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Partitioning of Cotton Field Evapotranspiration under Mulched Drip Irrigation Based on a Dual Crop Coefficient Model

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Abstract: Estimation of field crop evapotranspiration (ET_c) and its partitioning into evaporation and transpiration, are of great importance in hydrological modeling and agricultural water management. In this study, we used a dual crop coefficient model SIMDualKc to estimate the actual crop evapotranspiration ($ET_{c\ \mathrm{act}}$) and the basal crop coefficients over a cotton field in Northwestern China. A two-year field experiment was implemented in the cotton field under mulched drip irrigation. The simulated $ET_{c\ \mathrm{act}}$ is consistent with observed $ET_{c\ \mathrm{act}}$ as derived based on the eddy covariance system in the field. Basal crop coefficients of cotton for the initial, mid-season, and end-season are 0.20, 0.90, and 0.50, respectively. The transpiration components of $ET_{c\ \mathrm{act}}$ are 96% (77%) and 94% (74%) in 2012 and 2013 with (without) plastic mulch, respectively. The impact of plastic mulch cover on soil evaporation is significant during drip irrigation ranging from crop development stage to mid-season stage. The extent of the impact depends on the variation of soil moisture, available energy of the soil surface, and the growth of the cotton leaves. Our results show that the SIMDualKc is capable of providing accurate estimation of $ET_{c\ \mathrm{act}}$ for cotton field under mulched drip irrigation, and could be used as a valuable tool to establish irrigation schedule for cotton fields in arid regions as Northwestern China.

Keywords: SIMDualKc model; dual crop coefficient; eddy covariance; plastic mulch

1. Introduction

Crop evapotranspiration (ET_c) consumes a large amount of irrigation water, especially in arid areas; thus, accurate estimation of evapotranspiration is the basis of hydrological modeling and agricultural water management [1]. Transpiration (T) through plant stomata is a desirable component because this process is usually associated with plant productivity; evaporation (E) over bare soil is usually considered as water loss but sometimes also provides a benefit for maintaining a micro-climate around the crop under conditions of high irrigation levels [2]; therefore, ET_c partitioning is essential for agriculture water resource management as well as hydrological modeling [3,4]. Common ways to partition ET_c include experimental methods or simulation methods. For the experimental methods, lysimeters [5,6], soil water budget [7], sap flow [8,9], and stable isotope [10,11] methods are usually adopted to evaluate E and T individually in previous studies.

However, these experimental methods usually require costly equipment and can only be carried out at point scale, which provides poor spatial representation [10]. Therefore, a number of models have been developed to predict E and T conveniently and to simulate evapotranspiration for agricultural management [12–14]. In these models, the FAO-56 crop coefficient reference evapotranspiration methods [12], including single and dual crop coefficient methods, are commonly used to calculate ET_c [6,15–17]. The FAO-56 dual crop coefficient method separately calculates transpiration and evaporation, which has been widely used in agriculture science [5,18–23]. The SIMDualKc model is based on the FAO-56 dual crop coefficient approach and combined with the hydrological extension for complete water balance, which can be used to support general irrigation scheduling needs [24]. The modelemploys a graphic- and menu-driven user interface that can serve as a convenient and effective tool to calculate actual crop ET_c [24]. The model has been used worldwide for different crops, such as wheat, maize, barley, soybean, cotton, vineyard, and other kinds of ecosystems [22,23,25–30]; the model also exhibits good adaptation and efficiency under various irrigation methods [22–24,26,31] and ground cover [32–34]. Hence, the model was utilized in our study to implement the use of the dual crop coefficient of cotton under mulched drip irrigation in Northwest China. The model should be properly calibrated and validated before use when management options have not been initially tested, and the observed soil moisture and ET_c are common variables used for this purpose [22,30,35].

The eddy covariance (EC) system, which can directly measure ET_c, is widely used in the field and is recognized as the standard method to measure ET_c [1,36–38]. This system can accurately and continuously estimate crop coefficients in real time [11]. Studies on ET_c and crop coefficient by EC, have been conducted on cropland, as well as other ecosystems [39,40]. In our study, the EC system was used to measure ET_c in 2012 and 2013, and the measurements were used to calibrate the SIMDualKc model.

Cotton is an important and widely cultivated fiber crop in the United States, India, Pakistan, Uzbekistan, and China [41]. In 2012, the cultivated area for cotton production in Xinjiang Uygur Autonomous Region occupied more than 50% of China [42]. Xinjiang is in an arid area, thus, irrigation is critical for cotton growth [43–45]. Increased water consumption for irrigation leads to groundwater overexploitation and surface water overuse, which accelerates the deterioration of ecological environment especially in the downstream of inland rivers; excessive irrigation in arid areas can also induce secondary salinization which is harmful to the growth of crops [46–48]. The limited water resources and salinization constrain agriculture development in the region; thus, drip irrigation and plastic mulch are developed to conserve water [3]. Mulched drip irrigation is a useful and economic way to improve the soil micro-climate condition and increase the water efficiency [15,27,49,50]. Agricultural water consumption accounts for more than 90% of all water withdrawal from the Kaidu-Kongqi River Basin (a source basin of Tarim River in Xinjiang), and most cotton fields in the Kaidu-Kongqi River Basin are cultivated under mulched drip irrigation [38]. Mulched drip irrigation is a potential water-saving method also in other districts in China [20], as well as in Central Asia, where cotton is also heavily grown; these regions also exhibit a similar dry climate [41,51,52].

A few researchers have investigated dual crop coefficients under drip irrigation with mulching [15,27,49,53]. Nevertheless, research on cotton dual crop coefficient under mulched drip irrigation has been rarely reported. This study aimed to use an EC system and a SIMDualKc model to partition cotton field evapotranspiration under mulched drip irrigation and to evaluate the effect of plastic mulch on ET_c. The SIMDualKc model was calibrated on the basis of the observed evapotranspiration data; recommended parameters, including crop coefficients proposed by the FAO [12], were also evaluated to determine applicable values in our study area.

The objectives of this study are as follows: (a) to validate the SIMDualKc model by using the observed data obtained by eddy covariance system; (b) to analyze the temporal variations of dual crop coefficients and the partition of cotton field ET_c under mulched drip irrigation in different growth periods based on the simulated results; and (c) to estimate the effect of plastic mulch on ET_c.

2. Materials and Methods

2.1. Experimental Site

The study area is located in the Tsinghua University-Korla Oasis Eco-hydrology Experimental Research Station, which is 22 km away from the town of Xiborni in Korla City, Xinjiang Uygur Autonomous Region (Figure 1). This area lies on the alluvial plain of Kaiqu-Kongqi River, at the southern foot of the Tian Shan Mountains. The average elevation is 897–902 m. The study area has a continental desert climate with a warm temperate zone, scarce precipitation and intense potential evapotranspiration. The annual mean precipitation is approximately 60 mm, and annual mean potential evaporation is approximately 2800 mm. Average annual temperature is 11.5 °C and sunshine duration is 3036 h. The average relative humidity, net radiation, and wind speed during the cotton growth period were 40%, 110 $w\cdot m^{-2}$, and 1.90 $m\cdot s^{-1}$, respectively. We carried out a two-year (2012–2013) experiment in this field. The reference evapotranspiration (ET_o) is calculated based on the Peman-Monteith equation (as suggested by the FAO-56 [12]), using the observations from an automatic weather station within the experiment field. The variations of ET_o are shown in Figure 2.

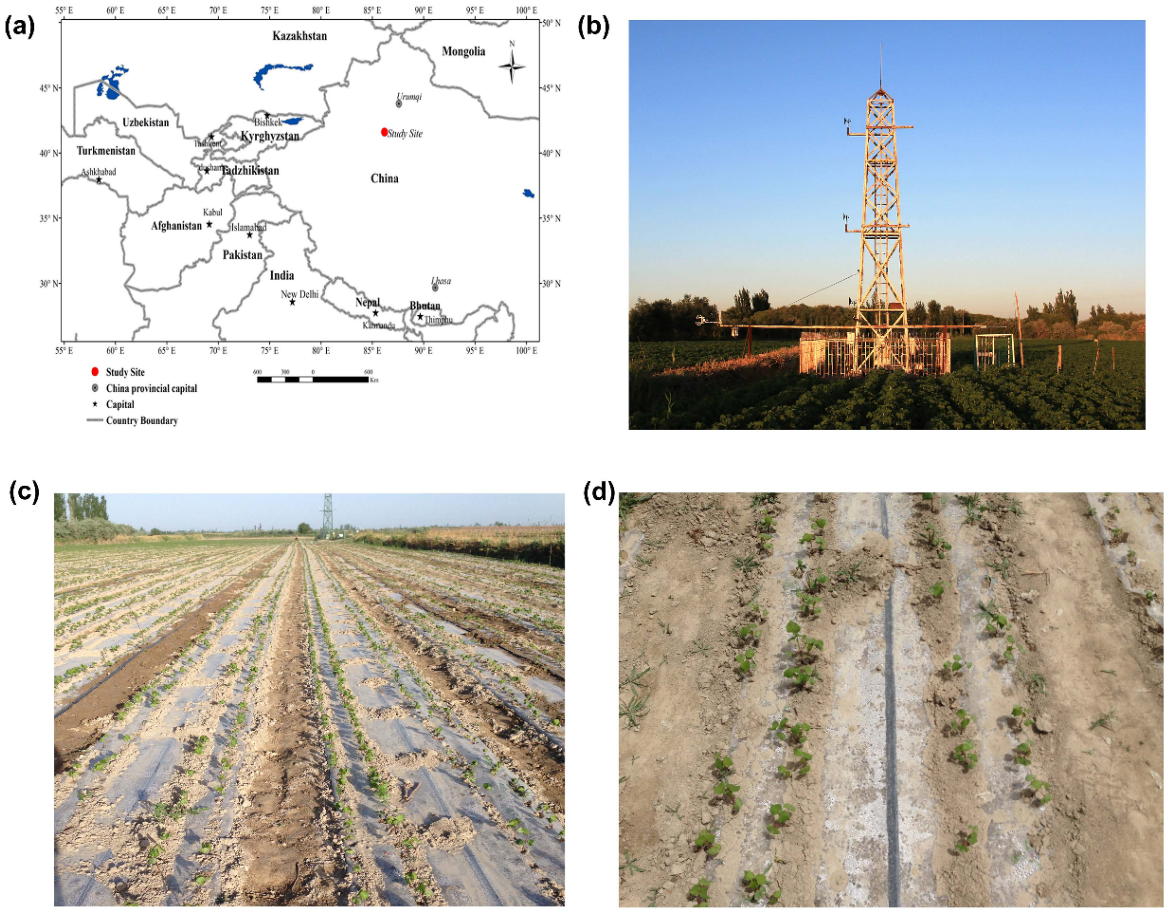


Figure 1. The location and eddy covariance system of the study area: (**a**) the location of the study areas; (**b**) the observing tower in the field; (**c**,**d**) the cotton under mulched drip irrigation and one-film, one-pipe, four-row mode.

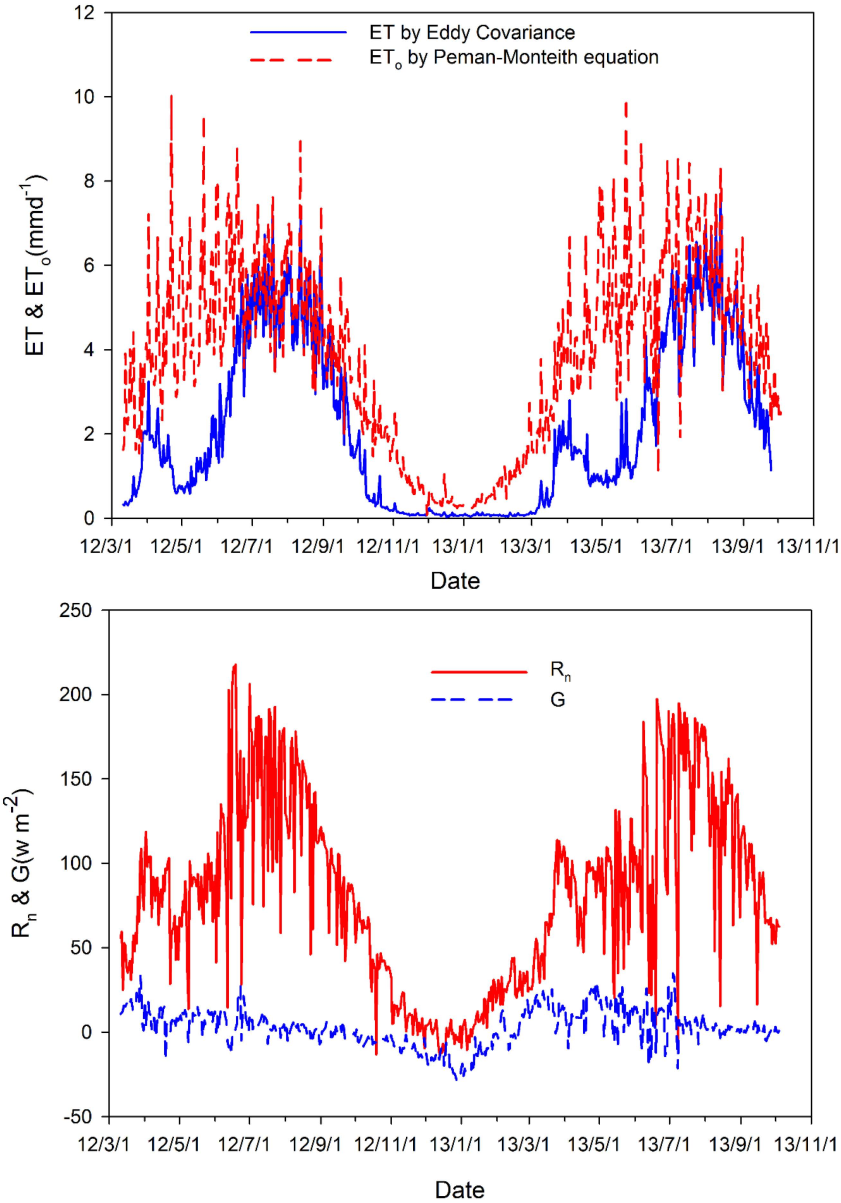


Figure 2. Evapotranspiration and energy flux measured by eddy covariance.

The groundwater table level was measured using an automatic water depth sensor (model HOBO U20 Titanium Water Level Data Logger, Onset Computer Corporation, Inc., Pocasset, MA, USA) installed in a groundwater well near the observation tower. The groundwater level varied from 1.0 m to 4.0 m throughout the entire growth period, reaching a high value at the beginning of cotton growth after flood irrigation. The flood irrigation was usually about two weeks before seeding, and from 25–29 March 2012 and from 22–26 March 2013 [54]. The total amount of the spring irrigation is about 375 mm for both the two years. The texture of the soil is loam, which is made up of 30% sand, 5% silt, and 65% loam. The soil bulk density of the experiment field is from 1.40 g· cm^{-3} to 1.64 g· cm^{-3} in the 1.5 m soil profile. The depth of frozen soil is approximately 60 cm. The saturated water content of soil is nearly 0.42 [50].

2.2. Cotton Planting

Cotton (*Gossypium hirsutum* L.) is planted under mulched drip irrigation in the entire growth period and the experimental field covers an area of 3.48 ha (see Figure 1). Mulched drip irrigation involves plastic mulch covering the drip tape and the surface soil. The cotton planting and drip irrigation tape employs one-film, one-pipe, four-row mode [38,44]. The drip irrigation tape is located beneath the middle of the mulch. Two cotton rows are symmetrically distributed on both sides of the tape. The mulch width is 110 cm, and the inter-mulch zone width is 40 cm. The widths of the cotton row spaces are 20, 44, and 20 cm (Figure 1). The irrigation schedules in the two-year experimental period are summarized in Table 1. Irrigation was performed roughly once a week starting in mid-June and ending in late August for both years. The irrigation lasts for about 12 h for each irrigation event and the flow is about 15 $m^3 \cdot h^{-1}$ with the meter measurement. The irrigation tape is made of plastic and the external diameter of the irrigation tape is 16mm, the wall thickness is about 0.2 mm, the space between the drip holes is about 0.3 m, the work pressure is 0.10 MPa, and the flow rate of each tape is 3.2 $L \cdot h^{-1}$.

Table 1. Irrigation schedules adopted for experiments in 2012 and 2013.

Growth Stage		Squaring Stage				Flowering Stage				Bolls Stage			
2012	Irrigation date	6–10 & 6–14 *	6–21	6–28	7–6	7–15	7–26	8–4	8–8	8–12	8–17	8–22	8–27
	Volume (mm)	65.2	34.4	35.3	36.8	33.3	44.1	40.0	59.3	46.7	42.2	50.8	52.2
2013	Irrigation date	6–13	6–20	6–28	7–3	7–9	7–16	7–27	8–2	8–8	8–13	8–18	8–22
	Volume (mm)	48.5	32.3	30.7	39.2	76.0	46.5	39.0	53.1	63.2	51.8	52.1	58.8

Note: * The total irrigation on 10 and 14 June 2012 was about 65.2 mm.

Cotton was sown in mid-April and harvested in early October. The growth stages of cotton are shown in Table 2. The seeds were sown with a spacing of 0.1 m between rows, and the planting densities were approximately 89,800 and 95,700 plants ha^{-1} in 2012 and 2013, respectively. The planting density in 2012 was approximately 6% less than that in 2013 because of sandstorm and freezing damage that caused a low emergence rate of cotton. The crop height, root depth, and leaf area index (LAI) were measured at an interval of two weeks, and the main crop physiological parameters of the growth stage are presented in Table 3. All of the leaves were stripped from each plant, and the leaf area was then obtained by directly scanning all of the leaves using a leaf area meter (model Yaxin-1241, Beijing Yaxinliyi Science and Technology Co., Ltd., Beijing, China). The LAI was calculated by dividing the leaf area by the area that each plant occupied [38].

Table 2. Cotton growth stages of 2012 and 2013.

Cotton Growth Stages	Phenological Growth Stages	2012	2013
Planting/initiation	Emergence & Squaring stage	23 April–23 May	22 April–5 June
Rapid growth	Squaring & Flower stage	24 May–6 July	6 June–14 July
Midseason	Flower & Boll stage	7 July–2 September	15 July–28 August
Maturity	Boll stage	3 September–7 October	29 August–4 October

Table 3. Main crop parameters of the growth stage.

Year	Physiological Parameter	Planting	Start Crop Development	Start Mid-Season	Start Late-Season	Harvest
2012	Root depth (m)	0	0.4	0.70	0.70	0.70
	Crop height (m)	0	0.20	0.76	0.76	0.76
	Fraction of ground cover	0	0.2	0.50	0.95	0.85
2013	Root depth (m)	0	0.4	0.62	0.62	0.65
	Crop height (m)	0	0.4	0.62	0.62	0.67
	Fraction of ground cover	0	0.20	0.50	0.95	0.85

2.3. EC System

The EC system was installed in a 10 m-high stationary tower (see Figure 1 for more details). The main components of EC system are as follows: a fast response open-path infrared gas (H_2O

and CO_2) analyzer (model EC150, Campbell Scientific Inc., Logan, UT, USA), a fast response 3D sonic anemometer (model CSAT3, Campbell Scientific Inc.), air temperature/humidity sensor (model HMP155A, Vaisala Inc., Woburn, MA, USA), a micro logger (model CR3000, Campbell Scientific Inc.) and net radiometer (model LITE2, Kipp and Zonen, Delft, The Netherlands). The abovementioned equipment was installed at a height of 2.25 m. The soil heat flux plates (model HFP01SC, Hukseflux, The Netherlands) were imbedded 0.05 m below the ground surface under the film-mulched zone and inter-film zone to obtain the soil heat flux (G). Data processing and energy closure have been discussed in the literature [38], and the data over two years from the EC system were used in this study. The latent heat flux was calculated by multiplying vertical velocity fluctuations by a scalar concentration fluctuation [55]:

$$\lambda ET = \lambda \rho_a \overline{w'q'} \tag{1}$$

where λ ET is the latent heat flux (W· m^{-2}), λ is the latent heat of vaporization (J· kg^{-1}), ρ_a is the air density (kg· m^{-3}), and $\overline{w'q'}$ is the covariance between fluctuations of vertical wind speed w' (m· s^{-1}) and air humidity q' (kg· kg^{-1}).

The azimuth angle of the CSAT3 sensor is 50° from true north. The maximum height of the crop is approximately 70 cm, which ensures that the EC systems maintain an appropriate footprint. The data were measured at a frequency of 10 Hz and the fluxes were computed in half-hour. Energy closure was used to evaluate the quality of the measurement data. The net radiation (R_n), G, sensible heat (H) and latent heat (LE) were all obtained through the EC systems. The slope of the energy balance equation ($LE + H = R_n - G$) for this site in 2012 and 2013 was 0.72 ($r^2 = 0.90$, $n = 21,886$) [38]. The ratio was similar to the values obtained in previous studies (0.70–0.90) [7]. Thus, the data can be regarded as reliable, considering the influence of the plastic mulch to the energy transport between the soil and atmosphere [56]. The calculated ET and variation of radiation and soil heat flux are shown in Figure 2.

2.4. SIMDualKc Model

The actual ET was simulated by using the SIMDualKc model, which is an irrigation scheduling simulation model. The actual crop ET is estimated by the dual crop coefficient equation as follows [12,24]:

$$ET_{c\ act} = (K_s K_{cb} + K_e) ET_o \tag{2}$$

where K_{cb} is the basal crop coefficient, K_s is the water stress reduction coefficient, K_e is the soil evaporation coefficient, $ET_{c\,\mathrm{act}}$ is the actual crop evapotranspiration and ET_o is the reference evapotranspiration (mm· day^{-1}), which is calculated using the FAO Penman-Monteith equation [12,18].

The model considers the different influence of irrigation and precipitation on the variation of soil evaporation. The K_e is divided into two parts, $K_e = K_{ei} + K_{ep}$, where K_{ei} is the soil evaporation coefficient induced by irrigation and precipitation that raise soil moisture, and K_{ep} is the soil evaporation coefficient induced by the precipitation only [57]. The effects of crop height, crop density, and canopy architecture on K_{cb} were calculated through the density coefficient (K_d) [24,32].

Crop management is also considered in the model, such as using mulch to decrease the evaporation; that is, the model considers the fraction of soil covered by the plastic sheet and estimated the influence compared to the fraction of ground cover [24].

The input data of the model consist of the following [24]:

(a) Soil data: the total available water (TAW, mm· m^{-1}). It can be calculated with the field soil content and wilting point soil moisture or use the suggested the values; amount and depth of the soil layers; effective depth of the evaporation layer (Z_e, m); readily and total evaporable water (REW and TEW, mm); and textural classes of that layer when the values are calculated by the model.

(b) Meteorological daily data: minimum and maximum air temperature, $T_{\max}$ and $T_{\min}$ (°C); reference evapotranspiration (ET_o, mm); minimum relative humility ($RH_{\min}$, %); precipitation (P, mm); and wind speed at 2 m height (u_2, ms^{-1}).

(c) Crop data: data for the initial, crop development, mid-season, late-season and harvest or end-of-season growth stages; initial and end-of-season data of frozen soil; basal crop coefficient (K_{cb}) for the initial, mid-season and harvest growth stages; soil water depletion fraction without stress (p), and the fraction of ground cover (f_c), for all growth stages; root depths (Z_r, m) and crop height (h, m).

(d) Irrigation data: irrigation system; irrigation data; fraction of soil surface wetted by irrigation (f_w) and the depth of each irrigation.

(e) Other data: data used for the capillary rise and deep percolation equations; mulch data, including related management; active ground cover characteristics; and runoff data.

In this study, the effects of crop density, height, and canopy architecture on K_{cb} are evaluated using a K_d and the effect of using mulches is also included for assessing the water saving effect of plastic mulch covering [12]. The model contains a module which can consider the influence of the plastic mulch according to the actual situation. The model provides two alternative methods *i.e.*, a simplified procedure described in Doorenbos and Pruitt [58] and the parametric equation proposed by Liu *et al.* [1] to evaluate the deep percolation and capillary rise. Considering the available data (soil water parameters, LAI and water table depths) (Figure 3), the parametric equation proposed by Liu *et al.* [34] was chosen to calculate the deep percolation and capillary rise.

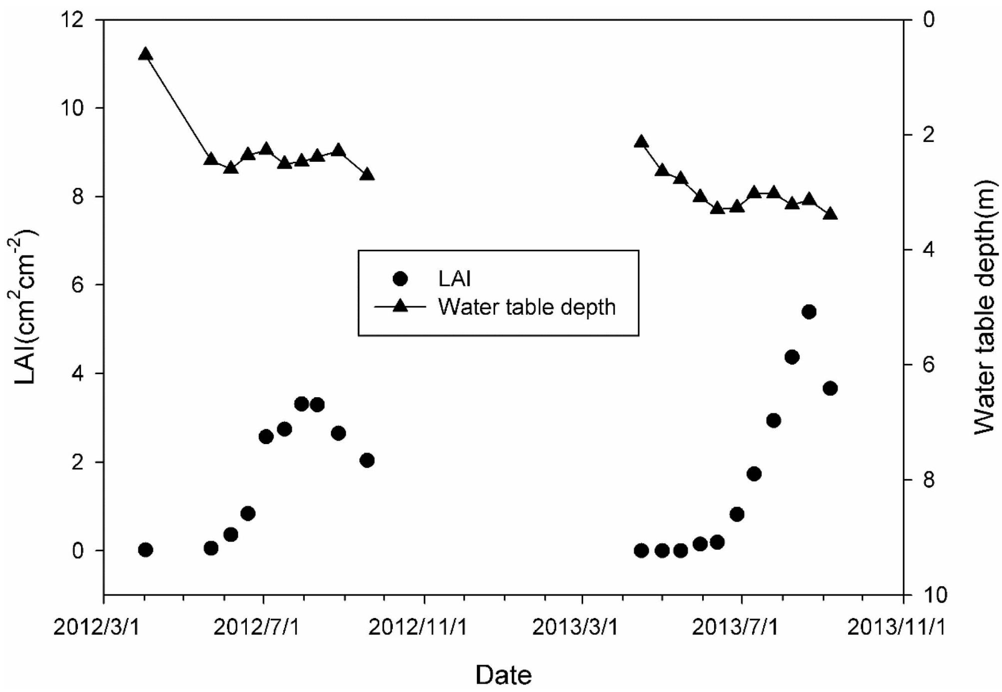


Figure 3. LAI and water table depth during the growing season for two years.

2.5. Model Calibration and Validation

The SIMDualKc model initially simulated the ET_{cct} through the table values of the crop (K_{cb} and p), the soil (Z_e, TEW and REW), and the percolation equation (a_p and b_p) suggested by the FAO-56 [12] and other previous studies [34]. The model was further calibrated to minimize the differences between the simulated and observed $ET_{c\ act}$. Model calibration utilized a trial and error procedure and a gradual change in the parameters from crop to soil, is described with more details in Rosa *et al.* [35]. The initial and calibrated values for the soil and crop parameters of the growth season are presented in Table 4. In our study, the data observed during the 2012 growth season was used to calibrate the model, and the observed data of 2013 was used for model validation. The real irrigation amount and respective data were used in simulation for calibration and validation.

Table 4. The initial and calibrated values of the crop and soil parameters of the growth stage.

Parameter	Initial Values [12,34]	Calibrated
	Crop coefficients	
$K_{cb\ ini}$	0.15	0.20
$K_{cb\ mid}$	1.15	0.90
$K_{cb\ end}$	0.50	0.50
	Depletion fraction	
p_{ini}	0.65	0.70
p_{mid}	0.65	0.60
p_{end}	0.65	0.60
	Soil evaporation	
REW (mm)	8	8
TEW (mm)	20	33
Z_e (cm)	10	15
	Deep percolation	
a_p	408	390
b_p	−0.0173	−0.0173
	Capillary rise	
a_1	320.8	320.8
a_2	303.2	303.2
a_3	−0.15	−0.15
a_4	7.55	7.55
b_1	−0.16	−0.16
b_2	−0.54	−0.54
b_3	2.1	2.1
b_4	−2.03	−2.03

Several goodness-of-fit indicators were applied in previous studies to evaluate the model predictions [35,59]. The simulated and observed ET_{cct} were compared through the figure, and regression was also calculated throughout the growth season. The linear regression between simulate and observed $ET_{c\ act}$ was firstly been obtained. The determination coefficient r^2 of the regression is:

$$r^2 = \left[\frac{\sum_{i=1}^{n} (O_i - \overline{O})(S_i - \overline{S})}{\sqrt{\sum_{i=1}^{n} (O_i - \overline{O})^2} \sqrt{\sum_{i=1}^{n} (S_i - \overline{S})^2}} \right]^2 \tag{3}$$

where O_i and S_i (i = 1, 2, . . . , n) represent the observed and simulated ET, and $\overline{O}$ and $\overline{S}$ are the corresponding mean values, when the value is close to 1.0, the predicted values are statistically close to the observed ones.

The indicators to evaluate the estimation errors are calculated as follows:

(a) The Nash–Sutcliffe model efficiency coefficient NSE, which is the ratio of the mean square error to the variance in the observed data [27]:

$$NSE = 1 - \frac{\sum_{i=1}^{n} (O_i - S_i)^2}{\sum_{i=1}^{n} (O_i - \overline{O})^2} \tag{4}$$

(b) The root mean square error, which characterizes the variance of the errors:

$$RMSE = \left[\frac{\sum_{i=1}^{n} (S_i - O_i)^2}{n} \right]^{0.5} \tag{5}$$

(c) The ratio RSR of the RMSE to the standard deviation of observed data (sd) that standardizes RMSE using the sd of observations:

$$RSR = \frac{\left[\sum_{i=1}^{n}(S_i - O_i)^2\right]^{0.5}}{\left[\sum_{i=1}^{n}(\overline{S}_i - O_i)^2\right]^{0.5}} \tag{6}$$

(d) The average absolute error, which expresses the magnitude of estimation errors in alternative to $RMSE$:

$$AAE = \frac{1}{n}\sum_{i=1}^{n}|S_i - O_i| \tag{7}$$

(e) The average relative error, which indicates the size of errors in relative terms and is expressed as a percentage:

$$ARE = \frac{100}{n}\sum_{i=1}^{n}\left|\frac{S_i - O_i}{O_i}\right| \tag{8}$$

(f) The percent bias, which indicates measures the average tendency of the simulated data to be larger or smaller than their corresponding observations:

$$PBIAS = 100\frac{\sum_{i=1}^{n}|S_i - O_i|}{\sum_{i=1}^{n}O_i} \tag{9}$$

3. Results and Discussion

3.1. Model Calibration and Validation

The initial soil related parameters were set according to local conditions. In common farming practice, the spring flush was employed two weeks before cultivation to leach soil salt, which significantly increases soil moisture. Afterward, however, intensive potential evaporation causes a remarkable depletion of surface soil water [17,50]. Accordingly, the initial depletion of the evaporable layer was set at 80% of TEW, and the initial depletion of the root zone of TAW was estimated at 20% in 2012 and 2013.

The capillary rising parameters (a_1 = 320.8, a_2 = 303.2, a_3 = −0.15, a_4 = 7.55 and b_1 = −0.16, b_2 = −0.54, b_3 = 2.1, and b_4 = −2.03) and deep percolation equation (a_p = 408, b_p = −0.0173) are adopted from Liu *et al.* [34]. LAI and water table depth are shown in Figure 3. The spring flush was applied in March, and the initial water table depth was approximately 1–2 m in April, decreased to approximately 3–4 m in June and varied in the drip irrigation period from June to August during the two experimental years.

The daily variation of the simulated (calibration and validation) and observed $ET_{c\,\mathrm{act}}$ (mm· day^{-1}) are shown in Figure 4. The results show that the simulation results fit the observed data well and no significant biases were detected. The regression coefficient is 0.95 and 1.08 for 2012 and 2013, respectively. The calibrated parameters of the model are presented in Table 5. The parameters p are close to the suggested values by Allen *et al.* [12]. $K_{cb\,\mathrm{ini}}$, $K_{cb\,\mathrm{mid}}$ is 33% more, 25% less than the suggested values by Allen *et al.* [12], while the $K_{cb\,\mathrm{end}}$ is nearly the same. The minimal variation in the parameters of deep percolation equation in the calibration showed the feasibility of the adopted equation.

The indicators of goodness-of-fit relative to the model tests are presented in Table 5. The observed $ET_{c\,\mathrm{act}}$ was 3.3 mm· day^{-1} and 3.2 mm· day^{-1} in 2012 and 2013, respectively, and the simulated $ET_{c\,\mathrm{act}}$ was 3.4 mm· day^{-1} and 3.2 mm· day^{-1}, which were very close to the observed $ET_{c\,\mathrm{act}}$. NSE, r^2, $RMSE$, AAE, ARE, RSR, and $PBIAS$ in 2012 were 0.89, 0.87, 0.68 mm· day^{-1}, 0.50 mm· day^{-1}, 21.8%, 0.38, and 15.0%, respectively, and 0.84, 0.87, 0.72 mm· day^{-1}, 0.50 mm· day^{-1}, 18.1%, 0.40 and 15.4% in 2013.

The goodness-of-fit of the model in this area is close to the study for the maize and wheat in Northern China [22] and the study for peach orchard in Portugal [28].

Table 5. Indicators of goodness of fit relative to the model tests of the crop evapotranspiration for the cotton under mulched drip irrigation.

Year	b *	r^2	RMSE (mm·day^{-1})	NSE	RSR	ARE (%)	PBIAS (%)	AAE (mm·day^{-1})
2012 (calibration)	0.95	0.87	0.68	0.89	0.38	21.8	15.0	0.50
2013 (validation)	1.03	0.87	0.72	0.84	0.40	18.1	15.4	0.50

Note: * The b is the slope of regression line.

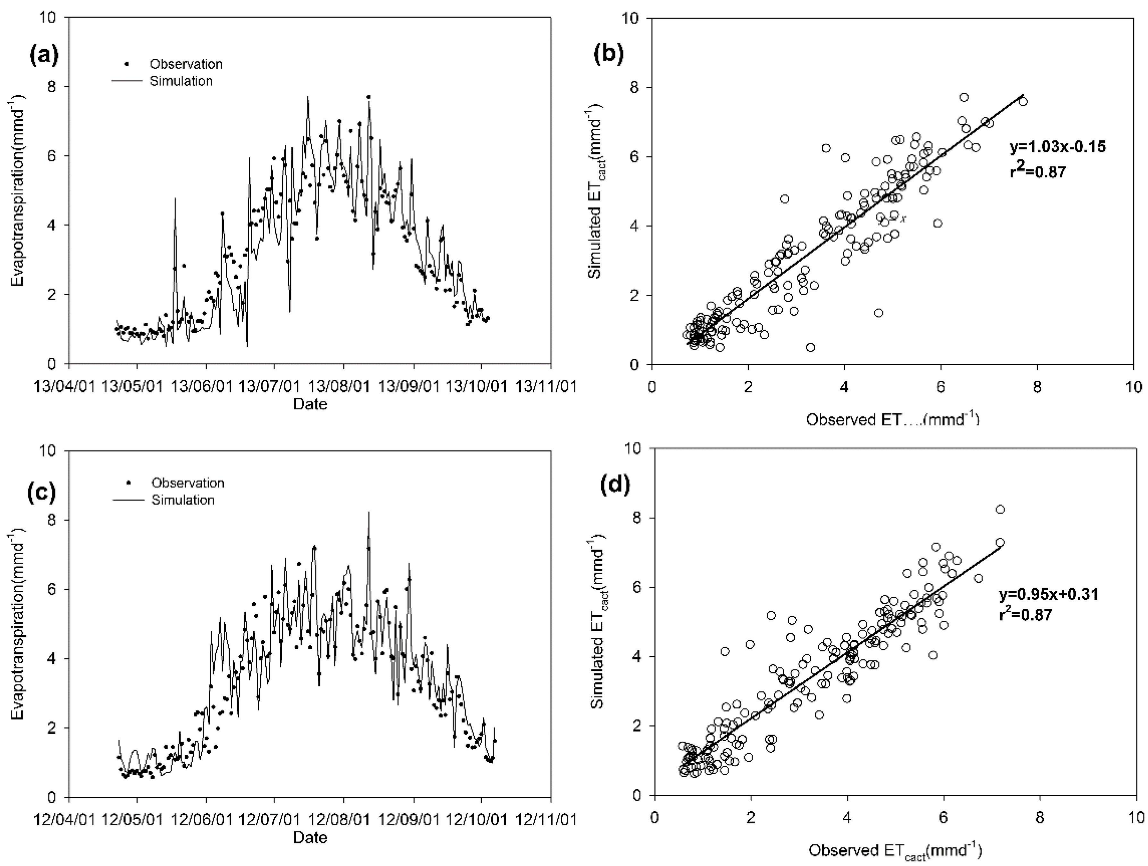
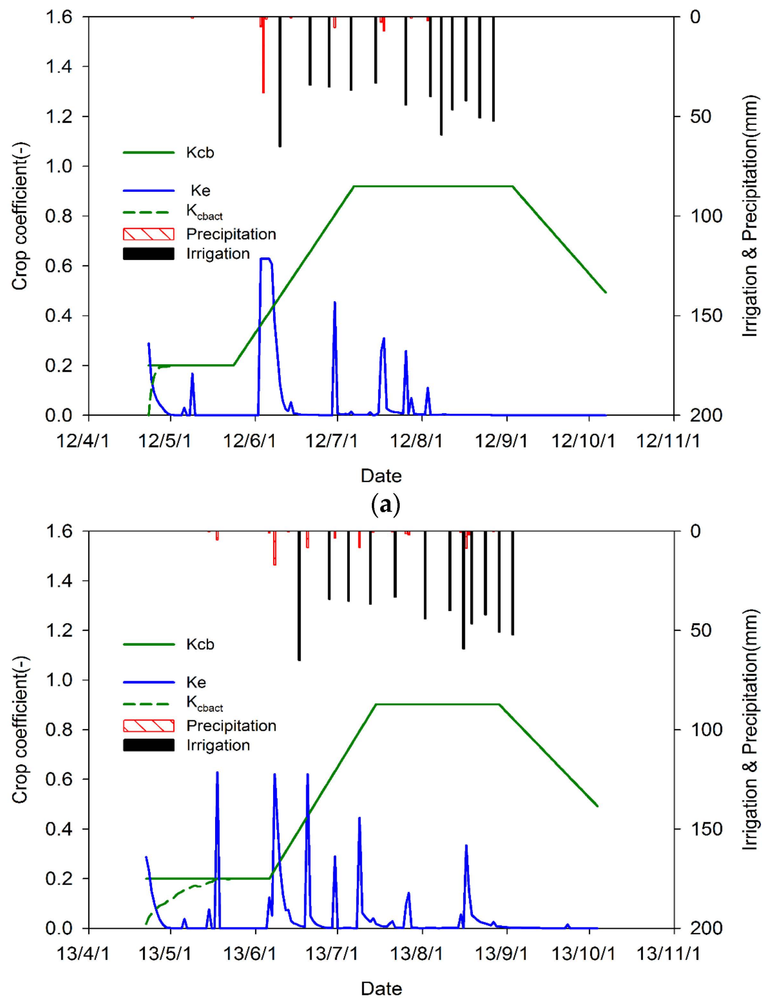


Figure 4. The comparison between observed (EC) and simulated $ET_{c\ \text{act}}$: (**a**,**b**) the results of 2012 (calibration); and (**c**,**d**) the results of 2013 (validation).

3.2. Crop Coefficients

The seasonal variations of K_{cb}, K_{cbct}, and K_e are presented in Figure 5. The calibrated basal crop coefficient $K_{cb\ \text{ini}} = 0.20$ was higher than the value of 0.15 (Table 4) proposed by Allen *et al.* [12]. In fact, $K_{cb\ \text{ini}}$ is sensitive to irrigation management [16]. In our study area flood irrigation is usually implemented for approximately two weeks before sowing which rapidly increases the soil moisture and, thus, evaporation. Moreover, the soil was ploughed in the sowing period which increased the moisture of the soil surface. The calibrated mid-season basal crop coefficient $K_{cb\ \text{ini}} = 0.90$ was lower by 20% than the proposed value of 1.10–1.15. The difference can be attributed to the influence of plastic mulch which may decrease the suggested K_{cb} by 10%–30% [12]. The end basal crop coefficient $K_{cb\ \text{end}} = 0.50$ which is within the range of proposed values of 0.40–0.50. The influence of plastic mulch on $K_{cb\ end}$ is insignificant compared to $K_{cb\ \mathrm{mid}}$. In the end growth stage, the ground was fully covered with the cotton, and when the irrigation ended, the influence of plastic mulch was negligible. The K_{cb} increased with the growth stage from start to end, whereas the $K_{cb\ \mathrm{act}}$ maintained the same values as the calibrated K_{cb} except in the initial stage when the irrigation started. The soil moisture was lower in this periods which may cause the soil water stress of the cotton. The K_e values of the cotton were high in the initial stage when the soil moisture was high during sowing (Figure 5).



(**a**) (**b**)

Figure 5. Seasonal variation of K_{cb}, $K_{cb\ \mathrm{act}}$, K_e, irrigation, and precipitation for cotton: (**a**) in calibration period (2012); and (**b**) validation period (2013).

The parameter K_e was divided into two components in the model, namely, K_{ei} which was related to the exposed fraction of soil wetted by both irrigation and precipitation, and K_{ep}, which was related to the exposed fraction of soil wetted by precipitation only [24]. Considering drip irrigation, the soil wetted conditions with irrigation and precipitation are different. The variations of K_e with the precipitation and irrigation are shown in Figure 5. The large variation range of K_e before the irrigation is mainly because of the precipitation. K_e was sensitive to the irrigation in the initial period which is due to the rapid increase in the surface soil moisture when the irrigation started. The influence of irrigation on K_e decreased in the late middle stage as it was affected by the growth of the cotton leaves. The inter-film zone was covered by the leaves in late July, decreasing the soil evaporation. After this stage, the K_e value stayed at low levels (close to zero), which implied that almost no soil evaporation occurred in that stage.

Allen [18] reported that $K_{cb\,\text{mid}}$ equals to 1.0 in Turkey and suggested that the 15% reduction of the tabled values in the FAO-56 report were due to low planting density and non-uniform irrigation. Rosa *et al.* [24] proposed the $K_{cb\,\text{mid}}$ equals to 1.15 with furrow irrigation in Uzbekistan. Howell *et al.* [60] proposed that $K_{cb\,\text{mid}}$ equal to 1.23 with the lysimeters in the Northern Texas High Plains of the USA with sprinkle irrigation. $K_{cb\,\text{mid}}$, in our study, was less than the two cases above by approximately 10% and 25%, respectively. The differences can be mainly attributed to the influence of plastic mulch and location.

3.3. Partitioning of Evapotranspiration

The $ET_{c\,\text{act}}$ (mm· day^{-1}) and its components in different growth stages during the two-year experimental period which simulated by the model are shown in Table 6 and Figure 6. In the initial stage, T comprised 80%–90% of the entire $ET_{c\,\text{act}}$. In the crop development stage, T accounted for 90% of the entire $ET_{c\,\text{act}}$, increasing with crop growth to 100% during the late season. For the full growth season, T under plastic mulch averaged 96% and 94% in 2012 and 2013, respectively. The components of $ET_{c\,\text{act}}$, without mulch, are presented in Table 6 according to simulation. The transpiration components of initial stage, crop development stage, mid-season, and late season in the two-year experimental period (2012–2013) are 77%, 61%, 79%, and 94%, respectively. The ratio of $E/ET_{c\,\text{act}}$ of cotton without mulch was significantly higher than that with mulch, with the highest ratio observed during the crop development stage. The plastic mulch is the main reason for the rapid decrease in soil evaporation. In the initial stage, the soil moisture is low (Figure 7) and the values of E and T were both low. When irrigation started in the crop development stage, T and T both increased, with T increasing more slowly than E because of undeveloped leaves and, therefore, the transpiration component becomes lower in this stage. In the mid-season, the soil was covered by leaves, and the available energy of the soil evaporation decreased, thereby decreasing $E/ET_{c\,\text{act}}$. Irrigation usually ends by the end of the mid-season, and the lower soil moisture further decreases the ratio of $E/ET_{c\,\text{act}}$.

Sap flow gauges were used to measure individual plant transpiration in our experimental station in 2012, and the obtained ratio $T/ET_{c\,\text{act}}$ is approximately 87% in June, 82% in August, and nearly 100% in September [38]. Martins *et al.* [26] indicated that E of $ET_{c\,\text{act}}$ in sprinkler and drip experiments under mulched soil for maize ranged from approximately 91% to 94%, and Rosa *et al.* [35] reported that $T/ET_{c\,\text{act}}$ in furrow-irrigated cotton were 90% and 83% in two different years. These results are similar to those of our study in Xinjiang, and are higher than the other studies in the areas with similar climate, e.g., ~80% in Uzbekistan by Qureshi *et al.* [52] and 56%–68% by Forkutsa *et al.* [61] also in Uzbekistan.

Table 6. $ET_{c\,\text{act}}$ and their components for different growth stages.

Growth Stages	2012									2013								
	Observation	Plastic Mulch				No Mulch				Observation	Plastic Mulch				No Mulch			
	ET *	ET	T	E	T/ET	ET	T	E	T/ET	ET	ET	T	E	T/ET	ET	T	E	T/ET
Initial	0.9	1.0	0.9	0.1	88.3	1.1	0.9	0.2	78.4	1.3	1.1	0.9	0.2	81.8	1.2	0.9	0.3	76.1
Crop development	3.5	3.5	3.2	0.3	90.3	4.9	3.2	1.8	64.3	4.0	3.6	3.1	0.5	87.0	5.3	3.1	2.2	58.4
Mid-season	5.0	5.1	5.0	0.1	98.3	6.2	4.9	1.2	80.0	5.2	5.4	5.3	0.1	97.5	6.8	5.3	1.5	78.2
Late season	2.5	2.7	2.7	0.0	100.0	2.8	2.6	0.2	93.4	2.4	2.7	2.6	0.0	99.6	2.7	2.5	0.2	94.2
Full crop season	3.3	3.4	3.3	0.1	95.9	4.2	3.3	1.0	77.0	3.2	3.2	3.0	0.2	93.6	4.0	3.0	1.0	74.1

Notes: * The units of the value are below: ET: Evapotranspiration (mm· day^{-1}); T: Transpiration (mm· day^{-1}); E: Evaporation (mm· day^{-1}); T/ET: Fraction of transpiration to evapotranspiration (%).

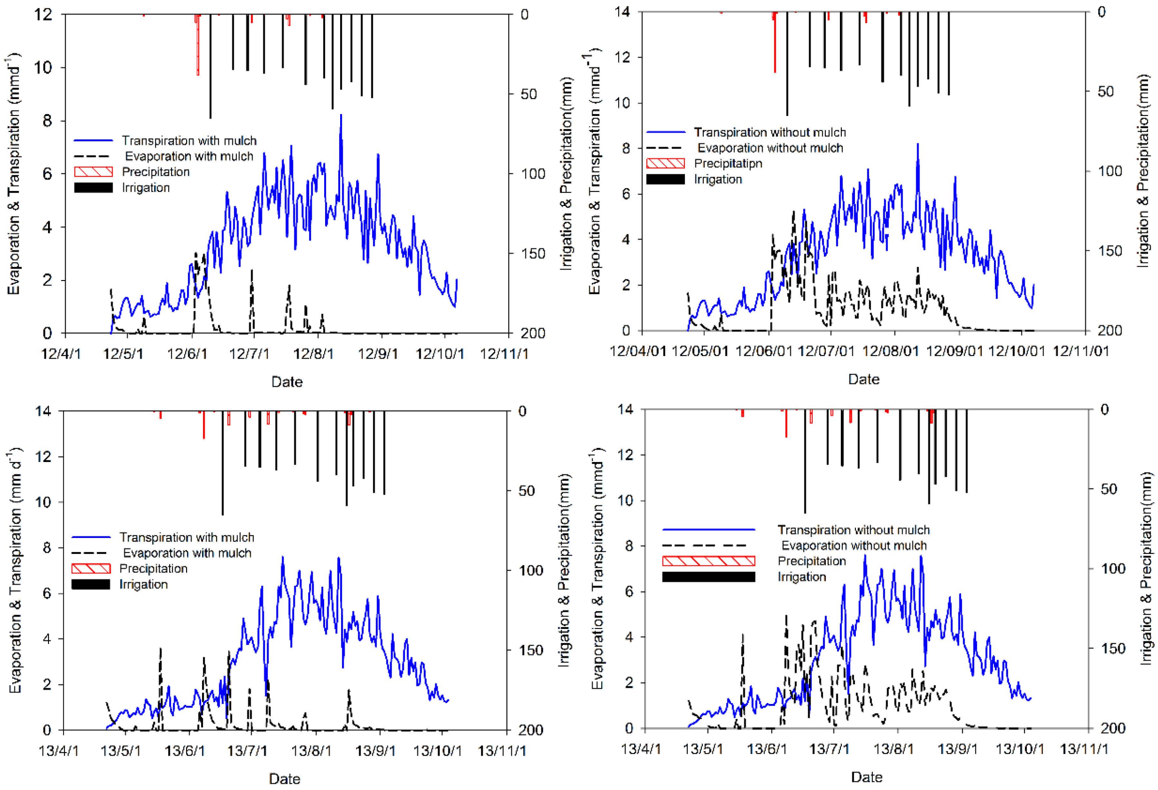


Figure 6. Daily variation of evaporation and transpiration for cotton in 2012–2013 (with and without mulch).

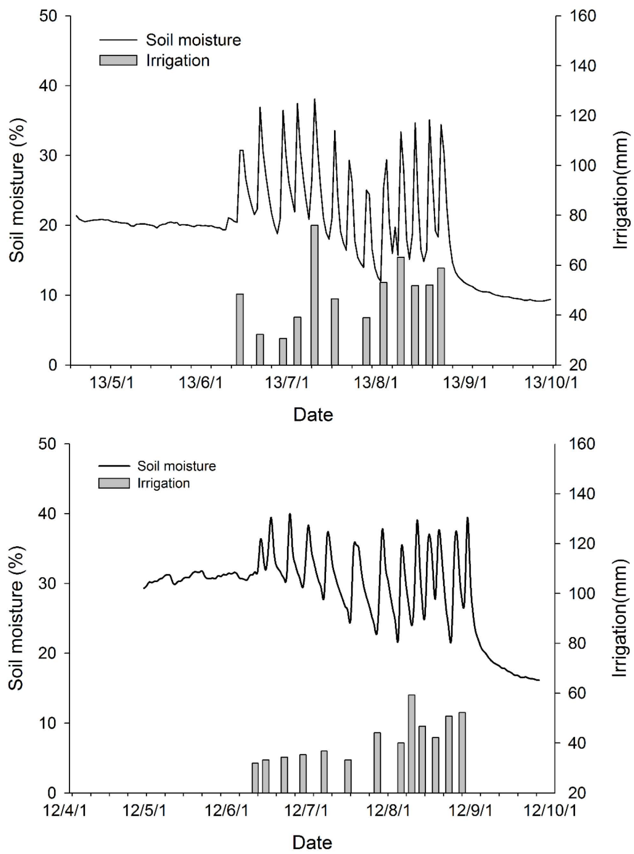


Figure 7. Daily variation of soil moisture under irrigation for cotton in 2012–2013.

3.4. Influence of Plastic Mulch

The influence of plastic mulch cover on $ET_{c\ \mathrm{act}}$ was simulated by the model, and the results are shown in Table 6 and Figures 6 and 8. The observation $ET_{c\ \mathrm{act}}$ data, with no mulch, was not obtained in our research. The calibrated and validated parameters with mulch was used to simulate the $ET_{c\ \mathrm{act}}$ with no mulch. The result is used to analyze the influence of mulch on $ET_{c\ \mathrm{act}}$. Plastic mulch has been proven to be able to increase soil temperature and moisture [36], as well as to conserve water [15,26].

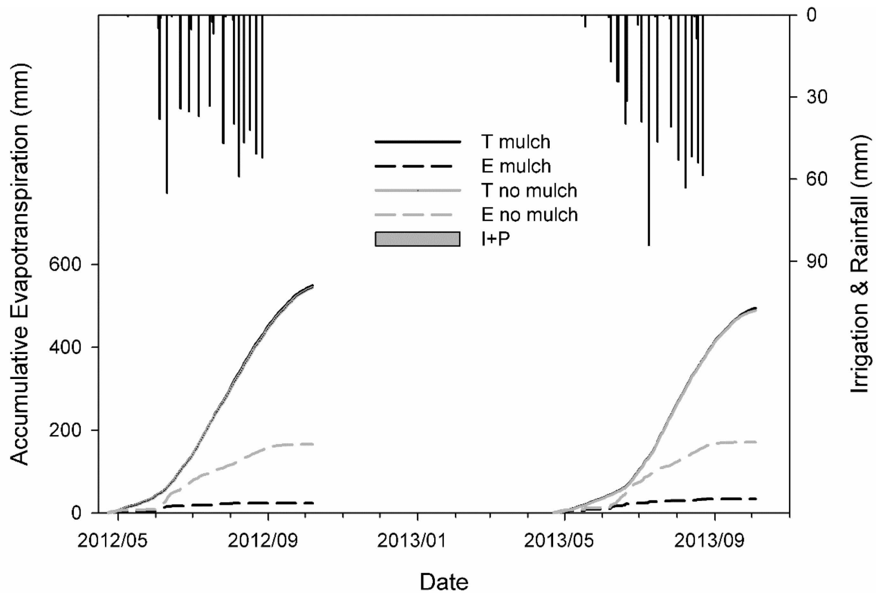


Figure 8. Evaporation and transpiration by the SIMDualKc during growing season for two years.

T values under plastic mulch cover were 549.2 mm and 495.0 mm in 2012 and 2013, respectively, and 545.2 mm and 493.2 mm without mulch cover, respectively. No significant difference was detected. *E* values under plastic mulch cover were 23.5 mm and 33.9 mm, in 2012 and 2013, respectively, and 163.1 mm and 170.8 mm without mulch cover, respectively. Thus, *E* increased by approximately 139.6 mm and 137.0 mm without mulch cover. For the entire growing season, the *T* components of $ET_{c\ \mathrm{act}}$ were approximately 96% under plastic mulch and 77% without mulch in 2012; the *T* components of $ET_{c\ \mathrm{act}}$ were approximately 94% and 74% in 2013, respectively.

The influence of plastic mulch cover on *E* is significant during the drip irrigation from the crop development stage to the mid-season stage. These phenomenon can be attributed to the variation of soil moisture and the available energy of the soil surface with the growth of the cotton leaves. Soil moisture is low in the initial stage and *E* is at a low rate; therefore, no remarkable disparity was detected between mulched and unmulched soil. Under initial irrigation, the soil moisture increases rapidly to promote soil evaporation, which decreases with plastic mulch, compared with unmulched soil. In the mid-season stage, the cotton leaves were enlarged, and the ground was covered by these leaves. The available energy of the soil surface was the key factor affecting soil evaporation instead of soil moisture. The sensitivity of soil evaporation to irrigation with and without mulch decreased, and the evaporation of the mulched soil largely declined to nearly 0 in combination with the impact of the plastic mulch.

The amount of percolation during the drip irrigation was approximately 152.1 mm and 223.6 mm for 2012 and 2013, respectively. The exchange water fluxes between soil and groundwater reservoir at 90 cm were 133.4 and 252.5 mm, respectively, as indicated in the water balance model [38]. These results indicate that simulated percolation is reasonable.

4. Conclusions

ET measurements using the eddy covariance system were conducted in a cotton field for two years, and the dual crop coefficient model SIMDualKc was successfully applied in the study area.

The goodness of fit showed that the predicted and observed values matched quite well. The regression coefficients were 0.95 and 1.08 for the two years, respectively. The $T/ET_{c\ \mathrm{act}}$ ratio increased with mulched drip irrigation; the ratios were equal to 96% and 94% during the two-year growth seasons, respectively. T occupied approximately 100% in mid-season and maturity stages. The SIMDualKc model can be used to assess ground cover, and the influence of plastic mulch is simulated via two setups; namely, with mulch and without mulch. The simulation results showed that the mulched cover reduced E by approximately 139.6 and 137.0 mm in 2012 and 2013, but barely affected T. The study showed that percolation amounts were approximately 152.08 and 223.62 mm in 2012 and 2013, respectively.

According to our results, the SIMDualKc model can be used to support irrigation schedules for cotton under mulched drip irrigation in Northwest China and other areas with similar climate and irrigation methods. The model can also be a useful tool to evaluate the influence of water saving methods and plastic mulches. Moreover, the validated parameters and basal crop coefficient in this study can be helpful and valuable for the further applications in arid land of Central Asia.

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Author Contributions: Fuqiang Tian performed the analyses, summarized the results, and outlined the manuscript. Pengju Yang conducted the field experiment, prepared and ran the SIMDualKc model, and prepared and revised the manuscript. Hongchang Hu designed the study, calibrated SIMDualKc model simulations and preprocessed the input data, and drafted the introduction section of the manuscript. Chao Dai conducted the field experiment.

Conflicts of Interest: The authors declare no conflict of interest.

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