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Modeling evapotranspiration and its components of maize for seed production in an arid region of northwest China using a dual crop coefficient and multisource models

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ABSTRACT

Accurately modeling evapotranspiration (*ET*) and its components of maize grown for seed production is essential for precision irrigation management. In this study, a dual crop coefficient method and a multisource model based on radiation interception by adjacent crop varieties were used to estimate *ET* and its components in the arid region of northwest China. The dual crop coefficient method and multisource model were validated using observed *ET* (ET_{EC}), transpiration (*T*) of female (T_{sf}) and male (T_{sm}) parents and evaporation (E_s). Observations were made using the eddy covariance system, sap flow measurements, and micro-lysimeter in 2013 and 2014. Results showed that *ET* estimated by the dual crop coefficient method was close to ET_{EC} at the midseason stage, and was higher than ET_{EC} both at the initial and the development stage due to the constant value of initial basic crop coefficient and linear interpolation at the development stage. The estimated *T* of female and male parents was greater than T_{sf} and T_{sm} in both years. Soil evaporation estimated by the dual crop coefficient method was greater than measured soil evaporation in the late growth stage. While the *ET*, *T* of female and male parents and *E* predicted by the multisource model were closer to the measurements. Estimated *ET* was 2% less (2013) and 4% greater (2014) than ET_{EC}, *T* of male parents was 8% and 3% less than T_{sm}, *T* of female plants was 8% and 6% less than T_{sm}, and *E* was 6% and 3% less than E_s. Thus the multisource model based on radiation interception by neighboring species is suitable for estimating *ET* and its components of maize grown for seed production in the arid region of northwest China.

List of Symbols

Symbol	Implication	Value	Units
A	The total available energy to the canopy		W m^{-2}
$A_{c,i}$	Available energy to the female or male parents		W m^{-2}
$A_{c,f}$	Available energy to the female parents		W m^{-2}
$A_{c,m}$	Available energy to the male parents		W m^{-2}
A_s	Available energy to the soil		W m^{-2}
a_f	The proportion coefficient of female parents		Dimensionless
a_m	The proportion coefficient of male parents		Dimensionless
C_p	Specific heat of dry air at constant pressure	1013	J kg^{-1}°C^{-1}
λET	Latent heat flux		W m^{-2}
λET_{ML}	Latent heat flux estimated by multisource model		W m^{-2}
ET_0	Reference evapotranspiration		mm d^{-1}
ET_c	Evapotranspiration estimated by crop coefficient method		mm d^{-1}
E_{cs}	Soil evaporation estimated by crop coefficient method		mm d^{-1}
$ET_{c,i}$	Evapotranspiration at the end of day i		mm d^{-1}
ET_{ML}	Evapotranspiration estimated by multisource model		mm d^{-1}
E_{ms}	Soil evaporation estimated by multisource model		mm d^{-1}
ET_{EC}	Evapotranspiration measured by eddy covariance		mm d^{-1}
E_s	Soil evaporation measured by micro-lysimeter		mm d^{-1}
F	Scaling factor	0-1	Dimensionless
f_m	The ratio of coverage of male parents to the total surface		Dimensionless
f_f	The ratio of coverage of female parents to the total surface		Dimensionless

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f_{ew}	The fraction of the soil that is both exposed to solar radiation and that is wetted	0.01-1	Dimensionless
f_w	The average fraction of soil surface wetted by irrigation or precipitation		Dimensionless
f_s	The ratio of bare soil to soil surface	0.25	m^2 m^{-2}
f_c	Fraction cover of the canopy		Dimensionless
f_i	The fraction of the incident radiation intercepted by the female or male parents		Dimensionless
$C_{c,i}$	The coefficients of crop		Dimensionless
C_s	The coefficient of soil		Dimensionless
CR_i	Capillary rise from the groundwater table on day i		mm
DAS	Days after sowing		d
$D_{e,\ i\text{-}1}$	The cumulative depth of evaporation from the soil surface layer at the end of day i-1		mm
$D_{e,i}$	The cumulative depth of evaporation from the soil surface layer at the end of day i		mm
$DP_{e,i}$	The deep percolation loss from the topsoil layer on day i if soil water content exceeds field capacity		mm
$D_{r,i-1}$	The root zone depletion at the end of day i-1		mm
$D_{r,i}$	The root zone depletion at the end of day i		mm
DP_i	The deep percolation loss from the root zone on day i		mm
G	Ground heat flux		W m^{-2}
h_c	Mean canopy height		m
h_f	The crop height of female parents		m
h_m	The crop height of male parents		m
K_f	Extinction coefficient of female parents		Dimensionless
K_m	Extinction coefficient of male parents		Dimensionless
$k_{min\ i}$	The minimum extinction coefficient of female or male parents		Dimensionless
K_c	The crop coefficient		Dimensionless
$K_{c\ min}$	The minimum crop coefficient for bare soil		Dimensionless
K_s	Water stress coefficient		Dimensionless
K_{sm}	Water stress coefficient of male parents		Dimensionless
K_{sf}	Water stress coefficient of female parents		Dimensionless
K_{cb}	The basal crop coefficient		Dimensionless
K_e	Soil evaporation coefficient		Dimensionless
$K_{cb\ m}$	The basal crop coefficient of male parents		Dimensionless
$K_{cb\ f}$	The basal crop coefficient of female parents		Dimensionless
$K_{cbfulli}$	The estimated K_c for male or female parents during the midseason stage (at peak plant size or height) for full vegetation		Dimensionless
$K_{c\ max}$	The maximum value of K_c following rain or Irrigation		Dimensionless
K_r	Evaporation reduction coefficient		Dimensionless
n_m	The proportion of male parents in whole plants	1/6	Dimensionless
n_f	The proportion of female parents in whole plants	5/6	Dimensionless
N_m	The sample number of male parents for sap flow measurement	4	Plants
N_f	The sample number of female parents for sap flow measurement	4	Plants
P_i	Precipitation at the end of day i		mm
p_{table}	The standard fraction of *TAW* that a crop can extract from the root zone for no stress		Dimensionless
p	The fraction of *TAW* that a crop can extract from the root zone for no stress		Dimensionless
Q_{mi}	The sap flow rates of ith male individual		L d^{-1} $plant^{-1}$
Q_{fi}	The sap flow rates of ith female individual		L d^{-1} $plant^{-1}$
R_n	Net radiation		W m^{-2}
RH_{min}	The average minimum daily relative humidity		%
REW	Readily evaporable water		mm
RO_i	Runoff from the soil surface on day i		mm
LAI	The mean leaf area index		m^2 m^{-2}
LA_{mi}	The leaf area of ith male individual		m^2
LA_{fi}	The leaf area of ith female individual		m^2
LAI_m	The average leaf area index of male parents		m^2 m^{-2}
LAI_f	The average leaf area index of female parents		m^2 m^{-2}
LAI_i	The average leaf area index of female or male parents		m^2 m^{-2}
$LAI_{eff,i}$	The effective leaf area index for female or male parents		m^2 m^{-2}
r_a^a	The aerodynamic resistance from reference height above the canopy to mean canopy height		s m^{-1}
r_a^s	Aerodynamic resistance from soil surface to mean canopy height		s m^{-1}
r_s^s	Soil resistance		s m^{-1}
$r_a^{c,i}$	The leaf bulk boundary resistance of female or male parents		s m^{-1}
r_c^i	The canopy resistance of female or male parents		s m^{-1}
γ	Psychrometric constant		kPa K^{-1}
TEW	Total evaporable water		mm
TAW	Total available soil water in the root zone		mm
T_a	Air temperature		°C
T	The total transpiration of maize for seed production		mm d^{-1}
T_{mi}	The transpiration of female or male parents calculated by the multisource model		mm d^{-1}
T_{ci}	The transpiration of female or male parents calculated by the dual crop coefficient method		mm d^{-1}
$T_{ew,i}$	The depth of transpiration of the soil surface layer on day i	0	mm
u_2	The wind speed at 2.0 m height		m s^{-1}
Z_r	The depth of root zone		m
Δ	Slope of the saturation water vapor pressure versus temperature curve		kPa K^{-1}
ρ_a	Air density	1.03	kg m^{-3}
$\theta_{F,e}$	The soil water content at field capacity in the topsoil layer		cm^3 cm^{-3}
$\theta_{w,e}$	The soil water content at wilting point in the topsoil layer		cm^3 cm^{-3}
$\theta_{F,r}$	The water content at field capacity		cm^3 cm^{-3}
$\theta_{w,r}$	The water content at wilting point		cm^3 cm^{-3}
VPD	Deficit vapor pressure of the air at the reference height		kPa
VPD_0	Deficit vapor pressure at the canopy height		kPa
β	Solar elevation angle		°

1. Introduction

Evapotranspiration (*ET*) is the total amount of water lost through evaporation (*E*) from the soil and transpiration (*T*) from plant surfaces. Its accurate estimation is essential for accurate irrigation water management and improving water productivity. Because the arid region of northwest China is naturally isolated and receives abundant solar radiation, maize for seed production develops rapidly, and it has become the primary irrigated crop in that region (Jiang et al. 2014). Maize for seed production differs from common field maize, because male and female parents differ in canopy, and thus *T* differs between female and male parents, as does *E*. A mixture of two or more species in the same field is also widely found in intercropping and agroforestry systems. Thus, the fundamental understanding of water use and the partitioning of *ET* is important to account for the heterogeneous canopy, and different irrigation schedules were adopted for different plants to develop a more precise irrigation methodology.

The single and dual crop coefficient methods proposed by Allen et al. (1998) have been used to estimate *ET* and its components. The dual K_c method can better represent the effect of rain or irrigation on soil wetting and can quantify the effects of film mulching, which keeps part of the soil dry, suppress soil evaporation (Allen et al. 1998; Zhang et al. 2013). Thus the dual K_c method can more accurately compute *ET* and its components than the single crop coefficient model (Allen and Pereira 2009; Allen et al. 2011; Rosa et al. 2012; Qiu et al., 2015). The K_c and K_{cb} values for many crops have been reported (Allen et al. 1998, 2007). Many studies have used the single and dual K_c method to estimate *ET* for many crops, including maize and wheat (Zhao et al. 2013; Zhang et al. 2013; Qiu et al., 2013; Hou et al. 2014). Few studies have focused on a heterogeneous canopy when two or more species or varieties are mixed in the same field. Allen et al. (1998) estimated total

Table 1
Irrigation scheduling, reference evapotranspiration (ET_O, mm), and total precipitation (P, mm) at different growth stages in 2013 and 2014.

Year	Growth stage	Period	Irrigation time	Irrigation amount (mm)	ET_O (mm)	P (mm)
2013	Initial	Apr.19-May.19		0	114.3	6
	Development	May.20-Jun.28	Jun. 6, Jun.26	200	165.1	18.2
	Middle	Jun. 29-Aug.18	Jul.11, Jul.30,Aug. 18	280	179.3	32.6
	Late	Aug.19-Sept.12		0	90.3	11.6
	Whole	Apr.19-Sept.12		480	549	68.4
2014	Initial	Apr.20-May.21		0	118.13	20.2
	Development	May.22-Jun.30	Jun. 9	100	162.09	22.6
	Middle	Jul.1-Aug.25	Jul.1,Jul.20,Aug.23	280	199.95	151.2
	Late	Aug.26-Sept.20		0	87.83	12.2
	Whole	Apr.20-Sept.20		380	568	206.2

K_{cb} for a mixture of two or more species in the same field by weighting K_c values for the individual crop species according to the area covered by each crop and the height of the crop. However the crop parameters for estimating total K_{cb} for a heterogeneous canopy need further study; the performance of this method in estimating ET for a heterogeneous canopy remains uncertain.

Despite of the practical simplicity, the dual K_c method was reported to have a drawback, i.e., the adoption of generalized K_c curves can lead to relevant difference in the estimation of ET and its components (Allen et al., 1998; Katerji and Rana, 2006). Shuttleworth and Wallace (1985) proposed a two-source P–M model (the S–W model) to estimate ET and apportion ET between T and E for a sparse canopy. The S–W model assumes that crop canopy is uniformly distributed and thus it is not applicable to the canopies of two or more species or varieties in the same field. Wallace (1997) developed a multisource model from the S–W model that estimated T from n crop species and E from the soil surface. Total ET from the canopy is the sum of the different evaporations for the n species. The evaporation for each species is calculated by P–M-type equations which combined corresponding parameters for canopy resistance and aerodynamic resistance. The water and heat fluxes in multi-species canopies and radiation interception for neighboring species were estimated by developing a simple and useful model (Wallace, 1997). Compare to K_c method, the multisource model is a direct method, and need the data measured above the canopy, which usually had better performance (Rana and Katerji, 2009). The multisource model was now mostly used with theoretical formulation only (Brenner and Incoll 1997; Lhomme et al. 2012, 2013). Lhomme et al. (2012; 2013) developed a simplified formulation considering the effect of stomatal characteristics on evapotranspiration. This model rarely used to estimate ET and its components because of the complexity in the theoretical formulation and difficulties in obtaining crop parameters for n crop species (Verhoef and Allen 2000; Gao et al. 2013). Verhoef and Allen (2000) estimated the ET of a dry-land savannah that consisted of shrubs, forbs, grasses and bare soil using the multisource model, and the prediction of the model was in good agreement with the measurement of ET. Gao et al. (2013) used the multisource model to simulate soil evaporation and plant transpiration in a maize–soybean intercropping system; the model overestimated plant T for maize and soybean and underestimated E. The interactions between crops primarily occur at the intersections between female and male parents, and it is necessary to quantify the radiation interception of adjacent species (especially at the edge rows), canopy resistance, and boundary layer resistance for each species in the multisource model. The mechanism of using the multisource model to estimate ET and its components of maize for seed production should be further studied.

In this study, the dual crop coefficient method for a mixed crop of female and male parents and the multisource model based on the radiation interception of different species were used to estimate daily ET, T of female and male parents and E. The objectives of this study are to validate the dual crop coefficient method and the multisource model using observed ET, T and E measured by eddy covariance system, sap flow, and micro-lysimeters; to determine an accurate model that predicts ET and its components for a heterogeneous canopy; and to provide a scientific basis for the precision irrigation management of maize for seed production in the arid region of northwest China.

2. Materials and methods

2.1. Experimental site and arrangement

The field experiments were carried out during the periods April to September in 2013 and 2014 at the Shiyanghe Experimental Station of China Agricultural University located in Wuwei City, Gansu Province of northwest China (latitude 37°52′N, longitude 102°50′E, altitude 1581 m). The station is in a typical continental temperate climate zone; it has a mean annual sunshine duration > 3000 h and a mean annual temperature of 8.8 °C. This climate is suitable for growing maize for seed production. The region is limited in water resources. The mean annual precipitation is 164 mm, and the mean annual pan evaporation is 2000 mm. An automatic weather station (Hobo, Onset Computer Corp., USA), which was located near the experimental field, measured solar radiation, air temperature, relative humidity, wind speed and direction at 2 m height, and precipitation. All data were recorded at intervals of 15 min. Reference evapotranspiration (ET_O) was calculated by the P–M equation (Allen et al. 1998). Precipitation and ET_O during the 2013 and 2014 growing seasons are given in Table 1.

Maize for seed production (*Zea mays* L. cultivar Funong 963) was sown in one-line male parents and five-line female parents in the experimental plot. The eddy covariance (EC) system was installed in the middle of the field (field size 400 m × 200 m). The planting area was large enough to provide adequate fetch length for the EC system. Female parents were sown on 2013-04-13 and 2014-04-16, and the hybrid seeds were harvested on 2013-09-12 and 2014-09-20. Two batches of male parents provided the pollen to fertilize the female parents were sown on 2013-04-20 and 2013-04-23 and two batches on 2014-04-23 and 2014-04-26. The soil surfaces were partly mulched using plastic film with a width of 120 cm, leaving a 40 cm width of bare soil between two rows of plastic film. The maize was sown in 5 cm diameter holes under the film with the interplant spacing of 25 cm and interrow spacing of 40 cm. The planting densities were 97 500 plants ha^{-1} in both years. The four growth stages in each year were determined according to the general lengths for grain maize reported by Allen et al. (1998) and local observations (Table 1).

Border irrigation was used over the whole growing season; the amount and time of each irrigation event are shown in Table 1. The soil in the experimental area was a light sandy loam. The maximum rooting depth for the maize was 1.0 m. For the 0–1.0 m soil depth, mean soil dry bulk density was 1.38 g cm^{-3}, the field capacity was 0.29 cm^{-3} cm^{-3}, and the wilting point was 0.12 cm^{-3} cm^{-3} (Jiang et al. 2014).

2.2. Measurements and methods

2.2.1. Crop parameters

Crop height (h), leaf area index (LAI) and the fraction of canopy cover (f_c) for female and male parents were measured at 7–10 d intervals over the growing season. Twenty female parents and twenty male parents were randomly selected to measure leaf length, maximum width, and h. Total leaf area was obtained by summing the rectangular areas of each fully expanded leaf (i.e., leaf length × maximum width) and multiplying by 0.74 (Li et al. 2008). Leaf area index (LAI) is the ratio of leaf area per plant to surface area per plant. Five female rows and five male rows were randomly selected to measure f_c using a digital camera directly overhead, and f_c was obtained by calculating the ratio of leaf pixels to the pixel count of the whole photo using Adobe Photoshop CS6 (Adobe Inc., USA). Daily LAI, h and f_c (y_i) were obtained through observation, and days after sowing (DAS) was calculated using a quadratic function (Xu et al. 2011):

$$y_i = a_1 \times DAS^2 + b \times DAS + c \quad (1)$$

where a_1, b and c are constants, which were fitted using observed h, LAI, f_c and DAS;

Five female rows and five male rows were randomly selected to measure photosynthetically active radiation above the canopy (I_{0i}) and at the bottom (I_i) using a nondestructive sunscan canopy analysis system (Delta–T Devices Ltd., England) at 12:00 h every 10–15 d. The minimum extinction coefficient (k_{mini}) of female or male rows was given by (Monsi and Saeki 2005):

$$I_i = I_{0i} e^{-k_{\min i} LAI_i} \quad (2)$$

where LAI_i is the LAI of female or male parents on an observation day.

2.2.2. Soil water content

The 5TE soil moisture sensors (Decagon Devices, Inc. USA) were installed to measure the volumetric soil water content in the root zone of female and male parents below the mulched or bare soil surface (Fig. 1). The sensors were calibrated using the gravimetric method to measure the soil water content of soil samples as near as possible to the sensors. The sensors were installed every 20 cm for the entire root zone (i.e., to a depth of 1.0 m). Each set of five sensors was connected to an automated data logger (EM50; Decagon Devices Inc. USA) which was used to record all data at 30 min intervals.

2.2.3. Measurement of soil evaporation, transpiration and evapotranspiration

Six microlysimeters were used to measure soil evaporation (Fig. 1). Each micro-lysimeter, consisting of an inner and an outer cylinder made of PVC tubes, was installed in the bare soil between two rows of plastic film mulch. The inner and outer cylinder diameters were 10 cm and 11 cm and the height was 20 cm. The inner cylinders were weighed on an electric scale with a precision of 0.1 g at 19:00 h every day. Further details of the installation and theoretical background can be found in Jiang et al. (2016a).

The sap flow rates of female and male parents were measured by the Dynagage Flow32-1 K system (Dynamax, Houston, TX, USA), using the heat balance method (Sakuratani 1981; Baker and Van Bavel 1987). Four female parents and four male parents, 15 m distant from the eddy covariance apparatus, were randomly selected to be monitored during the periods 2013-06-29–2013-09-12 and 2014-06-27–2014-09-20 (Fig. 1). The gauges were installed on the second internode above the ground surface to minimize any asymmetric influence on sap temperature caused by heat conduction of energy stored in the soil (Weibel and De Vos 1994). Leaf sheaths on the second internode were removed, and the plastic film was wrapped around to avoid stem transpiration. Gauges were fixed using layers of silica gel and wrapped with three layers of aluminum foil to avoid the effects of direct radiant heating and rainfall. The gauges were transferred from the instrumented plants to other plants every 10–15 d to avoid tissue damage from heat and constraining stem growth (Gao et al. 2013). They were disconnected before irrigation to avoid damage and reinstalled within 2 d after irrigation. A CR1000 data logger (Campbell Scientific, Logan, UT, USA) recorded sensor output every 15 min. Further details on the methods and theoretical background can be found in previous studies (Jara et al., 1998; Bethenod et al. 2000; Ding et al. 2013; Zhang et al. 2011). Sap flow rates of the individual plants were converted to a vapor flux per unit land area using the leaf area indexes:

$$T = \frac{n_f}{N_f} \sum_{i=1}^{N_f} \frac{Q_{fi}}{LA_{fi}} LAI_f + \frac{n_m}{N_m} \sum_{i=1}^{N_m} \frac{Q_{mi}}{LA_{mi}} LAI_m \quad (3)$$

Maize evapotranspiration was measured by the EC system in each case (Fig. 1). The EC system consisted of a fast response 3-D sonic anemometer (model CSAT3) to measure wind velocity and vertical temperature fluctuations, a Krypton hygrometer (model KH20) to measure water vapor density, a temperature and humidity sensor (model HMP45C) to measure temperature and humidity at 1.0 m above the canopy surface, and a data logger (model CR5000, Campbell Scientific Inc., USA). The sensor heights were adjusted every week to ensure a height of 1.0 m between sensors and canopy surface, and the minimum fetch length of the EC systems was 100 m. We also installed a net radiometer (model NR-LITE, Kipp&Zonen, Delft, Netherlands) and two soil heat flux plates (HFP01) to measure net radiation (R_n) 1.5 m above the canopy surface and soil heat fluxes below the plastic mulch and bare soil. The data logger was used to record the data of all sensors at 0.1 s intervals and to provide a calculation of 30 min averages. The details of installation, theoretical background and correction of the eddy covariance measurements can be found in Jiang et al. (2014) and Jiang et al. (2016a; 2016b).

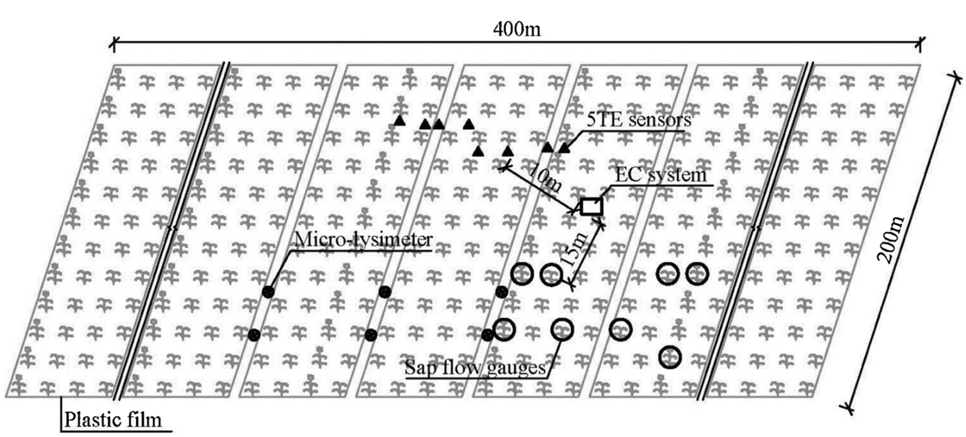

Fig. 1. Scheme of the study area and the installations of eddy covariance (EC) system, sap flow gauges, micro-lysimeters and 5TE sensors.

3. Models

3.1. The dual crop coefficient method

In the dual crop coefficient method, the crop coefficient (K_c) is divided into the basal crop coefficient (K_{cb}), accounting for crop transpiration, and the soil evaporation coefficient (K_e), accounting for evaporation from the soil surface. Crop evapotranspiration (ET_c) can be calculated as (Allen et al. 1998):

$$ET_c = (K_s K_{cb} + K_e)ET_0 \tag{4}$$

where K_s is determined by soil water availability in the root zone.

Maize for seed production requires different cultivars of female and male parent plants, which we consider as different crops. According to Allen et al. (1998), total K_{cb} should be calculated by weighting the K_{cb} values for the individual crops according to the proportion of land area covered by each crop and by the height of the crop:

$$K_{cb} = \frac{f_m h_m K_{cb\,m} + f_f h_f K_{cb\,f}}{f_m h_m + f_f h_f} \tag{5}$$

In our study, f_m and f_f were determined using the leaf area indexes (LAI_i) of female and male parents:

$$f_m = \frac{LAI_m}{LAI_m + LAI_f} \tag{6}$$

$$f_f = \frac{LAI_f}{LAI_m + LAI_f} \tag{7}$$

The transpiration of female (T_{cf}) and male (T_{cm}) parents and soil evaporation (E_{cs}) were calculated using the equations:

$$T_{cm} = K_{sm} K_{cb\,m} ET_0 \tag{8}$$

$$T_{cf} = K_{sf} K_{cb\,f} ET_0 \tag{9}$$

$$E_{cs} = K_e ET_0 \tag{10}$$

3.1.1. Basal crop coefficient

Allen et al. (1998; 2007) and Allen and Pereira (2009) provide the standardized K_{cb} values for many crops for a sub-humid climate (the average minimum daily relative humidity, RH_{min}, is about 45%) with moderate wind speeds, u (the average u is about 2 m s^{-1}). The standardized K_{cbmid} and $K_{c\ end}$ values of maize for seed production were not given in these studies. The daily K_{cb} for each crop (K_{cbi}) at the mid-season and late season which has large canopy coverage, can be calculated using LAI for each crop (LAI_i):

$$K_{cb\ i} = K_{c\,\min} + \left(1 - e^{-0.7LAI_i}\right)\left(K_{cbfulli} - K_{c\,\min}\right) \tag{11}$$

The value of $K_{c\ mini}$ is between 0.15 and 0.2; we use the $K_{c\ mini}$ value of 0.15 in this study. According to Allen et al. (1998), $K_{cbfulli}$ for female or male parents in Eq. (11) is a function of mean crop height and it is adjusted for climate conditions:

$$K_{cbfulli} = \min(1.0 + 0.1h_i, 1.20) + [0.04(u_2 - 2) - 0.004(RH_{\min} - 45)]\left(\frac{h_i}{3}\right)^{0.3} \tag{12}$$

K_{cb} for female or male parents ($K_{cb\ ini}$) during the initial stage can be used directly from Allen et al. (1998). Since the difference between female and male plants is small, we defined $K_{cb\ ini}$ as 0.15. K_{cb} increases linearly with the increase in days after sowing at the development stage, and its slope is determined by the K_{cb} at the initial and midseason stages (Allen et al. 1998).

3.1.2. The soil evaporation coefficient

K_e is determined by the energy available at the soil surface and soil water content and is calculated according to Allen et al. (1998) as:

$$K_e = \min\{K_r(K_{c\,\max} - K_{cb}), f_{ew} K_{c\,\max}\} \tag{13}$$

where f_{ew} is the fraction of surface soil evaporation. We introduced the ratio of bare soil to the soil surface (f_s) to include the effect of plastic film mulching on soil evaporation, and calculated f_{ew} as:

$$f_{ew} = \min\{f_s(1 - f_c), f_w\} \tag{14}$$

where $K_{c\ max}$ is the upper limit of the evaporation and transpiration from any crop-bearing surface (Allen et al. 1998). This value needs to be adjusted according to crop height and local climate conditions:

$$K_{c\,\max} = \max\left(\left\{1.2 + [0.04(u_2 - 2) - 0.004(RH_{\min} - 45)]\left(\frac{h_c}{3}\right)^{0.3}\right\}, \{K_{cb} + 0.05\}\right) \tag{15}$$

The calculation of K_r in Eq. (13) can be separated into a two-stage drying cycle (Ritchie 1972; Allen et al. 1998, 2005), the energy-limited stage and the water-limited stage. K_r is 1 at the energy-limited stage, and K_r begins to decrease at the water-limited stage when the evaporable water becomes less than readily evaporable water (REW) in the soil upper layer:

$$K_r = \begin{cases} \dfrac{TEW - D_{e,i-1}}{TEW - REW}, & D_{e,i-1} > REW \\ 1, & D_{e,i-1} \le REW \end{cases} \tag{16}$$

where TEW is the maximum cumulative depth of evaporation from the soil surface layer when $K_r = 0$ and is calculated as:

$$TEW = 1000(\theta_{F,e} - 0.5\theta_{W,e})Z_e \tag{17}$$

According to Allen et al. (1998), the cumulative depth of water depleted from the soil surface layer at the end of day i ($D_{e,i}$) in Eq.16 is calculated using the soil water balance method:

$$D_{e,i} = D_{e,i-1} - (P_i - RO_i) - \frac{I_i}{f_w} + \frac{E_{s,i}}{f_{ew}} + T_{ew,i} + DP_{e,i} \tag{18}$$

3.1.3. Water stress coefficient

The soil water stress coefficient (K_s) is calculated according to available water in the effective root zone:

$$K_s = \begin{cases} \dfrac{TAW - D_{r,i-1}}{TAW - RAW} = \dfrac{TAW - D_{r,i-1}}{TAW(1-p)}, & D_{r,i-1} > RAW \\ 1, & D_{r,i-1} \le RAW \end{cases} \tag{19}$$

The total available soil water (TAW) is the amount of water absorbed by the crop in the effective root zone and can be calculated using the water content at field capacity ($\theta_{F,r}$) and wilting point ($\theta_{w,r}$) as (Allen et al. 1998):

$$TAW = 1000(\theta_{F,r} - 0.5\theta_{W,r})Z_r \tag{20}$$

$D_{r,i-1}$ in Eq. (19) is calculated using the daily water balance equation:

$$D_{r,i} = D_{r,i-1} - (P_i - RO_i) - I_i - CR_i + ET_{c,i} + DP_i \tag{21}$$

CR_i and DP_i were negligible according to Allen et al. (1998) and Jiang et al. (2014).

3.2. The multisource model

3.2.1. Evapotranspiration model

Total ET from the canopy is simply the sum of each evaporation component (λE_i) (Wallace 1997), and is calculated separately from P–M types of equations using the corresponding available energy (A_i) and vapor pressure deficit (VPD_0) at the mean canopy source height (z_m) (Lhomme et al. 2013). The model considers the canopy and

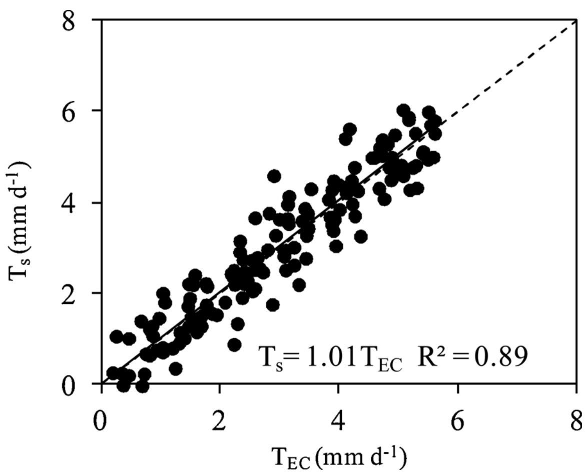

Fig. 2. Comparison of daily crop transpiration measured by sap flow (T_s) with daily transpiration calculated as the difference between evapotranspiration measured by eddy covariance and soil evaporation measured by micro-lysimeters (T_{EC}) in 2013 and 2014.

aerodynamic resistances of each maize cultivar, and it is assumed that the canopy and aerodynamic resistances interact at the mean canopy height (z_m) and that only aerodynamic resistance ($r_a^{\,a}$) between the reference height above the canopy and z_m needs to be considered. Thus, total ET of the canopy can be calculated as:

$$\lambda ET_{ML} = \sum_{i=1}^{n+1} \lambda E_i = \sum_{i=1}^{n+1} C_i PM_i = \sum_{i=1}^{n} C_{c,i} PM_{c,i} + C_s PM_s \tag{22}$$

where $PM_{c,i}$ and PM_s are the P–M-type equations for crop components and soil evaporation and are given by:

$$PM_{c,i} = \frac{\Delta A + \{\rho_a C_p VPD - \Delta r_a^{c,i}(A - A_{c,i})\}/(r_a^a + r_a^{c,i})}{\Delta + \gamma\{1 + r_c^i/(r_a^a + r_a^{c,i})\}} \tag{23}$$

$$PM_s = \frac{\Delta A + \{\rho_a C_p VPD - \Delta r_a^s(A - A_s)\}/(r_a^a + r_a^s)}{\Delta + \gamma\{1 + r_s^s/(r_a^a + r_a^s)\}} \tag{24}$$

In Eqs. (22),(23) and (24), λ, VPD, Δ, ρ_a, γ and C_p were determined by climate variables (Shuttleworth and Gurney 1990; Allen et al. 1998). $C_{c,i}$ and C_s were combined coefficients of crop resistance and soil resistance that were determined using the equation (Wallace 1997):

$$C_{c,i} = \left[1 + \frac{\frac{1}{R_s} + \sum_{j=1, j\neq i}^{n} R_{c,j}}{\frac{1}{R_{c,i}} + \frac{1}{R_a}}\right] \tag{25}$$

$$C_s = \left[1 + \frac{\sum_{i=1}^{n} R_{c,i}}{\frac{1}{R_s} + \frac{1}{R_a}}\right] \tag{26}$$

$R_{c,i}$, R_s and R_a in Eqs. (25) and (26) can be calculated by:

$$R_{c,i} = (\Delta + \gamma) r_a^{c,i} + \gamma r_c^i \tag{27}$$

$$R_s = (\Delta + \gamma) r_a^s + \gamma r_s^s \tag{28}$$

$$R_a = (\Delta + \gamma) r_a^a \tag{29}$$

Aerodynamic resistances $r_a^{\,s}$ and $r_a^{\,a}$, bulk boundary layer resistance ($r_a^{\,c,i}$), canopy resistance ($r_c^{\,i}$) for female or male parents and soil resistance ($r_s^{\,s}$) in Eq. (27)–(29) can be calculated as described in Jiang et al. (2016b).

The available energy ($A_{c,i}$) for female or male parents in Eq.(23) is given by:

$$A_{c,i} = f_i R_n \tag{30}$$

The available energy of soil evaporation (A_s) can be calculated by:

Table 2
The parameters for female and male parents and soil used for the dual crop coefficient model in 2013 and 2014.

Parameters	2013		2014	
	female	male	female	male
p	0.6		0.6	
REW (mm)	13		13	
TEW (mm)	21		21	
RAW (mm)	107		107	
TAW (mm)	170		170	
h_{max} (m)	1.42	1.08	1.70	1.33
Z_r (m)	0.2/1.0		0.2/1.0	
RH_{min} (%)	32.91		35.95	
u_2 (m s-1)	0.32		0.41	
f_w	1		1	

$$A_s = \left(1 - \sum_{i=1}^{n} f_i\right) R_n - G \tag{31}$$

The f_i were determined by the method proposed by Wallace (1997), which considered the extreme case of two species. If the female parent is very much taller than male parent, then the fraction of the incident radiation intercepted by the female ($f_f^{\,d}$) and male ($f_m^{\,s}$) parents is calculated by:

$$f_f^d = 1 - e^{-K_f LAI_f} \tag{32}$$

$$f_m^s = e^{-K_f LAI_f}(1 - e^{-K_m LAI_m}) \tag{33}$$

If the male parent is much taller than the female parent, the fraction of the incident radiation intercepted by the male ($f_m^{\,d}$) and female ($f_f^{\,s}$) parents is given by:

$$f_m^d = 1 - e^{-K_m LAI_m} \tag{34}$$

$$f_f^s = e^{-K_m LAI_m}(1 - e^{-K_f LAI_f}) \tag{35}$$

The extinction coefficient of female (K_f) or male (K_m) rows (K_i) is given by:

$$K_i = k_{\min i}/\sin\beta \tag{36}$$

If the female and male parents are similar heights, their canopies overlap, and their fraction of light-interception is somewhere between these two extreme cases. The incident radiation intercepted by the male ($f_m^{\,n}$) and female ($f_f^{\,n}$) parents is determined by the relative heights of female and male parents:

$$f_f^n = f_f^s + F(f_f^d - f_f^s) \tag{37}$$

$$f_m^n = f_m^s + (1 - F)(f_m^d - f_m^s) \tag{38}$$

F is between 0 and 1, and F is a function of the height of the male (h_m) and female parent (h_f):

$$F = \frac{h_f}{h_f + h_m} \tag{39}$$

The ratio of male to female parent in this study is 1:5. Thus the interference in light interception occurred only in two adjacent rows of female and male parents. The proportional coefficient of female (a_f) and male (a_m) parents is:

$$a_f = \frac{LAI_f}{LAI_m + 5LAI_f} \tag{40}$$

$$a_m = \frac{LAI_m}{LAI_m + 5LAI_f} \tag{41}$$

The fraction of the incident radiation intercepted by the male (f_m) and female (f_f) parents is:

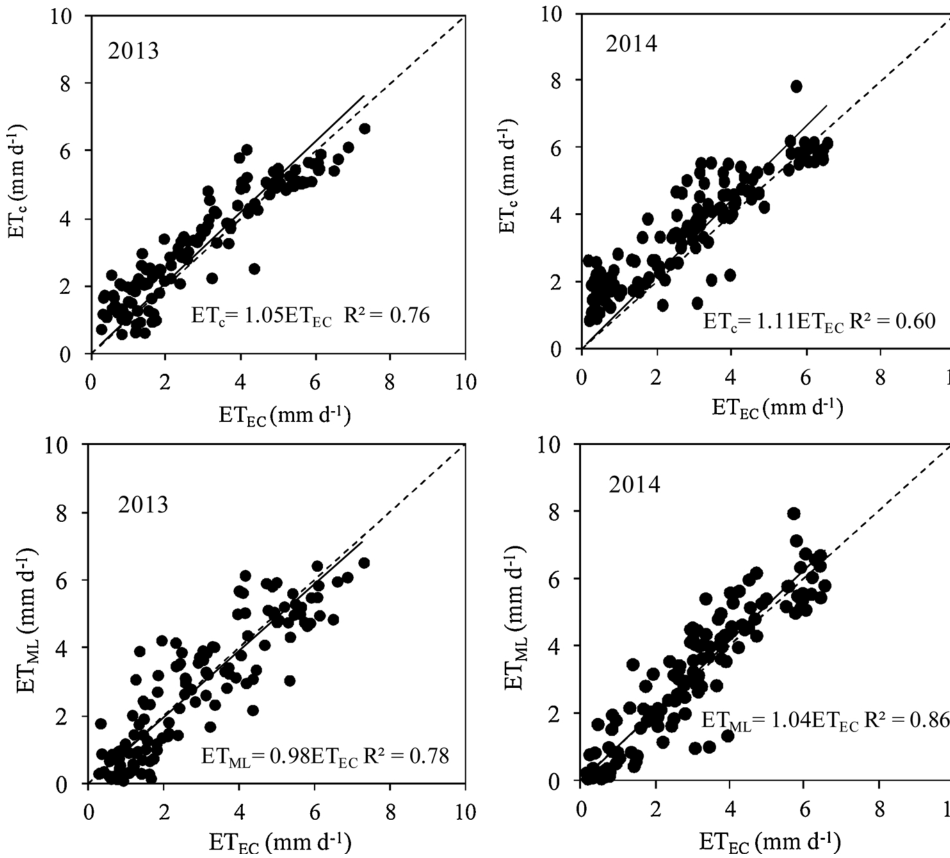

Fig. 3. Comparison of daily evapotranspiration predicted by the dual crop coefficient model and the multisource model with *ET* measured by eddy covariance (ET_{EC}) in 2013 and 2014.

Table 3
Statistical results of daily evapotranspiration, transpiration of female and male parents and soil evaporation calculated by the dual crop coefficient model and the multisource model in comparison with observed values.

Season	Regression equation	n	R^2	MAE	RMSE	E_1
2013	$ET_c = 1.05ET_{EC}$	132	0.76	0.67	0.80	0.58
	$ET_{ML} = 0.98ET_{EC}$	132	0.78	0.60	0.74	0.62
	$T_{cm} = 1.17T_{sm}$	62	0.70	0.70	0.84	0.39
	$T_{mm} = 0.92T_{sm}$	62	0.68	0.53	0.66	0.44
	$T_{cf} = 1.04T_{sf}$	62	0.81	0.44	0.54	0.56
	$T_{mf} = 0.92T_{sf}$	62	0.76	0.50	0.62	0.48
	$E_{cs} = 1.16E_s$	59	0.30	0.21	0.24	−0.08
	$E_{ms} = 0.94E_s$	59	0.63	0.13	0.18	0.48
2014	$ET_c = 1.11ET_{EC}$	145	0.60	0.86	1.05	0.45
	$ET_{ML} = 1.04ET_{EC}$	145	0.86	0.60	0.79	0.59
	$T_{cm} = 1.27T_{sm}$	72	0.56	1.06	1.20	0.19
	$T_{mm} = 0.97T_{sm}$	72	0.64	0.58	0.76	0.43
	$T_{cf} = 1.21T_{sf}$	72	0.60	0.93	1.06	0.02
	$T_{mf} = 0.94T_{sf}$	72	0.77	0.39	0.62	0.51
	$E_{cs} = 1.03E_s$	64	0.31	0.18	0.22	0.14
	$E_{ms} = 0.97E_s$	64	0.77	0.09	0.13	0.50

n is sample size, R^2 is determination coefficient, MAE is mean absolute error (mm d^{-1}), RMSE is root mean square error (mm d^{-1}), E_1 is the modified coefficient of efficiency.

$$f_f = (a_f + a_m)f_f^n + (1 - a_f - a_m)f_f^d \quad (42)$$

$$f_m = (a_f + a_m)f_m^n \quad (43)$$

3.2.2. Evapotranspiration partitioning

According to Eq. (22), each evaporation factor (λE_i) is calculated from P–M-type equations and *T* for male (T_{mm}) and female parents (T_{mf}) and E_{ms} can be calculated using the P–M model:

$$\lambda T_{mm} = \frac{\Delta A_{c,m} + \rho_a C_p VPD_0/r_a^{c,m}}{\Delta + \gamma(1 + (r_c^m/r_a^{c,m}))} \quad (44)$$

$$\lambda T_{mf} = \frac{\Delta A_{c,f} + \rho_a C_p VPD_0/r_a^{c,f}}{\Delta + \gamma(1 + (r_c^f/r_a^{c,f}))} \quad (45)$$

$$\lambda E_{ms} = \frac{\Delta A_s + \rho_a C_p VPD_0/r_a^s}{\Delta + \gamma(1 + (r_s^s/r_a^s))} \quad (46)$$

According to Wallace (1997), VPD_0 in Eqs. (44)–(46) is given by:

$$VPD_0 = VPD + \frac{r_a^a}{\rho C_p}\{\Delta A - (\Delta + \gamma)\lambda ET\} \quad (47)$$

3.3. Model calibration and evaluation

Transpiration (T_s) of the maize sap flow was calibrated using the difference between *ET* as observed by the EC system and *E* as observed using the micro-lysimeters (T_{EC}). The results showed that T_s agreed well with T_{EC} (Fig. 2), indicating that both sap flow and the micro-lysimeters accurately measure transpiration and soil evaporation. These results are consistent with previous studies (Ding et al. 2013; Bethenod et al., 2000; Granier et al. 1996; Hatton et al. 1995; Ham et al. 1990). Therefore, the data observed by both sap flow and the micro-lysimeters can be used to determine the accuracy of our model.

The crop data required for the crop coefficient method are shown in Table 2. According to Allen et al. (1998), the standard value of the soil water depletion fraction for no stress (p_{table}) is 0.5. This value needs to be adjusted for the mean daily *ET* (ET_{EC}) that was observed by the EC system in 2013 (Allen et al., 1998):

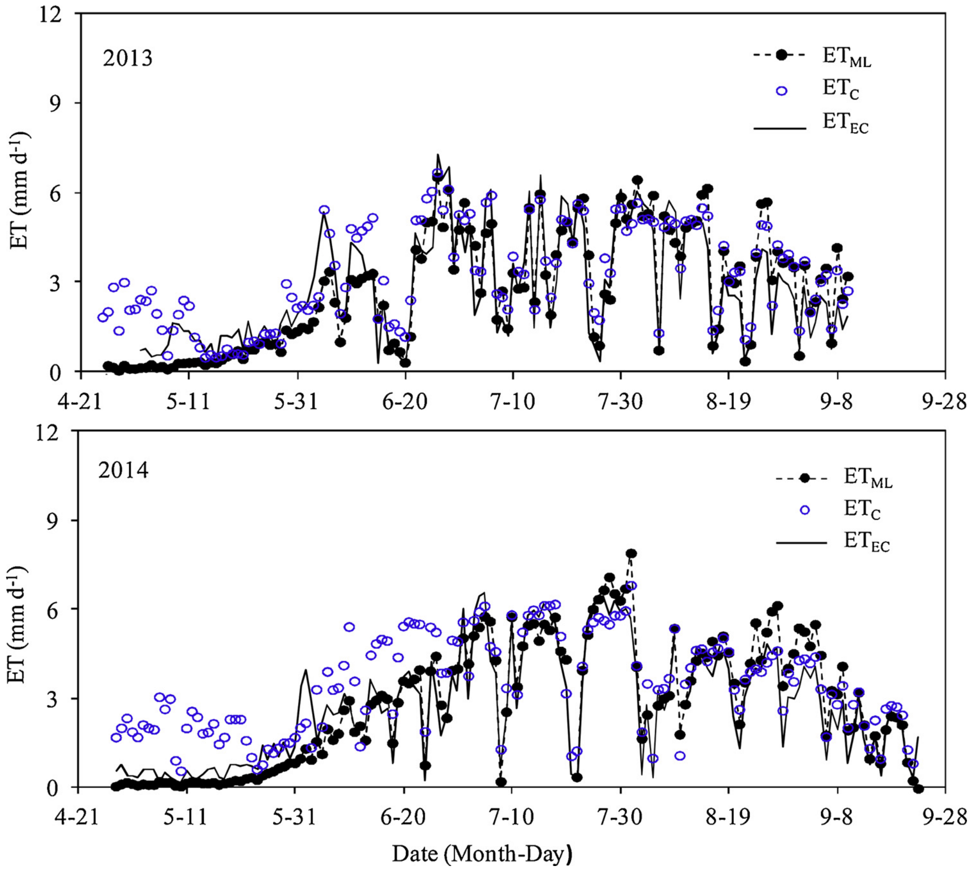

Fig. 4. Seasonal variation in daily evapotranspiration predicted by the dual crop coefficient model, the multisource model, and ET measured by eddy covariance (ET_{EC}) in 2013 and 2014.

$$p = p_{table} + 0.04(5 - ET_{EC}) \tag{48}$$

The soil (REW, TEW, RAW and TAW) and irrigation (f_w) parameters were determined according to Allen et al. (1998) (Table 2).

The model is evaluated by linear regression between estimated (E_i) and observed value (Q_i). The statistical parameters include the coefficient of determination (R^2), mean absolute bias error (MAE), root mean square error (RMSE) and the modified coefficient of efficiency (E_1). They are calculated as follows:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|Q_i - E_i| \tag{49}$$

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(Q_i - E_i)^2\right]^{\frac{1}{2}} \tag{50}$$

$$E_1 = 1.0\frac{\sum_{i=1}^{n}|Q_i - E_i|}{\sum_{i=1}^{n}|Q_i - \bar{Q}|} \tag{51}$$

where $\bar{Q}$ is the mean of the observed value.

4. Results and discussion

4.1. Comparison of maize evapotranspiration estimated by the dual crop coefficient method and multisource model

Daily evapotranspiration (ET) was calculated by the dual crop coefficient (K_c) method (ET_c) and the multisource model based on radiation interception by neighboring species (ET_{ML}). When compared to daily ET observed by the EC system (ET_{EC}), ET_c was greater than ET_{EC} in 2014 (Fig. 3). In 2013, ET_c was close to ET_{EC}. It was only 5% greater than ET_{EC} with a coefficient of determination (R^2), root mean square error (RMSE), mean absolute bias error (MAE) and modified coefficient of efficiency (E_1) of 0.76, 0.80 mm d^{-1}, 0.67 mm d^{-1} and 0.58, respectively. However, in 2014 ET_c was 11% greater than ET_{EC}, with R^2 = 0.60, RMSE = 1.05 mm d^{-1}, MAE = 0.86 mm d^{-1} and E_1 = 0.45 (Table 3). Similar results have been obtained by other authors. For example, Zhang et al. (2013) found that ET for summer maize calculated by the dual K_c method was 7% greater than ET_{EC}. Ding et al. (2013) found that ET for spring maize calculated by the dual K_c method was 2% greater than ET_{EC}. Jiang et al. (2014) found that ET for maize for seed production calculated by the dual K_c method was 9% greater than ET_{EC}. Over all the growth stages, ET_c was close to ET_{EC} at both the midseason and late season stages, while ET_{EC} was significantly overestimated at the initial and development stages (Fig. 4). Jiang et al. (2014) also found that ET for maize for seed production calculated by the dual K_c method overestimated ET_{EC} at the initial and development stages. The principal reason for this result is that the basic crop coefficient (K_{cb}) at the initial stage was a constant value and thus it fails to reflect crop growth. K_{cb} at the development stage is determined by linear regression between K_{cb} at the initial stage and K_{cb} at the midseason stage. The regression does not account for the nonlinear dynamic behavior of K_{cb} due to variation in crop canopy coverage (Raes et al. 2009; Ding et al. 2013).

Using the multisource model, better agreement was found between ET_{ML} and ET_{EC} (Fig. 4), with greater E_1 and R^2, and lower MAE and RMSE. In 2013, ET_{ML} was only 2% less than ET_{EC}, ET_{ML} was 4% greater than ET_{EC} in 2014 (Fig. 3 and Table 3). Over all the growth stages, ET_{ML} slightly underestimated ET_{EC} at the initial stage. This was because the canopy resistance (r_c) is determined by LAI, and low LAI resulted in overestimating r_c.

However, a few ET_c and ET_{ML} values deviated significantly from ET_{EC}. These differences occurred mainly after irrigation or on rainy

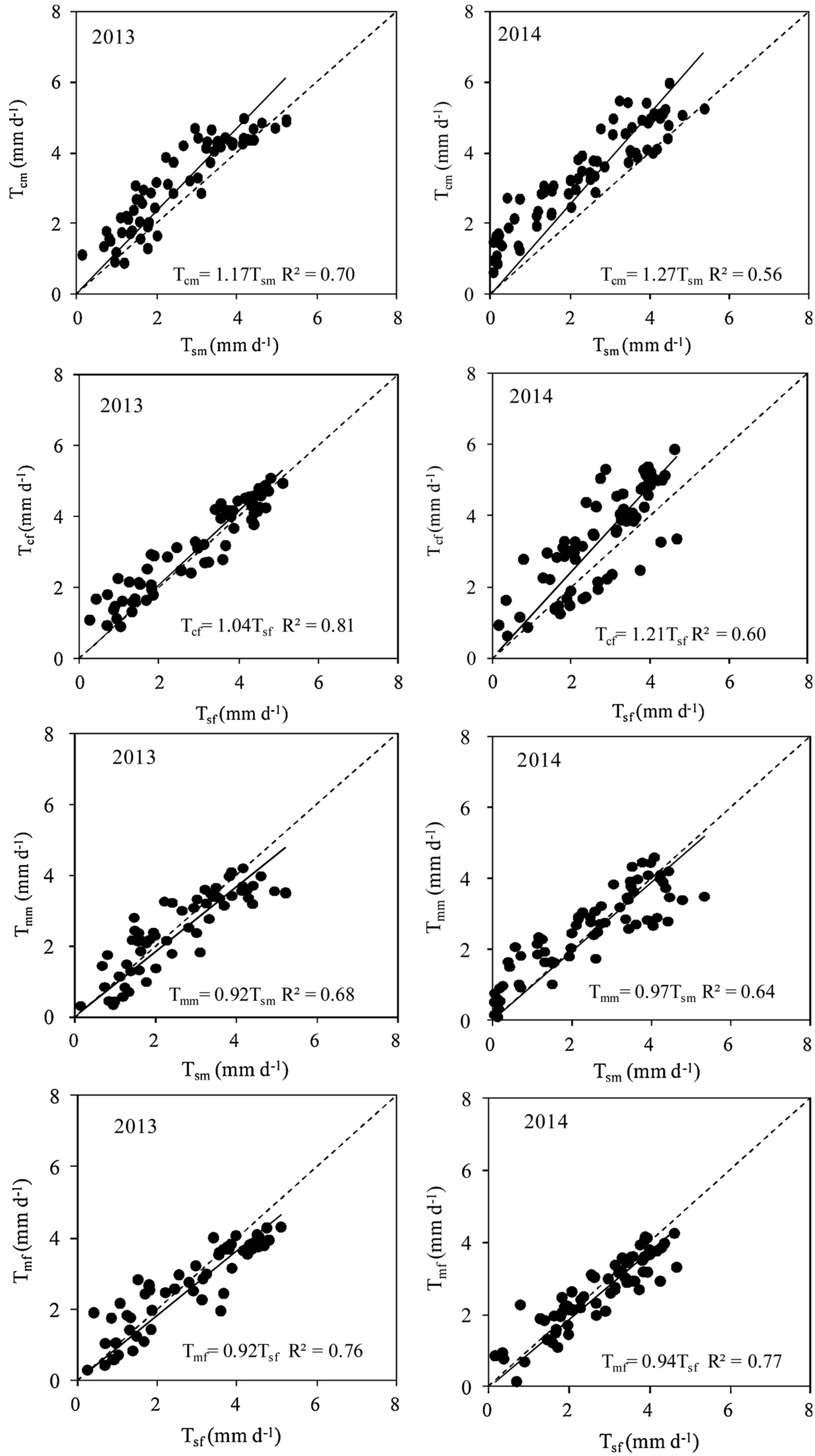

Fig. 5. Comparison of daily transpiration of female and male plants predicted by the dual crop coefficient model and the multisource model with *T* measured by sap flow in 2013 and 2014.

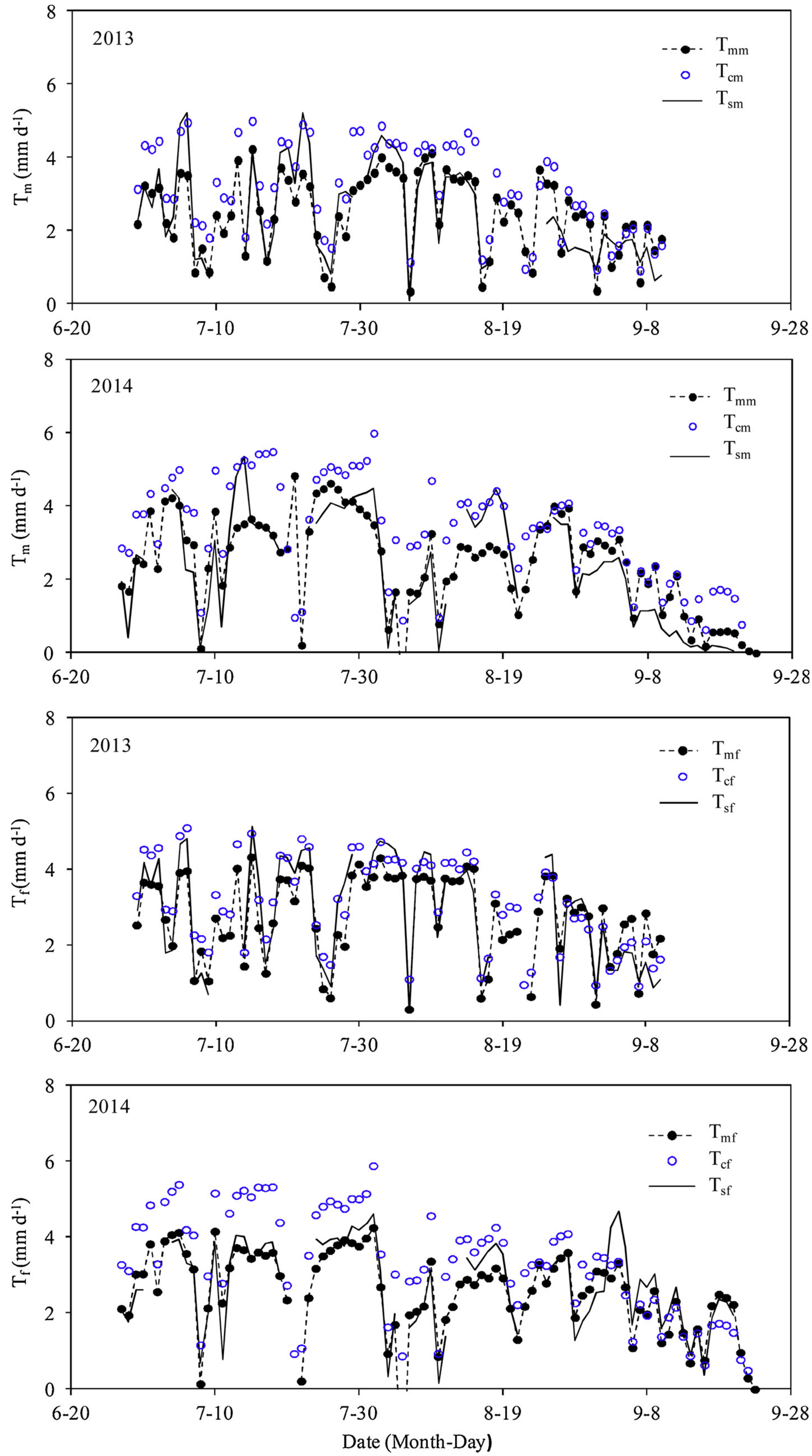

Fig. 6. Seasonal variation in daily transpiration of female and male parents predicted by the dual crop coefficient model, the multisource model, and daily transpiration measured by sap flow in 2013 and 2014.

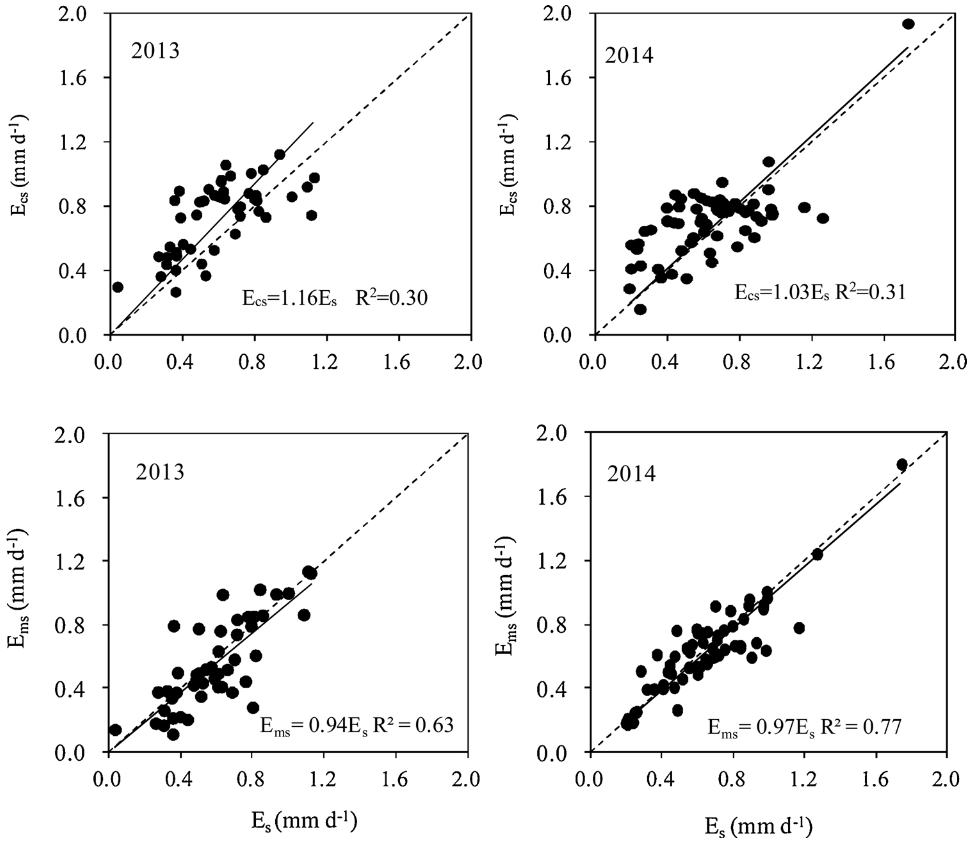

Fig. 7. Comparison of daily soil evaporation prediction by the dual crop coefficient model and the multisource model with the evaporation measured by micro-lysimeters (E_s) in 2013 and 2014.

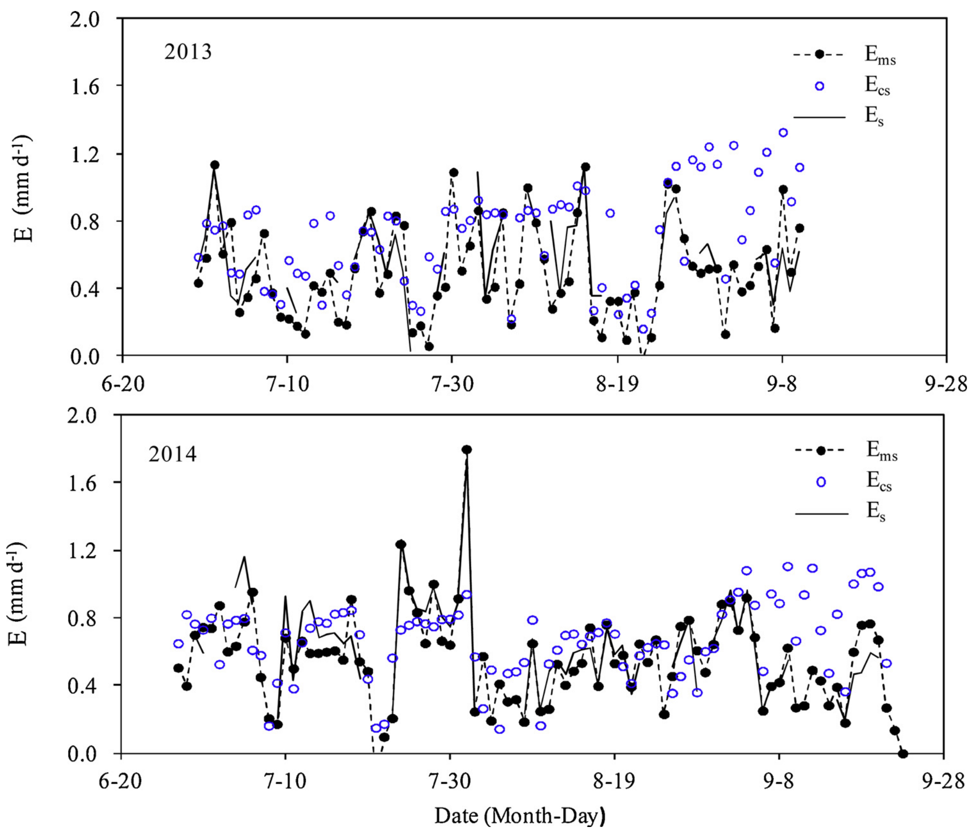

Fig. 8. Seasonal variation in daily soil evaporation predicted by the dual crop coefficient model, the multisource model, and observed by micro-lysimeters (E_s) in 2013 and 2014.

days, such as on 2013-06-06 (the first irrigation) and 2013-08-23 (rain), and on 2014-06-02 (rain) and 2014-08-24 (the fourth irrigation) (Fig. 4). These values were observed because of measurement errors in the EC system after irrigation and on rainy days. ET_c and ET_{ML} overestimated ET_{EC} in the late season stage in 2013 (Fig. 4), mainly because of severe damage to the leaves caused by insect pests. The observed values of *LAI* and canopy coverage were higher than the actual values, causing the overestimation of crop transpiration.

4.2. Comparison of maize transpiration estimated by the dual crop coefficient method and multisources model

Fig. 5 shows that the dual K_c method overestimated T for male parents (T_{cm}) compared to the sap flow method (T_{sm}). T_{cm} was 17% and 27% greater than T_{sm} in 2013 and 2014, with lower R^2 and E_1 values and greater MAE and RMSE (Table 3). For female plants (T_{cf}), T estimated by the dual K_c method in 2013 was similar to that measured by sap flow (T_{sf}). In 2014, T_{cf} was greater than T_{sf} with lower R^2 and E_1 values and greater MAE and RMSE (Table 3). Over all the whole growth stages, T_{cm} was overestimated when compared to T_{sm} in both years. In 2013, T_{cf} was close to T_{sf} at the midseason stage and greater than T_{sf} at the late growth stage. In 2014, T_{cf} was significantly overestimated when compared to T_{sf} (Fig. 6). The main reason is that the dual K_c method overestimated the K_{cb} of female and male parents during the midseason stage for full vegetation ($K_{cbfulli}$). Ringersma and Sikking (2001) also found that the dual K_c method overestimated $K_{cbfulli}$, even after they introduced a resistance-correction factor.

The multisource model accurately calculated T for female (T_{mf}) and male (T_{mm}) parents. Both T_{mf} and T_{cf} were close to the observed values of T in 2014. T_{mf} was closer than T_{cf} to T_{sf} in 2014 (Fig. 6). The multisource model gave more accurate predictions of T for male plants; T_{mm} was only 8% (2013) and 3% (2014) less than T_{sm}, with greater R^2 and E_1 values and lower MAE and RMSE (Fig. 5, Table 3). Fig. 5 shows that the multisource model only slightly overestimated T_{sf} and T_{sm} in the late season stage in 2013. This was because of the large *LAI* measurement error caused by plant diseases and insect pests. Gao et al. (2013) used the multisource model to estimate T for maize and soybean in maize–soybean intercropping system. Their results showed that the model agreed well with observation. Estimated T for maize was 7% greater than observed values with $R^2 = 0.83$ and estimated T for soybean was 8% greater than observed values with $R^2 = 0.83$.

4.3. Comparison of soil evaporation estimated by the dual crop coefficient method and multisource model

Fig. 7 shows that soil evaporation (E) calculated by the dual K_c method (E_{cs}) significantly exceeded that measured by the micro-lysimeter (E_s) in both seasons. E_{cs} was 16% greater than E_s with $R^2 = 0.30$, MAE $= 0.21$ mm d^{-1}, RMSE $= 0.24$ mm d^{-1} and $E_1 = -0.08$ in 2013. E_{cs} was 3% greater than E_s in 2014, with low values of R^2 and E_1 and higher MAE and RMSE values. The maximum difference between E_{cs} and E_s was after the last irrigation in the late season stage (Fig. 8). Er-Raki et al. (2010) also found a large difference between E predicted by the dual K_c method and the observed value for grapevines. Estimated E was significantly less than the observed values in the midseason stage and significantly greater than the observed values in the late season stage. Zhao et al. (2013) used the dual K_c method to calculate E in a winter wheat and summer maize rotation systems. Their calculated E for winter wheat was significantly greater than the observed value in September. The slope of the regression line between predicted and observed E for summer maize was close to 1 and predicted E was also greater than the observed values in the late season stage.

The multisource model performed better than the K_c method. In 2013, the estimated E by the multisource model (E_{ms}) was closer to E_s (Fig. 8), and was only 6% less than E_s. In 2014, E_{ms} was only 3% less than E_s (Fig. 7 and Table 3). Gao et al. (2013) also found good agreement between E calculated by the multisource model and E measured by micro-lysimeters for maize–soybean intercropping system, with estimated E 3% greater than the observed values with $R^2 = 0.90$.

5. Conclusions

In this study, the dual crop coefficient (K_c) method and the multisource model based on radiation interception by neighboring species were both used to predict daily evapotranspiration (*ET*) and its components of maize for seed production. Both *ET* estimated by the dual K_c method (ET_c) and *ET* estimated by the multisource model (ET_{ML}) were close to observed *ET* as measured by the eddy covariance system (ET_{EC}). ET_{ML} was closer than ET_c to ET_{EC}, while ET_c was higher ET_{EC} at the initial and development stage due to the constant value of initial basic crop coefficient and its interpolation during the development stage. Transpiration of male plants calculated by the dual K_c method was significantly higher than transpiration measured by sap flow in both seasons. T for female plants calculated by K_c method was greater than observed T in 2014 and close to observed T in 2013. The multisource model predicted T values for female and male parents that were closer to observed T than those predicted by the dual crop coefficient model, with greater R^2 and E_1, and lower MAE and RMSE. Evaporation predicted by the dual K_c method was greater than observed E as measured by micro-lysimeters (E_s), and was 16% (2013) and 3% (2014) greater than E_s. E calculated by the multisource model was closer to E_s, and was 6% (2013) and 3% (2014) less than E_s, with higher values of R^2 and E_1, and lower MAE and RMSE. The multisource model can be used to accurately predict *ET* and its components from the heterogeneous canopy.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agwat.2019.05.025.

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