

Article

Water Use Effectiveness Is Enhanced Using Film Mulch Through Increasing Transpiration and Decreasing Evapotranspiration

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Abstract: Water shortage is a main limitation of crop growth and yield in drought northwest China, which is an important area of seed maize growth. Plastic film mulch is widely adopted to reduce soil evaporation (E) and conserve water resources, which changes evapotranspiration (ET) and its components, E and transpiration (Tr) and crop growth. The AquaCrop model, one of widely used crop models powered by water, can well simulate crop ET components and growth. However, there are few studies that examine ET partitioning and growth with and without plastic film mulch. The calibrated AquaCrop model was used to partition ET and simulate growth of seed maize with and without plastic film mulch in a drought region of northwest China in 2014 and 2015. The AquaCrop model can well simulate canopy cover curve (CC), and the dynamic and accumulated courses of ET and ET components. Plastic film mulch could advance the growth stage of seed maize and reduce seasoned ET . The initial stage with plastic film mulch was 37–42 days, while it was 46–48 days for no-mulch. Plastic film mulch increased Tr by 14.16% and 14.48% and significantly decreased E by 57.25% and 34.28% in 2014 and 2015, respectively, resulting in the reduction of seasonal total ET . Plastic film mulch increased averaged mid-season crop coefficient for transpiration (Kc_{Tr}) by 0.88% and decreased soil evaporation coefficient (Ke) by 62.50%. Collectively, the results suggest that, in comparison with no-mulch, plastic film mulch advanced crop growth, and decreased total ET and increased Tr related with crop production, i.e., improve water use effectiveness.

Keywords: plastic film mulch; water use effectiveness; evapotranspiration; transpiration; AquaCrop model; maize

1. Introduction

Water resources scarcity is the main cause of crop failure [1]. The trend is further worsened by climate change, since climate change projections indicate that vapor pressure deficit (VPD), and thus, evaporation demand, will become an expected increase [2]. Crop evapotranspiration (ET) is the largest proportion of ET , precipitation and irrigation in cropland water balance component [3,4] because more than 90% of water used in agriculture is lost through soil evaporation and crop transpiration, referred to as evapotranspiration [5]. Soil evaporation cannot promote the increase of crop yield and should be controlled by management measures (e.g., plastic film mulch) [6,7]. On the contrary, transpiration occurs simultaneously through stomata and photosynthesis in leaves and is closely related to crop growth and production [8], whereas the two independent processes Tr and E occur simultaneously and are difficult to distinguish [9]. Therefore, in order to better understand the water

consumption law of seed maize and formulate accurate irrigation scheduling, so as to improve the water use effectiveness (*EUW*, means effective use of water, usually represents a process, and not water use efficiency (*WUE*)) and save water resources [10], *ET* needs to be accurately partitioned and growth simulated through models.

There are many crop models which have been widely used to estimate *ET* and its components and crop growth, such as DSSAT [11], WOFOST [12], APSIM [13], EPIC [14,15], WAVES [16], and Crop-Syst [17]. However, these models are complex and often require a large number of hard-to-obtain input variables and calibration parameters. The AquaCrop model is the newest international water-driven crop model developed by FAO to estimate *ET* and crop growth and yield [18,19]. The AquaCrop model can simulate canopy cover and estimate *Tr* and *E* depending upon canopy cover curve. The AquaCrop model was widely used in annual field crops, e.g., Stricevic et al., Nyakudya and Stroosnijder, Abedinpour et al., Hsiao et al., and Paredes et al. [20–24] for maize; Mkhabela and Bullock, Wang et al., Andarzian et al., Iqbal et al., and Toumi et al. [25–29] for wheat; Linker et al., and Garcia-Vila et al. [30,31] for cotton; Maniruzzaman et al. [32] for rice; Todorovic et al., and Stricevic et al. [20,33] for sunflowers; Araya et al. [34] for barley, and others.

In the drought region of northwest China, a major yield limiting factor is water shortage, where seed maize plays an important role in major cereal crops because of its high price and income. To save water resources by reducing soil evaporation in the field, plastic film mulch practice has been widely used in this area since this century [35–37]. Many studies indicate that plastic film mulch can not only reduce soil evaporation, but also accelerate crop growth due to increased soil temperature and weeds control [37,38]. Several studies used the AquaCrop model to partition *ET* into *E* and *Tr* [24,39–41]. However, there are few studies that used the AquaCrop model to partition *ET* and investigate crop growth with and without plastic film mulch.

The objectives of this study were to quantify the differences of *ET* partitioning and maize growth, and to analyze the causes of the differences between mulched and unmulched plastic film field using the AquaCrop model.

2. Material and Methods

2.1. Experimental Site and Design

The experimental observation occurred, respectively, in 2014 and 2015 from April to September in northwest China's Gansu province Wuwei city the Shiyanghe Experimental Station for Water-saving in Agriculture and Ecology of China Agricultural University (N 37°51', E 102°52', and 1581 m elevation). This region is typical of arid continental temperate climate, where it is rich in light and heat resources. The average annual sunshine time is more than 3000 h, and the hottest monthly daily temperature is 29 °C in July, with more than 150 days of frost-free period. However, the region is short of water, with an average annual precipitation of 164 mm and an average annual evaporation from a free water surface of 2000 mm. The groundwater table is 30–40 m below the ground surface. For sandy loam soil and corresponding mean soil dry bulk density of 1.40 g·cm⁻³, field capacity of 30%, and permanent wilting point of 11% for the 0–100 cm layers, the average saturated water content of 0.41 cm³·cm⁻³. Saturated hydraulic conductivity is 500 mm·d⁻¹.

The experimental design was a completely random design, including two treatments with and without plastic film mulch (M, N). Each treatment was repeated three times with a length of 9 m from north to south and 12.6 m from east to west. The bare soil surface was mulched with a transparent plastic thin film strip every 20 cm. The plastic film thickness was 0.04 mm and the width was 140 cm. Each film strip was mulched with four rows of seed maize. For seed maize, holes with a diameter of 5.0 cm, a plant spacing of 25 cm, and a row spacing of 40 cm were opened on the plastic film to sowing of single row male parents and five rows female parents, and there were no maize plants in the bare ground. Therefore, due to the existence of bare soil and holes, the actual mulching rate was 0.70. In 2014 and 2015, seed maize was sown on April 15 and 17, and harvested on September 20.

The experimental irrigation method was border-irrigation with uniform water infiltration according to the local actual agricultural production. The irrigation schedule in the experiment was estimated by subtracting precipitation from preceding ET calculated by crop coefficient method, and the water deficit was calculated by the difference between root area, field capacity and observed soil water content (SWC). The actual irrigation water in the experiment was measured and recorded by turbine flow meters. The precipitation and irrigation schedule in 2014 and 2015 are shown in Table 1. According to the local practice, the ratio of fertilizers application for $420 \text{ kg}\cdot\text{ha}^{-1}$ N in 2014 and $390 \text{ kg}\cdot\text{ha}^{-1}$ N in 2015. At the same time, $240 \text{ kg}\cdot\text{ha}^{-1}$ P_2O_5 and $50 \text{ kg}\cdot\text{ha}^{-1}$ K_2O were applied in each year. Full doses of potassium and phosphate were applied prior to seeding, with half of the N used as a base treatment at seeding and the rest applied during the first irrigation.

Table 1. Irrigation schedules for treatments with and without plastic film mulch (M and N) and precipitation during the growth season of seed maize in 2014 and 2015.

Years	Treatments	Irrigation Schedules and Irrigation Depth (mm)											Irrigation (I) (mm)	Precipitation (P) (mm)	I + P (mm)		
		6/8	6/13	6/27	7/7	7/12	7/19	7/25	7/31	8/6	8/15	8/20				8/21	9/2
2014	M		80.6			80.6			80.6				30.7		272.5	241.0	513.5
	N		86.4		98.6			98.6					53.8		337.4	241.0	578.4
2015	M	69.1		53.6			72.9			87.2		51.9		90.6	425.3	150.6	575.9
	N	69.1		75.7			77.0			78.5		72.2		102.9	475.4	150.6	626.0

2.2. Data Measurements

2.2.1. Meteorological Data

Meteorological data, including solar radiation (R_s , $\text{W}\cdot\text{m}^{-2}$), precipitation (P , mm), air temperature (T , $^{\circ}\text{C}$) relative humidity (RH , %), and wind speed (u_2 , $\text{m}\cdot\text{s}^{-1}$), were continuously measured at a standard automatic weather station (Hobo, Onset Computer Corp, Bourne, MA, USA), 2.0 m above the ground. The data were collected every 5 s, and the data recorder recorded an average of 15 min. The FAO Penman-Monteith method [38] was used to calculate daily reference crop evapotranspiration (ET_0 , mm). The daily maximum, minimum temperatures, precipitation, and ET_0 for each growing season are shown in Figure 1.

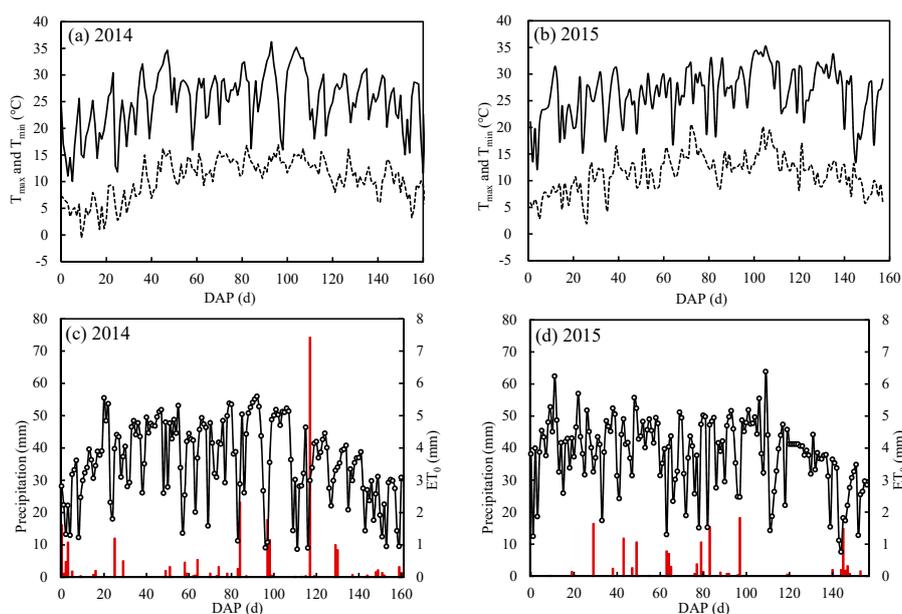


Figure 1. Variations in daily meteorological data against days after planting (DAP) of seed maize in 2014 and 2015, including maximum (T_{max} , —) and minimum (T_{min} , ----) air temperature, precipitation (■), and reference evapotranspiration (ET_0 , —○—).

2.2.2. Canopy Cover

In 2015, canopy cover (CC) was directly measured by an overhead digital camera, and image analysis software was used to calculate the ratio of weekly green leaf pixels in each plot to the whole picture. In 2014, it was derived from the leaf area index (LAI) by the following empirical equation, given by Hsiao et al. [23]:

$$CC = 1.005[1 - \exp(1 - \exp(-0.6LAI))]^{1.2} \quad (1)$$

Five maize plants were randomly selected and the plant height of each treatment plot was measured every 10 days. The leaf area index (LAI) was taken to be leaf area per unit of area.

2.2.3. Soil Water Content

Volumetric soil water content (SWC) was measured by a tubular soil water probes (Trime-TDR, Imko, GmbH, Ettlingen, Germany). The maximum soil depth was 1.0 m, with an interval of 0.2 m per week. Each plot was fitted with two detection tubes, one in the mulched area and the other in the bare soil area. The frequency of the SWC measurements would increase before and after each irrigation and precipitation.

2.2.4. Evapotranspiration

In this study, the water balance equation was used to estimate *ET*.

$$ET = P + I + W - D - R - \Delta S \quad (2)$$

where *P* is the precipitation (mm), *I* is the irrigation quantity (mm), *W* is the groundwater flow into the root zone (mm), *D* is the drainage (mm), *R* is the surface runoff (mm), ΔS is the change of soil moisture storage. The terrain of the experimental site was flat and the precipitation was not strong, so surface runoff and deep drainage could be ignored. *W* could also be ignored, as the groundwater table was 30–40 m below the ground surface, which is not enough to affected the growth of seed maize. Therefore, the Equation (2) can be simplified as:

$$ET = P + I - \Delta S \quad (3)$$

$$\Delta S = 1000 \times Z \times (\theta_2 - \theta_1) \quad (4)$$

where *Z* is the depth of root zone (m) with the change of plant growth, and θ_2 and θ_1 are average soil water contents in the root zone at two measurement times ($\text{m}^3 \cdot \text{m}^{-3}$).

2.3. Model Description

2.3.1. Model Principles and Algorithms

The AquaCrop model is a crop model powered by water. It first calculates transpiration and then converts it into biomass through water productivity, which combines four sub-models: (1) The atmosphere sub-model, treatment of rainfall, evaporative demand (reference evapotranspiration, ET_0), and CO_2 concentration; (2) the development, growth and yield of crops; (3) the management sub-model, including irrigation and fertilization; and (4) the balance with soil water. The AquaCrop model use a “ K_c-ET_0 ” approach to estimate *Tr* and *E*, depending on the daily time step used for canopy cover. *Tr* is calculated as:

$$Tr = CC^* K_{cTr,x} ET_0 \quad (5)$$

where ET_0 is reference evapotranspiration (mm) calculated using the FAO Penman-Monteith method ($\text{mm} \cdot \text{d}^{-1}$), $K_{cTr,x}$ is the maximum standard crop transpiration coefficient (non-dimensional) (well-watered soil and complete canopy, canopy cover = 100%), and CC^* is the actual crop canopy cover (%) adjusted for micro-advective effects. The actual transpiration is obtained by adjusting *Tr* to soil

water stress conditions using the water stress coefficient K_s (0–1), i.e., $Tr_{adj} = K_s \Delta Tr$. The coefficient K_s describes the effects of soil water stress on the following crop growth processes including water logging ($K_{s_{aer}}$), stomatal closure ($K_{s_{sto}}$) and soil salinity stress ($K_{s_{salt}}$). There was no water stress in this study, so the effect of K_s was not considered.

CC^* is calculated as:

$$CC^* = 1.72CC - CC^2 + 0.30CC^3 \quad (6)$$

Under optimal conditions, the development and senescence of the green canopy is described as:

$$CC = CC_0 e^{t \text{ CGC}} \text{ for } CC \leq CC_x/2 \quad (7)$$

$$CC = CC_x - 0.25 \frac{(CC_x)^2}{CC_0} e^{-t \text{ CGC}} \text{ for } CC > CC_x/2 \quad (8)$$

$$CC = CC_x \left[1 - 0.05 \left(e^{\frac{CDC}{CC_x} t} - 1 \right) \right] \text{ for } CC \text{ decline} \quad (9)$$

where CC_0 is the initial canopy cover at 90% emergence, CC_x is the maximum canopy cover, CGC is the canopy growth coefficient (d^{-1}), and t is time (d).

CGC and CDC are the two most important parameters for building up the CC , which are modified by soil water stress, as follows:

$$CGC_{adj} = K_{s_{exp}} CGC \quad (10)$$

$$CDC_{adj} = (1 - K_{s_{sen}}^8) CDC \quad (11)$$

where CGC_{adj} is CGC adjusted for water stress (d^{-1}), $K_{s_{exp}}$ is the water stress coefficient for canopy expansion (0–1), CDC_{adj} is CDC adjusted for water stress (d^{-1}), and $K_{s_{sen}}$ is the water stress coefficient for early canopy senescence (0–1).

The soil evaporation is also obtained by CC^* and ET_0 :

$$E = Kr(1 - CC^*)Ke_x ET_0 \quad (12)$$

The calculation equation of soil evaporation under plastic film mulch is as follows:

$$E = Kr(1 - f_m f_{r \text{ mulch}})(1 - CC^*)Ke_x ET_0 \quad (13)$$

where Ke_x is the maximum soil evaporation coefficient (non-dimensional) of completely wet and unshaded soil surface, and AquaCrop model defaults to 1.10. Kr is the evaporation reduction coefficient (0–1), and when the surface soil moisture is insufficient, $Kr < 1$, in response to atmospheric evaporation requirements. f_m is a regulator of the influence of mulch on soil evaporation, $f_{r \text{ mulch}}$ is a fraction of the mulch ($f_{r \text{ mulch}} = 0.70$).

2.3.2. Parameters Sensitivity Analysis

Accurate estimation of the AquaCrop model parameters is imperative for the accuracy of model outputs. A sensitivity analysis (SA) quantifies the impact of each uncertain factor (parameter or driving variable) on the variability of the model output and helps to understand the model's response to the changing behavior of these factors [42,43]. The SA methods are typically classified as local (i.e., derivative-based) or global [44]. A local SA only studies the influence of the change of one parameter on the output of the model and fixes all other parameters to an arbitrary value [42]. For these reasons, local methods are criticized as not suitable for nonlinear models [45]. A global SA (GSA) studies the average response of model output to changes in all parameters within a defined range. GSA technique fully considers parameter interactions or nonlinear responses, but requires repeated analysis of the changing parameter values in the parameter space, so it has high requirements for calculation and workload [46–48]. There are many existing GSA techniques, and this study used a combination of

screening and variance-based methods. First, the Morris screening method [49] (was used to identify the parameters with the greatest influence. Then, using the Sobol' [50] sensitivity analysis method, the first-and higher-order effects of these most influential model parameters on the selected model output were quantified. In this study, the Morris SA method was used to screen the 29 input parameters affecting the AquaCrop model to select the first 15 input parameters that are most sensitive to E and Tr , and then the Sobol's SA method was used to analyze the global sensitivity of the selected 15 parameters. The 15 parameters were base temperature ($BaseTemp$), upper temperature ($UpperTemp$), soil water depletion factor for canopy expansion—upper threshold ($PexpUpper$), soil water depletion factor for canopy expansion—lower threshold ($PexpLower$), shape factor for water stress coefficient for canopy expansion ($SFexp$), soil water depletion factor for canopy senescence—upper threshold ($PsenUpper$), shape factor for water stress coefficient for canopy senescence ($SFsen$), crop coefficient when canopy is complete but prior to senescence ($Kc_{Tr,x}$), minimum effective rooting depth ($MinRootDepth$), maximum effective rooting depth ($MaxRootDepth$), soil surface covered by an individual seedling at 90% emergence (CC_0), canopy growth coefficient (CGC), canopy decline coefficient (CDC), the time from sowing to emergence ($Emer$), and the time from sowing to maturity (Mat), respectively. This combinatorial approach has been applied successfully in other studies (e.g., Kendall et al. [51]).

2.3.3. Model calibration and Performance Evaluation

The model was calibrated with the data during the field experiment in 2014 and validated in 2015, including ET and canopy cover. In order to evaluate the “goodness-of-fit” of the model, a variety of statistical methods were used, such as the previous study [24,52]. These indicators are computed from the pairs of measured and simulated values M_i and S_i ($i = 1, 2, \dots, n$) whose means are, respectively, \bar{M} and \bar{S} , thus:

$$R^2 = \left\{ \frac{\sum_{i=1}^n (M_i - \bar{M})(S_i - \bar{S})}{\left[\sum_{i=1}^n (M_i - \bar{M})^2 \right]^{0.5} \left[\sum_{i=1}^n (S_i - \bar{S})^2 \right]^{0.5}} \right\}^2 \quad (14)$$

$$RMSE = \left[\frac{\sum_{i=1}^n (M_i - S_i)^2}{n} \right]^{0.5} \quad (15)$$

$$NRMSE = \frac{100}{\bar{M}} \left[\frac{\sum_{i=1}^n (M_i - S_i)^2}{n} \right]^{0.5} \quad (16)$$

$$EF = 1.0 - \frac{\sum_{i=1}^n (M_i - S_i)^2}{\sum_{i=1}^n (M_i - \bar{M})^2} \quad (17)$$

$$d = 1 - \frac{\sum_{i=1}^n (S_i - M_i)^2}{\sum_{i=1}^n (|S_i - \bar{M}| + |M_i - \bar{M}|)^2} \quad (18)$$

It indicates that when d and R^2 values are close to 1, the simulated values and the measured values are statistically close. It was reported that when the value of R^2 is >0.5 , the simulation results are acceptable in the basin simulation. For the value of $RMSE$ (root mean squared error), when the value of $RMSE$ is close to zero, the consistency between simulation results and measured results is good. The value of $NRMSE$ (normalized root mean squared error) may indicate the extent of agreement as a whole and has been applied in several studies. To test the quality of the modelling approach the Nash and Sutcliffe [53] modelling efficiency (EF , non-dimensional) was used. Willmott's [54] index of agreement (d). However, none of the parameters can be generally accepted by most people as the evaluation criteria. We also recognize the complexity of partitioning evapotranspiration into evaporation and transpiration. Considering only one indicator is not comprehensive enough, so we considered all

indicators including d , R^2 , $RMSE$, $NRMSE$, and EF to indicate the efficiency and accuracy of the models used in this study.

3. Results and Discussion

3.1. Differences in Model Parameters Sensitivity and Calibration with and without Mulch

The parameters sensitivity analysis of the AquaCrop model was shown in Figure 2. Since soil evaporation accounts for a small proportion in total ET and is less affected by crops, the values of parameters sensitivity were small and the sensitivity difference was small. Compared with the results of the unmulched treatment, plastic film mulch significantly reduced the sensitivity of 15 parameters, especially the global sensitivity, namely the interaction between parameters. As shown in Figure 2a, Mat is the most sensitive parameter under the condition of plastic film mulch. The GDD_{days} (growing degree days) from sowing to maturity significantly influenced on E through affecting maize growth stage. Plastic film mulch can reduce external environment influence on soil temperature, resulting in conservative GDD_{days} for the whole growth period. As a result, the effect obviously reduced the global sensitivity of the parameters for the impact of E due to the external environment change.

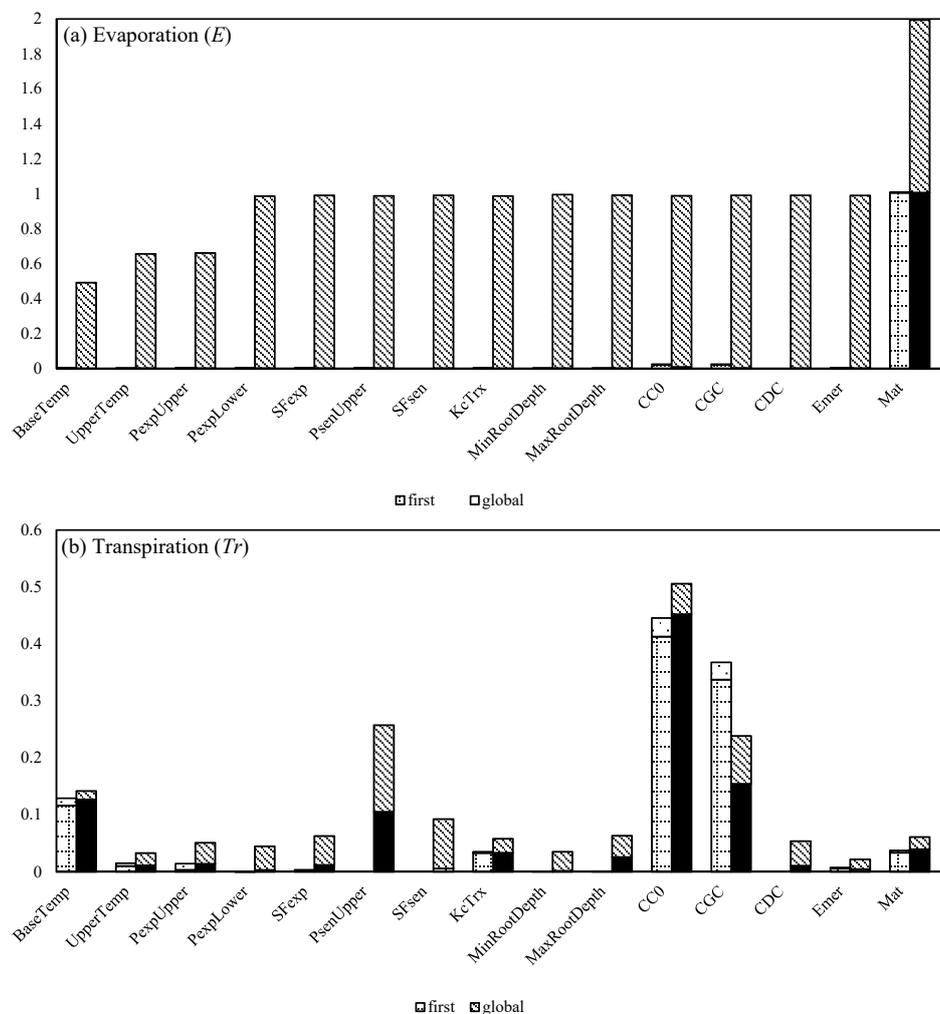


Figure 2. The Sobol' global sensitivity analysis (GSA, M_{\square} ; N_{\square}), and first order sensitivity analysis (SA, M_{\blacksquare} ; N_{\blacksquare}) indices for the AquaCrop model output of evaporation (E) and transpiration (Tr). Model input parameters were those sensitive by the Morris screening method.

As shown in Figure 2b, for the Tr of seed maize, the sensitivity values of parameters were larger than E due to the large proportion of Tr in total ET , and the sensitivity difference between parameters was large. The most sensitive parameter to Tr was CC_0 . For seed maize, CC_0 was mainly related to planting density and canopy architecture, which was determined by field management and genotype, and was relatively conservative. So, although CC_0 was sensitive, it did not need to be adjusted in the later parameter calibration. The CGC was sensitive parameter next to CC_0 . The CGC determines the shape of the CC curve of seed maize, and the simulation performance of ET by AquaCrop model depends on the simulation of CC curve. Therefore, we tuned the CGC during the parameter calibration process. The $BaseTemp$ was also a relatively sensitive parameter, which affected Tr through the $GDDays$, thus affecting the whole growth process of seed maize. The sensitivity of most parameters (except CGC) for Tr was reduced by plastic film mulch, which was consistent with the effect of E . These results suggest that plastic film mulch could provide a relatively stable growth environment for seed maize and reduce the interference of the external environment on the growth of seed maize. The improved CGC 's sensitivity by plastic film mulch might be because of ET directly dependence on CC determined by CGC .

The default and calibrated parameters of the AquaCrop model for both M and N treatments were shown in Table 2. The calibration of parameters was based on the above sensitivity analysis. Our study aims to use the AquaCrop model to partition ET on the basis of accurate simulation of ET , so we need to simulate ET as accurately as possible. The simulation accuracy of ET depends on the simulation of CC . Because CGC , CDC , and CC_x affect the shape of CC curve and the change process of CC , we gave different values of CDC , CGC , and CC_x for each year and each treatment, respectively (Table 2). Plastic film mulch increased CGC from 1.15% GDD^{-1} to 1.34% GDD^{-1} in 2014, and from 0.94% GDD^{-1} to 1.18% GDD^{-1} in 2015, respectively. The larger the CGC , the faster growth of canopy, i.e., the less time it takes to reach a specific maximum CC . This corresponds to the fact that plastic film mulch can increase $GDDays$, advance the growth stage and shorten the time required for maturity. For CDC , plastic film mulch slightly improved the CDC , indicating it could accelerate the senescence and maturity of seed maize.

Table 2. Default and calibrated values of parameters of seed maize in the AquaCrop model.

Description	Default Values	Calibrated Values			
Base temperature, °C	8	8			
Upper temperature, °C	30	30			
Leaf growth threshold ($P_{expUpper}$)	0.14	0.14			
Leaf growth threshold ($P_{expLower}$)	0.72	0.72			
Leaf growth stress coefficient curve shape (S_{Fexp})	2.9	2.9			
Minimum effective rooting depth ($MinRootDepth$), m	0.3	0.3			
Maximum effective rooting depth ($MaxRootDepth$), m	Up to 2.80	0.8			
Senescence stress coefficient curve shape (S_{Fsen})	2.7	2.7			
Canopy cover per seedling at 90% emergence (CC_0), cm^2 per plant	6.5	6.5			
Stomatal conductance threshold ($P_{stoUpper}$)	0.69	0.45			
Senescence stress coefficient ($P_{senUpper}$)	0.69	0.5			
Crop coefficient for transpiration at $CC = 100\%$ ($Kc_{Tr,x}$)	1.05	1.25			
Time from sowing to emergence ($Emer$), $GDD, ^\circ C d$	50–100	30–77			
Time from sowing to maturity (Mat), $GDD, ^\circ C d$	$T_{SE}^a + 1450 - 1750$	1551–1691			
		14M	14N	15M	15N
Canopy growth coefficient (CGC), % ($^\circ C d$) $^{-1}$	1.2–1.3	1.34	1.15	1.18	0.94
Canopy decline coefficient (CDC), % ($^\circ C d$) $^{-1}$	1.0	0.29	0.29	0.68	0.66
Maximum canopy cover (CC_x), %	65–99	96	89	90	87

^a T_{SE} is the time from sowing to emergence. Bold values are the specific calibrated parameters in this study.

Another important influencing factor is $Kc_{Tr,x}$ for accurately simulate Tr according to Equation (5). Our calibrated $Kc_{Tr,x}$ was 1.25, which was slightly higher than default (1.05) and previous values. The $Kc_{Tr,x}$ was 1.08 for maize in Alpiarca, central Portugal by Paredes et al. [24]; the $Kc_{Tr,x}$ was 1.20 for seed maize in the same experimental site by Ran et al. [41]. In fact, $Kc_{Tr,x}$ is the transpiration coefficient when $CC = 100\%$. For different years and different climatic conditions, the values of $Kc_{Tr,x}$ are different. For our study, the experimental site was the same as Ran et al. [41], but the experimental years were

different, so the meteorological factors and other environmental conditions were different, resulting in slightly higher $Kc_{Tr,x}$ due to higher evaporative demand. The $Kc_{Tr,x}$ is similar to the $K_{cb,full}$ in FAO 56, the basic crop coefficient in the middle of growth when the plant completely covers the ground or when $LAI > 3$. The reference value of $K_{cb,full}$ is 1.20, which should be adjusted to local value according to relative humidity, wind speed, and plant height. The adjusted $K_{cb,full}$ was higher than the default value for dry and hot climatic region. Our $Kc_{Tr,x}$ was close to the adjusted $K_{cb,full}$, indicating that the calibrated $Kc_{Tr,x}$ was reasonable.

The $PstolUpper$ and $PsenUpper$ were slightly less than the default value. Raes et al. [19] indicated that these two parameters will be reduced correspondingly if there were some stresses. For our study, the research area is located in the arid area of northwest China, where the climate is hot and dry, and there may be some stress in the growth period of seed maize.

3.2. Differences in Canopy Cover and Growth With and without Mulch

As shown in Figure 3, a good agreement was found between the simulated and measured CC for both M and N treatments for the two years. The goodness-of-fit indicators presented higher R^2 (>0.9) and lower RMSE of 3.6% and 4.1% in 2014, and 4.1% and 4.0% in 2015, respectively, for the two treatments (Table 3), which was slightly lower than previous studies, e.g., Hsiao et al. [23] [4.8–13.6%] and Zeleke et al. [55] [8.4–12.4%]. Farahani et al. [56] stated that the most logical pathway for a systematic calibration of AquaCrop is first and foremost to ensure a sound prediction of the canopy cover. Because field management could influence CGC and CDC [24,57], it was required to perform distinct parameterizations of the CC curves for different field management. As mentioned above, in order to accurately simulate CC, we used different CGC and CDC values for different years and different treatment methods (Table 2), which was the same as the previous studies on maize and soybean [24,39]. Plastic film mulch advanced the growth stage of seed maize. This was clearly reflected in the length of the growth period, the initial stage for the M treatment was 37–42 days, while it was 46–48 days for the N treatment. These results show that plastic film mulch can accelerate the growth of maize canopy, improve the maximum canopy cover, and increase CC_x , thus increasing the effective utilization of water in seed maize.

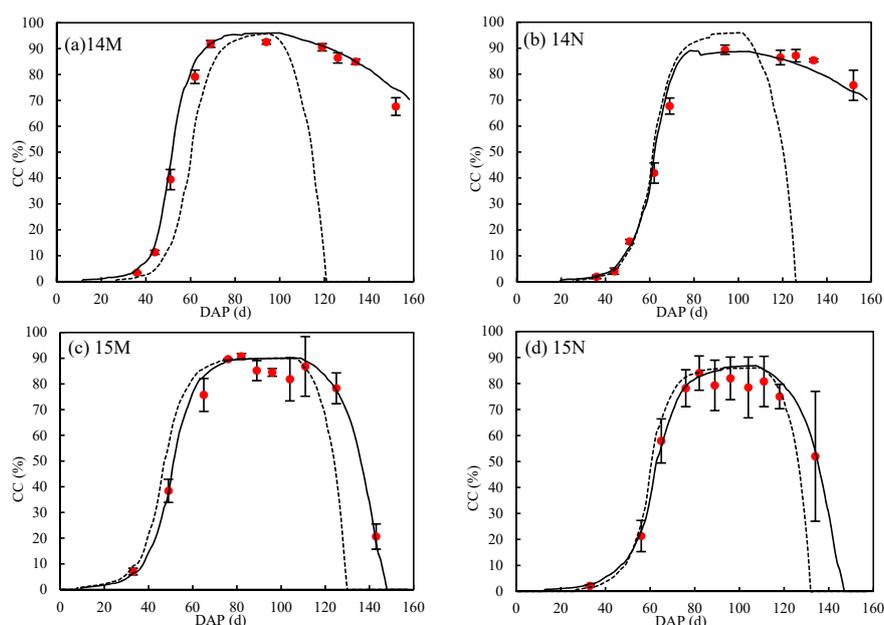


Figure 3. Simulated canopy cover (CC) using default (---) and calibrated (—) parameters and measurements (●) of seed maize in 2014 and 2015.

Table 3. Goodness-of-fit indicators between measurements and simulations for CC and accumulated evapotranspiration (ET) of seed maize for treatments with and without plastic film mulch (M and N) in 2014 and 2015.

Treatments	N	R ²	RMSE (%/mm)	NRMSE (%)	EF	d
CC (%)						
2014 M	10	1.00	3.6	5.5	0.99	1.00
2014 N	10	0.99	4.1	7.4	0.99	1.00
2015 M	11	0.99	4.1	6.1	0.98	1.00
2015 N	11	1.00	4.0	6.7	0.98	1.00
ET (mm)						
2014 M	12	0.98	17.827	8.1	0.99	1.00
2014 N	12	0.98	19.471	8.3	0.99	1.00
2015 M	21	1.00	10.740	4.4	1.00	1.00
2015 N	21	0.99	15.198	6.3	0.99	1.00

3.3. Differences in Evapotranspiration with and without Mulch

Although the simulated seasonal ET totals were slightly lower than the measurements for the two treatments of the two years, there was a good agreement between measured and simulated accumulated courses (Figure 4). The bias might be due to errors of measurement calculated using the water balance method [38]. The goodness-of-fit indicators were better, with the linear regression R² and RMSE of 0.98 and 17.827%, and 0.98 and 19.471% in 2014, 1.00 and 10.740%, and 0.99 and 15.198% in 2015, respectively, for the two treatments (Table 3), which was higher previous R² of 0.812 in Ran et al. [41]. In 2014, the simulated ET total was 512.6 mm for the M treatment, and 529.2 mm for the N treatment, respectively (Figure 4a,b). In 2015, the simulated ET total was 526.4 mm for the M treatment, and 534.5 mm for the N treatment, respectively (Figure 4c,d). Compared with the total ET of the two treatments in two years, the ET value under the plastic film mulch condition was significantly lower than that under the non-mulched condition. These results indicate that plastic film mulch could decrease ET, which was consistent with previous study [58].

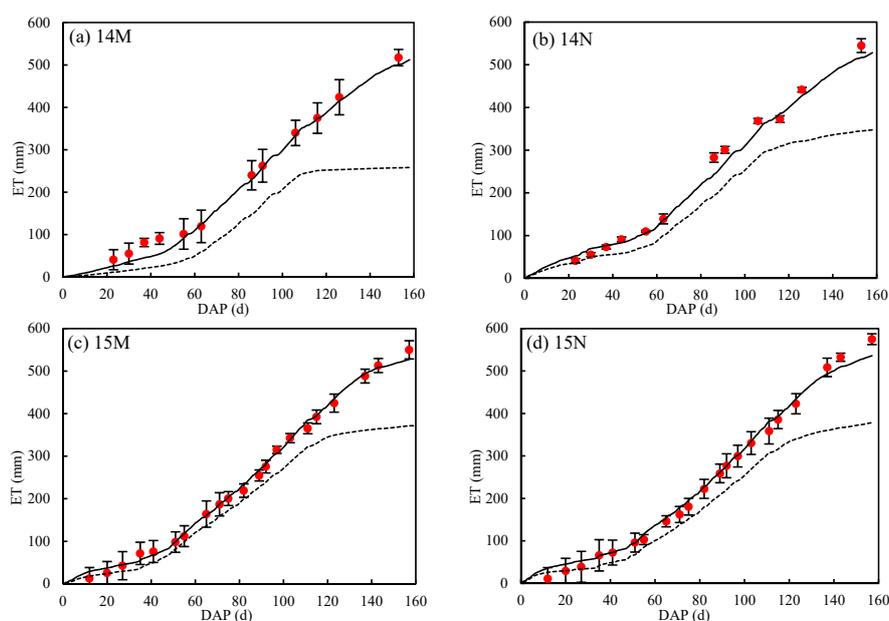


Figure 4. Simulated accumulated ET using default (---) and calibrated (—) parameters and measurements (●) of seed maize in 2014 and 2015.

3.4. Differences in Transpiration and Evaporation with and without Mulch

Seasonal variation of daily Tr was similar for the M and N treatments both years, but the M value was slightly higher than the N treatment (Figure 5). Daily Tr increased rapidly from less than $1.0 \text{ mm}\cdot\text{d}^{-1}$ at the initial growth stage to $7.0\text{--}8.0 \text{ mm}\cdot\text{d}^{-1}$ at the mid-season growth stage. Subsequently, daily Tr decreased to less than $1.0 \text{ mm}\cdot\text{d}^{-1}$ at the end of season for the two treatments in 2014 and 2015. The maximum daily Tr of M treatment is 3.2 mm larger than that of N treatment. E was larger due to lower CC at the initial and late-season stages before the development and after the senescence of maize canopy. After each precipitation or irrigation, there was a significant increase in E . In the mid-season with high CC, E was lower or near to zero. Seasonal variation of daily E was significantly different for the M and N treatments both years. The N E was distinctly higher than the M treatment, especially during the initial growth stage (Figure 5), which was attributed to the reduction of plastic film mulch. According to Equations (12) and (13), soil evaporation was not only dependent on the CC, but also related to the available water in the upper soil (Kr) and the effect of film mulch (f_m and $f_{r\text{ mulch}}$).

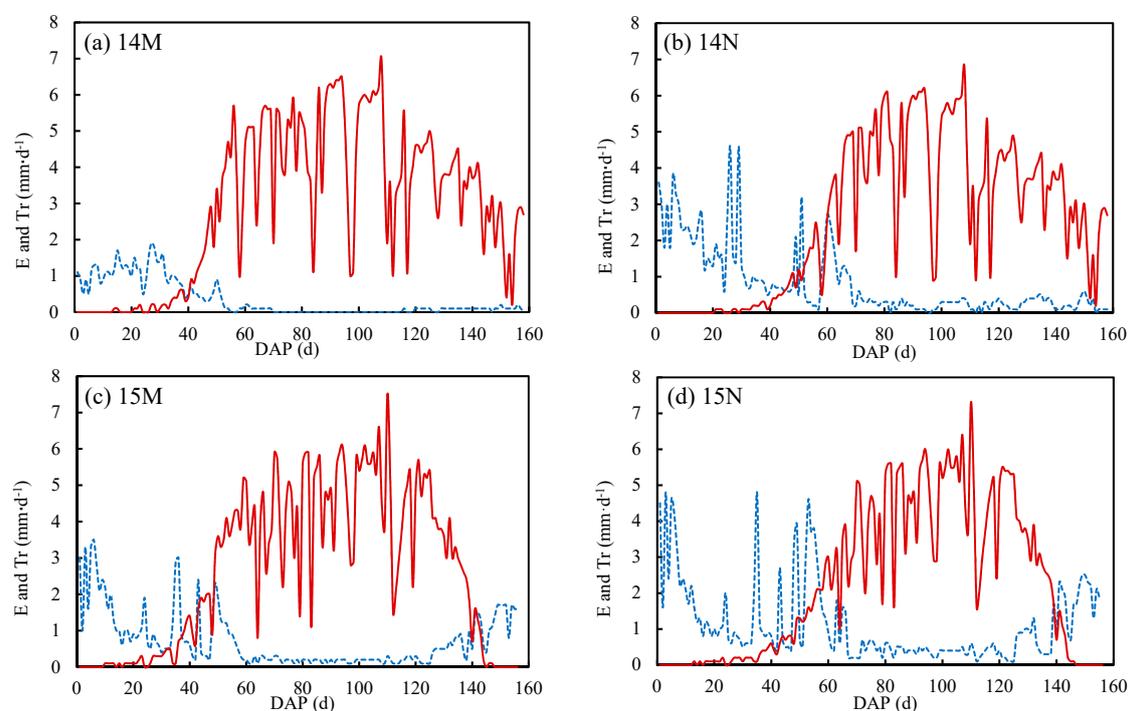


Figure 5. Variations in daily evaporation (E , - - - - -) and transpiration (Tr , —) against DAP of seed maize for treatments with and without plastic film mulch (M and N) in 2014 and 2015.

Table 4 presented total and daily averaged Tr , E , and ET during the different growth stages and whole period. Total Tr accounted for most of total ET , with a highest value of 89.31% for the M treatment in 2014. The maximum of total E was 32.80% for the N treatment in 2015. Total Tr during the mid-season stage was the largest proportion, with 98.91% of total ET for the M treatment in 2014. During the initial stage, E accounted for the largest proportion, with 91.65% of total ET for the N treatment in 2014 when precipitation was much. Compared to the N treatment, the ratio of Tr to ET increased from 75.77% to 89.31% in 2014, and 67.20% to 78.12% in 2015 for the M treatment. The lower ratio of Tr to ET in 2015 was due to pest and diseases. In conclusion, in 2014 and 2015, the ET was increased by 33 mm and 25 mm, respectively, by 6.30% and 4.55%.

Table 4. *ET*, *Tr*, *E*, and the percentage of *Tr* and *E* to *ET* in different growth stages for treatments with and without plastic film mulch (M and N) in 2014 and 2015.

Treatments	Stage	DAP	Days	<i>Tr</i> (mm)	Daily <i>Tr</i> (mm·d ⁻¹)	<i>E</i> (mm)	Daily <i>E</i> (mm·d ⁻¹)	<i>ET</i> (mm)	Daily <i>ET</i> (mm·d ⁻¹)	<i>Tr/ET</i>	<i>E/ET</i>
14 M	Initial	1–42 d	42	6.3	0.15	44.7	1.06	51	1.21	12.35%	87.65%
	Development	43–57 d	15	45	3.00	4.9	0.33	49.9	3.33	90.18%	9.82%
	Mid-season	58–150 d	93	391.1	4.21	4.3	0.05	395.4	4.25	98.91%	1.09%
	Late-season	151–158 d	8	15.4	1.93	0.9	0.11	16.3	2.04	94.48%	5.52%
	Whole	1–158 d	158	457.8	2.90	54.8	0.35	512.6	3.24	89.31%	10.69%
14 N	Initial	1–48 d	48	7.5	0.16	82.3	1.71	89.8	1.87	8.35%	91.65%
	Development	49–68d	20	48.2	2.41	24.4	1.22	72.6	3.63	66.39%	33.61%
	Mid-season	69–147 d	79	323.6	4.10	18.7	0.24	342.3	4.33	94.54%	5.46%
	Late-season	148–158 d	11	21.7	1.97	2.8	0.25	24.5	2.23	88.57%	11.43%
	Whole	1–158 d	158	401	2.54	128.2	0.81	529.2	3.35	75.77%	24.23%
15 M	Initial	1–37d	37	5.9	0.16	54.4	1.47	60.3	1.63	9.78%	90.22%
	Development	38–59 d	22	58.1	2.64	18.9	0.86	77	3.50	75.45%	24.55%
	Mid-season	60–126 d	67	301	4.49	12.3	0.18	313.3	4.68	96.07%	3.93%
	Late-season	127–156d	30	46.2	1.54	29.6	0.99	75.8	2.53	60.95%	39.05%
	Whole	1–156 d	156	411.2	2.64	115.2	0.74	526.4	3.37	78.12%	21.88%
15 N	Initial	1–46 d	46	8.4	0.18	72.5	1.58	80.9	1.76	10.38%	89.62%
	Development	47–71 d	25	61.5	2.46	40.7	1.63	102.2	4.09	60.18%	39.82%
	Mid-season	72–124 d	53	236	4.45	20.2	0.38	256.2	4.83	92.12%	7.88%
	Late-season	125–156 d	32	53.3	1.67	41.9	1.31	95.2	2.98	55.99%	44.01%
	Whole	1–156 d	156	359.2	2.30	175.3	1.12	534.5	3.43	67.20%	32.80%

Higher *M Tr* indicates that plastic film mulch improved the effective water use of maize or the ratio of *Tr* to *ET*, and then biomass production and yield [58]. In another rain-fed maize field, Zhou et al. [59] reported that partly ($f_m = 0.7$) and whole mulching with plastic film reduced total *ET* by 11.1% and 16.6%, respectively, comparing with no mulching. Averaged ratio of *E* to *ET* for the two years was 28.93% under no plastic film mulch, which was close to the ratios of no-mulch maize field reported by other researchers with 26.0% and 30.3% [16,60]. One of the main reasons for *ET* reduced by mulching was that the proportion of soil evaporation (*E*) was reduced. According to the Table 4, film mulch shortened the initial and development stages of maize. That is to say, film mulch could shorten the crop season duration and accelerate the growth of maize.

Equation (5) shows that the product of CC^* and $Kc_{Tr,x}$ was basal crop coefficient (Kc_{Tr}) as presented in the FAO 56 [38]. We gave the similar table with the FAO 56 basal crop coefficients (Table 17 in the FAO 56). As shown in the red solid line in Figure 6, the *M Kc_{Tr}* was significantly higher than that for the *N* treatment, which was consistent with the variation of *CC* curve (Figure 3). Both Kc_{Tr} of two conditions were lower in the initial stage, and gradually increased with the advance of the growth stage until reaching the maximum in the mid-season. The adjusted *Ke* was shown in the dotted line in Figure 6. The change trend of *Ke* was relatively consistent with that of *E*.

Table 5 presented stage-averaged Kc_{Tr} , *Ke*, and *Kc*. Kc_{Tr} was the largest in the mid-season (1.14) and the smallest in the initial stage (0.04). *Ke* is the largest at the initial stage (0.48) and the smallest at the mid-season stage (0.03). The total *Kc* reached the maximum at the mid-season stage (1.21) and the minimum at the initial stage (0.38). As shown in Table 5, in the initial stage, there was no difference in Kc_{Tr} between the two treatments, and *Ke* was reduced by 29.17% with plastic film mulch. In the development stage, the advantages of laminating were gradually shown. Laminating increased Kc_{Tr} by 3.33% and decreased *Ke* by 63.89%. In the middle-season, the Kc_{Tr} was increased by 0.88% and the *Ke* was reduced by 62.50% by the plastic film mulch. In the late-season *Ke* was reduced by 32.26% by plastic film mulch, while for Kc_{Tr} , there were pests and diseases in 2015, and plastic film mulch did not improve Kc_{Tr} .

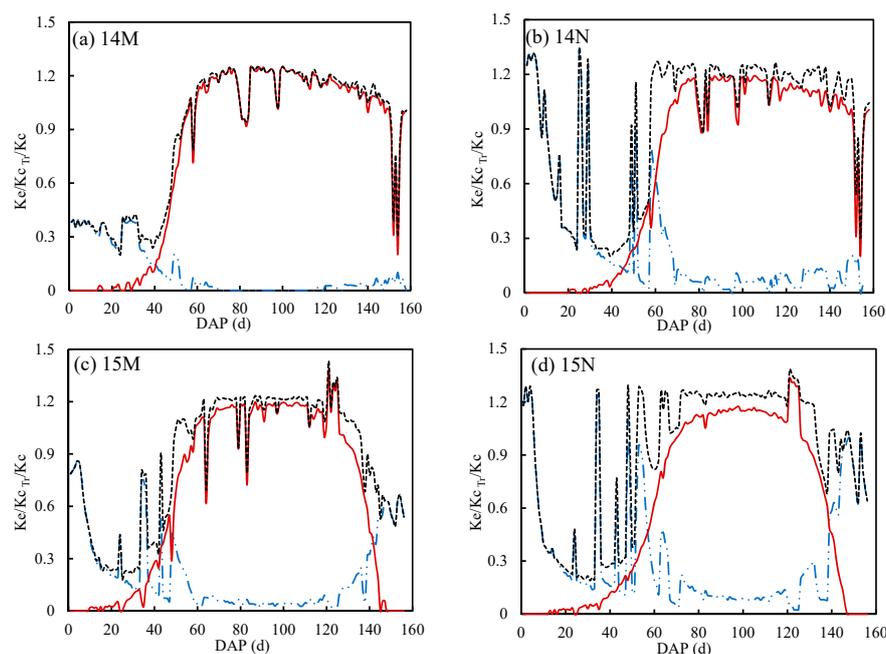


Figure 6. Variations in daily crop coefficient components against DAP of seed maize partitioned for treatments with and without plastic film mulch (M and N) in 2014 to 2015, including crop coefficient K_c (-----), soil evaporation coefficient K_e (-·-·-·-·-) and transpiration coefficient $K_c - T_r$ (—).

Table 5. Mean crop coefficient K_c , transpiration coefficient $K_c - T_r$, soil evaporation coefficient K_e of seed maize in different growth stages for treatments with and without plastic film mulch (M and N).

Components	Treatments	Initial	Development	Mid-Season	Late-Season
K_e	M	0.34	0.13	0.03	0.21
	N	0.48	0.36	0.08	0.31
$K_c - T_r$	M	0.04	0.62	1.14	0.58
	N	0.04	0.60	1.13	0.63
K_c	M	0.38	0.76	1.17	0.79
	N	0.52	0.96	1.21	0.94

4. Conclusions

The AquaCrop model performed well for simulating CC and ET , and can be used to partition ET and investigate crop growth of seed maize for treatments with and without plastic film mulch. Plastic film mulch increased the $GDDays$, changed the phenology, advanced the growth stage, increased beneficial Tr , and reduced E , which was not conducive to seed maize and ET during the growth period of seed maize, resulting in improved water use effectiveness (EUW).

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