially mulched conditions in 2016 and 2017. The averaged regression coefficient (b) was about 1. The consistency index (d) for 2016 and 2017 was in the range of 0.97–1 and 0.86–1, respectively. In 2017, the RMSE was about 6 mm under non-mulched conditions. The regression coefficient (b) was about 1. The coefficient of agreement (d) was in the range of 0.68–0.97, which was consistent with the observed values.

(2) The dual crop coefficient approach accurately partitioned summer maize evapotranspiration. The estimated transpiration over the entire growing season of summer maize under partially mulched conditions in 2016 and 2017 accounted for 78.7% and 76.0% of ET, respectively, and the evaporation accounted for 21.3% and 24.0% of ET, respectively. In 2017, the estimated transpiration over the entire maize growing season under non-mulched conditions accounted for 64.89% of ET, which was about 12% lower than that of the partially mulched treatments. The evaporation of non-mulched treatments accounted for 35.1% of ET, which was about 12% higher than that of the partially mulched treatments.

(3) In 2017, the average water consumption of summer maize under partially mulched treatments was about 350 mm, but the water consumption under the non-mulched conditions was about 380 mm. The water consumption over the entire growing season for the partially mulched maize was about 30 mm, which was about 10% lower than that of the non-mulched conditions, which suggested that partially mulched treatments can be used to improve water use efficiency.

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