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Transpiration of female and male parents of seed maize in northwest China

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ABSTRACT

Drip irrigation under mulch (DM) has been widely promoted and applied in arid regions. The process of crop growth and surface water and energy transfer will change significantly under the dual control of mulch and drip irrigation compared with those under the traditional border irrigation under mulch (BM) method, which will further affect the regional eco-hydrology process. The Hexi Corridor has become the largest seed maize production base in China due to its abundant solar radiation, and heat resources and large diurnal temperature difference. Unlike grain maize, seed maize can be divided into female and male parent plants. The growth conditions of the parent plants differ; male plants are planted 7–14 d later than female plants to produce preferable fertilization conditions, which distinctly influences the energy transfer process between the different parent plants and the soil and ultimately leads to significantly different plant water consumption in the maize field.

To determine the difference in the transpiration rate between a BM field and a DM field and to reveal the difference in water consumption characteristics between female and male plants, eddy covariance system (EC) measurements, a thermal balance sap flow system and micro-lysimeters were applied to conduct continuous, fixed-location comparison measurements of the total evapotranspiration from 2014 to 2016. The total evapotranspiration (ET), transpiration rates of the female (T_f) and male plants (T_m) and the soil evaporation (E_s) in seed maize fields were separately analysed in both the BM field and DM fields. Results indicated that T_f/ET, T_m/ET and E_s/ET dynamically varied with the crop growth during the whole growth period. Transpiration rates under the DM treatment were 2–8% higher than those under the BM treatment under the local agricultural management conditions. Besides, the female plant transpiration rate exceeded the male plant transpiration rate by 9–20% in the BM treatment and by 14–32% in the DM treatment field during the whole growth stages. However, male plant transpiration produced after the pollination of female plants is useless to final seed production. It is more practical to decrease the planting ratio of male to female plants to the appropriate level and remove the male plants earlier to increase the water use efficiency in seed maize fields. Moreover, the seed maize field in this study had a smaller proportion of soil evaporation than those in other grain maize field studies conducted around the world, which was probably due to the mulching effect and higher plant density.

1. Introduction

Drip irrigation under film mulch is a new agricultural water saving irrigation technology, which has been extensively used in arid regions in recent years for its effect in increasing the water use efficiency (Eid et al., 2013; Liu et al., 2017; Yaghi et al., 2013) and promoting the crop growth (Hou et al., 2010; Qin et al., 2016; Tiwari et al., 2003, 1998). Under the dual controls of mulching and drip irrigation technologies, water and energy transfer process would significantly change (Li et al., 2017; Wang et al., 2000; Zhang et al., 2017; Zotarelli et al., 2009), which will further affect the regional eco-hydrology process.

Maize is a densely planted crop in which crop transpiration represents most of the total evapotranspiration (Al-Kaisi et al., 1989; Ding et al., 2013; Kang et al., 2003; Zhou et al., 2017) and has been widely planted in arid areas. Many studies have been conducted on the water consumption of maize to reduce soil evaporation (Abu-Awwad, 1998; Li et al., 2013a,b; Martins et al., 2013), promote crop transpiration (Wu et al., 2011; Yang et al., 2012) and improve water use efficiency (Howell et al., 1998; Kang et al., 2003; Li et al., 2008; Payero et al., 2008). In addition, studies have shown that the agricultural microclimate that results from farming control measures and the physiological and growth characteristics of maize have important influences on

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water consumption by maize (Djaman et al., 2013; Feng et al., 2017; Steduto and Hsiao, 1998; Suyker and Verma, 2008; Zeggaf et al., 2008). However, maize generally falls into two categories: one is grain maize, which is used for producing grain, and the other is seed maize, which is used for producing seed. In contrast with grain maize, seed maize is cross-fertilized by female and male plants, which are planted between lines strictly according to the planting ratio (the ratio of male to female plants numbers), and female plants are seeded 7–14 d earlier than male plants to guarantee favourable fertilization conditions. Finally, the male plants, which were useless for final seed production, and were removed before the harvest. As a result, female plants have a higher transpiration rate with a higher leaf area index than male plants during the early growing stages. Under these conditions, female plants and male plants grow with different physiologic characteristics, which have a combined interactive influence on the agricultural microclimate.

Currently, 70% of the maize seeds in China are produced in the Hexi Corridor where is full of solar radiation and heat resources. Plenty of water consumption produced by seed maize in this region. It is very urgent to carry out researches on the water consumption of seed maize and increase the water use efficiency. However, little attention has been paid on the transpiration partitioned by female plants and male plants above the seed maize field, and further research on the interactive influence between the cross-fertilized crops and the agricultural microclimate is still in challenging. Hence, the aim of our work is to quantify the water consumption difference between border irrigation under mulch (BM) field and drip irrigation under mulch (DM) field, reveal the interactive influence of physiological growth characteristic of female and male plants and the agricultural microclimate under the two treatments. We conducted continuous, fixed-station, comparison observations for 3 years of the total evapotranspiration (ET), female plant transpiration (T_f), male plant transpiration (T_m) and soil evaporation in seed maize fields under both border irrigation under mulch (BM) field and drip irrigation under mulch (DM) field respectively using the eddy covariance (EC) system and sap flow and micro-lysimeter measurements to ascertain: (1) the difference between the physiological growth and water consumption properties of female and male seed maize plants under BM and DM treatments under the local farming management conditions and (2) the difference in the water consumption properties between seed maize and grain maize.

2. Materials and method

2.1. Experimental site and description

The experiment was conducted in Wuwei Experimental Station for Efficient Water Use in Agricultural Ministry of Agriculture (37°51′N, 102°53′E, 1585 m Alt) from 2014 to 2016. The experiment site is located in a typical continental temperate climate, rich in solar radiation and heat resources, having yearly sunshine hours more than 3000 h, average frostless season more than 150d over the years, mean annual maize growth period temperature 19–20 °C, > 0 °C annual cumulative temperature higher than 3550 °C, average precipitation 164 mm over the years, mean annual pan evaporation approximately 2000 mm, and the groundwater table in the station is 40–50 m below the ground surface (Li et al., 2015a,b; Li et al., 2016; Qin et al., 2016).

This study involved contrasting observation experiments on seed maize in a drip irrigation under mulch (DM) cornfield and a border irrigation under mulch (BM) cornfield over three years. Unlike grain maize, seed maize is cross-fertilized by female and male parents which were hybridized by Ganxin Professional Seed Companies. Female parents are castrated in the shooting stage so that only pollen from male plants. To ensure a preferable fertilization effect, male parents are always planted 7–14 d later than female parents and will be eliminated after completion of fertilization and before the final harvest period to meet different use such as feed crop or fertilizer. Professional semi-automated machines were applied to lay out plastic mulch and sow in both seed maize experiment fields. Male maize seeds and female maize seeds were sown fixed distance apart within each row, with one line for male plants and several lines for female plants. However, both experiment fields belong to different farmers so that there are slightly differences such as germination rates and planting ratios in management between two fields. In that follows, our measurement and analysis were based on the full respect for the local agricultural production practice. The planting density and management dates of farm activities in both treatments are shown in Table 2. The plastic transparent mulch applied in both treatments was plastic film of 8 μm thickness with a shortwave transmissivity reflectivity and absorptivity of 0.85, 0.10 and 0.05, respectively, and a longwave transmissivity of 0.74.

Specifically, in the BM treatment, the plastic mulch film with width of 1.2 m was laid out along the east and west by professional automation machinery, the ratio of the film width to the inter-film bare soil width was 3:1 with an area of 400 m*200 m during 2014–2016, and the ratio of female parents to male parents was 4:1 in 2014–2015 and 7:1 in 2016. The distance between seed rows under the same mulch was 0.25 m and seeds were sown 0.3 m apart within each row. Female and the male plants are companion planting in line according to the parents planting ratio. The 1 m-depth surface layer was composed of silty loam, with an average soil dry unit weight of 1.52 g cm^{-3} and a field capacity of 0.29 cm^3 cm^{-3} from 2014 to 2016.

The DM treatment has an area of 2000 m*1000 m during 2014–2015, and 400m*200 m in 2016, the film width, lay out and the mulching ratio were the same as the BM treatment. The space of drip irrigation belt was 0.4 m with the distance between neighbouring emitters of 0.3 m. And the ratio of female parents to male parents was 7:1 in 2014–2015 and 6:1 in 2016. The distance between seed rows under the same mulch was 0.25m. Seeds were sown 0.22 m apart within each row, both parent plants are companion planting in line according to the parents planting ratio. The soil texture at 0-0.8 m depth is silty loam, and that at 0.8-1.0 m depth is silt during 2014–2016.The average soil dry bulk density and averaged θ_{FC} at 0–1.0 m depth were 1.52 g cm^{-3} and 0.30 cm^3 cm^{-3} in 2014, and 1.46 g cm^{-3} and 0.29 cm^3 cm^{-3} in 2015 and 2016, respectively (Qin et al., 2016).

The total irrigation amount in BM experiment site was 360 mm, 442 mm, 480 mm in 2014, 2015 and 2016, respectively, and 350 mm, 449 mm, 388 mm under DM treatment in 2014, 2015 and 2016, respectively. Detailed description of irrigation and precipitation events could be seen in Qin et al. (2016).

2.2. Measurement and data correction

Continuous fixed-station observations were carried out on seed maize under both DM and BM treatments and each with an EC flux observation system, a thermal balance sap flow system (Flow32-k) and several micro-lysimeters (Fig. 1).

2.2.1. Meteorological data and eddy covariance

Evapotranspiration was measured using an eddy covariance (EC) system, which was located in the central south of the maize field. The eddy covariance (EC) system consisted of a sonic anemometer/thermometer (model CSAT3), a Krypton hygrometer (model KH20), a radiation meter (model NR-LITE) and a soil moisture meter (model EM50) in BM treatment in 2014 and a CO_2/H_2O open path gas analyzer (model EC150), a radiation meter (model CNR4), a surface temperature meter (model SI-111), a hygrothermograph (model HMP45C) and a soil moisture meter (model CS616) in BM treatment during 2015–2016 and in DM treatment during 2014–2016. The sonic anemometer/thermometer, the Krypton hygrometer/the CO_2/H_2O open path gas analyser and the surface temperature meter sensors were installed at 4.0 m height above the ground level during 2014–2015 and 3.5 m in 2016. And the radiation meter was installed at a 4.0 m height above the ground level during 2014–2015 and one meter above the canopy height in 2016. The soil moisture meters were installed distributed

Fig. 1. Locations of the equipment layout in the experiment during 2014–2016. Treatment **BM** represents the border irrigation under plastic mulch, while the treatment **DM** represents the drip irrigation under plastic mulch.

Table 1
List of measurement methods and instruments parameters in border irrigation under mulch **(BM)** treatment and drip irrigation under mulch **(DM)** treatment.

No	Parameters	Symbol	Unit	Measurement method	Sensors	Period	Data correction	Treatment
1	Energy flux	ET_{EC}, Rn	W m^{-2}	Eddy covariance system	EC150,USA	2014–2016	By eddyPro 4.0 software	DM
2	Energy flux	ET_{EC}, Rn	W m^{-2}	Eddy covariance system	KH20,USA	2014	By standard program	BM
3	Energy flux	ET_{EC}, Rn	W m^{-2}	Eddy covariance system	EC150,USA	2015–2016	By eddyPro 4.0 software	BM
4	Surface temperature	T_s	°C	Eddy covariance system	SI-111, USA	2014–2016	By standard program	BM and DM
5	Water vapor deficit	VPD	kpa	Eddy covariance system	HMP155A, USA	2014–2016	By standard program	BM and DM
6	Crop transpiration	Tsap	mm d^{-1}	Thermal balance system	Flow32–1 K, USA	2014–2016	By standard program	BM and DM
7	Female plant transpiration	$T_{f_}$sap	mm d^{-1}	Thermal balance system	Flow32–1 K, USA	2014–2016	By standard program	BM and DM
8	Male plant transpiration	$T_{m_}$sap	mm d^{-1}	Thermal balance system	Flow32–1 K, USA	2014–2016	By standard program	BM and DM
9	Soil evaporation	E_{lys}	mm d^{-1}	Weighing method	Micro-lysimeter	2014–2016	By standard program	BM and DM
10	Soil moisture	θ	$cm^3\,cm^{-3}$	TDR method	CS616,USA	2014–2016	By oven drying method	BM and DM

Table 2
Local farming scheduling of female plants and male plants in the seed maize field under **BM** treatment and **DM** treatment during 2014–2016.

Treatments		Planting density (ha^{-1})	Female parent			Male parent	
			Seeding date	Detasseling date	Harvesting date	Seeding date	Removal date
2014	BM	108,000	25-Apr	6-Jul	20-Sep	3-May	10-Sep
	DM	112,500	27-Apr	3-Jul	7-Sep	8-May	24-Jul
2015	BM	108,000	15-Apr	13-Jul	16-Sep	2-May	28-Jul
	DM	112,500	26-Apr	4-Jul	4-Sep	6-May	19-Jul
2016	BM	116,176	15-Apr	4-Aug	20-Sep	12-May	1-Sep
	DM	109,474	20-Apr	2-Aug	10-Sep	16-May	31-Aug

underground 0–1 m depth in 2014 and 2016, and 0-0.8 m depth in 2015. All the probes were connected to the data logger with a sampling frequency of 20 Hz, and sampling interval of 30 min. Specific observation indicators and methods are shown in Table 1.

Then EC flux data was disposed with Eddy Pro 4.0 software (Table 1). The software has powerful function which provides almost all the essential correction procedures followed as: (1) detection and elimination of raw peaks, (2) the double coordinate rotation method (Finnigan et al., 2003; Paw U et al., 2000), (3) the frequency loss correction, (4) air density correction (Webb et al., 1980). Then the quality of EC data and footprint of EC measurement were assessed based on Eddy Pro 4.0. The data for which the footprint extended out of the experimental area should be deleted. As for the missing data, the linear interpolation method was used for data gap filling when less than 4 observations missed, while the MDV (mean diurnal variation) method was adopted when five or more missed (Falge et al., 2001). After the above steps, for daytime EC-based data, the measured energy budget components were forced to close using 'Bowen-ratio closure' method proposed by Twine et al. (2000), assuming that Bowen-ratio is correctly measured by the EC system. During nighttime periods, the 'residual-λET closure' method proposed by Twine et al. (2000) was adopted in this study, which assumed that the EC-based H is accurately measured and solved for λET as the residual to the energy balance equation ($\lambda ET = Rn - G - H$) (Li et al., 2013a,b).The precipitation in both treatments was the same and measured with a standard automatic weather station near the experimental croplands at a height of 2.0 m above the ground. And Table 3 summarizes the main meteorological parameters for border irrigation under mulch (BM) treatment and drip irrigation under mulch (DM) treatment during the three growing seasons.

Table 3
Summary of seasonal meteorological variables above both **BM** and **DM** treatment in seed maize growing seasons during 2014–2016.

Treatments		Growth period	Surface temperature (°C)	Wind speed ($m\ s^{-1}$	Net radiation ($MJ\ m^{-2}d^{-1}$)	VPD (kPa)	Rainfall (mm)	Soil water content (cm^3cm^{-3})
2014	BM	4.25 – 9.20	19.02	1.68	9.48	1.12	202.1	0.258
	DM	4.27 – 9.07	17.70	1.72	10.34	1.40	195.4	0.269
2015	BM	4.15 – 9.16	18.63	1.21	11.70	1.36	148.1	0.225
	DM	4.26 – 9.04	17.88	1.32	12.19	1.57	119.4	0.262
2016	BM	4.15 – 9.20	19.20	1.59	11.33	1.40	120.2	0.271
	DM	4.20 – 9.10	19.84	1.59	11.72	1.59	115.2	0.307

2.2.2. Sap flow

The thermal balance sap flow system (model Flow32–1 K system, Dynamax, Houston, TX, USA) applied in previous research work was proved to be an effective method to measure maize transpiration (Ding et al., 2013; Jiang et al., 2016). In our research, the thermal balance sap flow system (model Flow32–1 K system, Dynamax, Houston, TX, USA) was used in both treatments during 2014–2016 to obtain the seed maize plant transpiration. Each thermal balance system has eight probes. And each probe was installed 20 cm above the ground stem part on five female plants and three male plants. All the probes in each treatment were connected to a CR1000 data logger with a sampling frequency of 20 Hz, and sampling interval of 30 min. The sap flow flux data ($L\ d^{-1}$) was firstly scaled to the specific monitored plants transpiration (mm d^{-1} per plant) using the average ground area. Then the average monitored female/male plant transpiration (mm d^{-1} per plant) calculated from the related monitored plants (five female plants and three male plants) was transformed to the field female/male crop transpiration (mm d^{-1}) using the average monitored female/male plant leaf area and the field female/male plant leaf area index, respectively (Jiang et al., 2014). And the specific calculations are listed as follows:

$$T_{i\_sap} = \frac{1}{N_{s,i}} \sum_{N_{s,i}}^{j=1} \frac{Q_{i,j}}{LA_{i,j}} LAI_i \tag{1}$$

Where N_i is the number of sap flow measurement for the male or female parent, $Q_{i,j}$ is the individual sap flow rate of the male or female plant (L day^{-1} $plant^{-1}$), $LA_{i,j}$ is the individual leaf area of male or female parent (m^2); LAI_i means leaf area index of male or female parent ($cm^2\ cm^{-2}$). The measured total transpiration of maize is the sum of the transpiration of female (T_{f_sap}) and male (T_{m_sap}) parents:

$$T_{sap} = (n_f T_{f\_sap} + n_m T_{m\_sap}) f_m \tag{2}$$

Where n_m and n_f are the ratio of the number of male and female parents to the total number of plants, f_m is the mulching ratio.

2.2.3. Soil evaporation

The micro-lysimeters were installed between crops (under the mulch) and bare soil (between mulches) in the surface soil with three replications in each experiment site. The micro-lysimeter composed of inner and outer tubes, both made from PVC tubes with the diameter of 11 cm for the outer tube and 10 cm for inner tube. The height of both tubes were 20 cm. The bottom of the inner tube was covered with nylon wire which was convenient for water vapour transfer in vertical direction. And the downward flux past the bottom of the micro-lysimeter was assumed to be negligible when calculated the soil water evaporation measured by the micro-lysimeter. Daily soil evaporation at each micro-lysimeter was obtained as the difference between the weights measured by an electronic scale (Mettler Toledo, PL6001-L, USA) with accuracy of 0.1 g at 19:00 every day. And the field daily soil evaporation under mulch (E_{ms_lys}) at each experiment site was averaged by daily soil evaporation at each micro-lysimeter installed under plastic mulch, while the field soil evaporation under bare soil (E_{bs_lys}) was averaged by daily soil evaporation at each micro-lysimeter installed under bare soil. Finally, the total field daily soil evaporation (E_{lys}) at each experiment site was calculated by the sum of E_{ms_lys} and E_{bs_lys} with weight of 3:1 (the ratio of mulched soil to the bare soil). Besides, soil water evaporation in irrigation or precipitation events was not observed because the measured data during these periods is inaccurate. Therefore, the averaged soil water evaporation values were computed using the measured values of observed dates during each growth period. And the micro-lysimeters were replaced within one or two days after each irrigation and heavy rainfall to minimize the difference between soil moisture inside and outside the tubes based on previous studies (Yunusa et al., 2004; Zhu et al., 2014).

2.2.4. Sap flow interpolation

The observations of stem flow often began in the heading stage and were carried out until the end of the growing period and the early growth stage stem flow data was lost due to the thinner stems of maize plants which was not suitable to measure with the thermal balance system. Interpolation of the maize transpiration data acquired in the seedling period was required to determine the dynamic variation of maize transpiration over the whole study period. In practice, the daily variations of the transpiration by female and male parents and its relationship with the LAI, surface temperature (T_s), vapour pressure difference (VPD), net radiation (R_n) and average soil moisture content (θ) in the 0–80 cm soil layer under BM treatment and DM treatment over 2014–2016 were analysed to obtain nonlinear regression equations, thereby extending the transpiration data of the plants in the seedling period. Within the observation period, the mean values of other observational days in the growing period were used for interpolation when plant transpiration or soil evaporation data were missing due to rainfall or irrigation. Male plants in the DM treatment in 2014 and in the BM treatment in 2015 were not observed due to instrumental failure, so the nonlinear regression equation was used for interpolation.

Evapotranspiration after energy balance closure (ET_{EC}) was taken as the standard and used to balance the water vapour associated with plant transpiration (transpiration by the female and male plants was added proportionally) determined by the thermal balance sap flow (Flow 32-k) and the micro lysimeter-observed soil evaporation ($E_{lys}+T_{sap}$) to finally calculate the evapotranspiration over the entire growing period. The actual female transpiration (T_m), male transpiration (T_f) and evaporation (E_s) could be obtained from the flowing equations:

$$(n_m T_{m\_sap} + n_f T_{f\_sap}) f_m + E_{lys} + \Delta ET = ET_{EC} \tag{3}$$

$$T_m = \frac{n_m T_{m\_sap}}{(n_m T_{m\_sap} + n_f T_{f\_sap}) f_m + E_{lys}} \Delta ET + T_{m\_sap} f_m \tag{4}$$

$$T_f = \frac{n_f T_{f\_sap}}{(n_m T_{m\_sap} + n_f T_{f\_sap}) f_m + E_{lys}} \Delta ET + T_{f\_sap} f_m \tag{5}$$

$$E_s = \frac{E_{lys}}{(n_m T_{m\_sap} + n_f T_{f\_sap}) f_m + E_{lys}} \Delta ET + E_{lys} \tag{6}$$

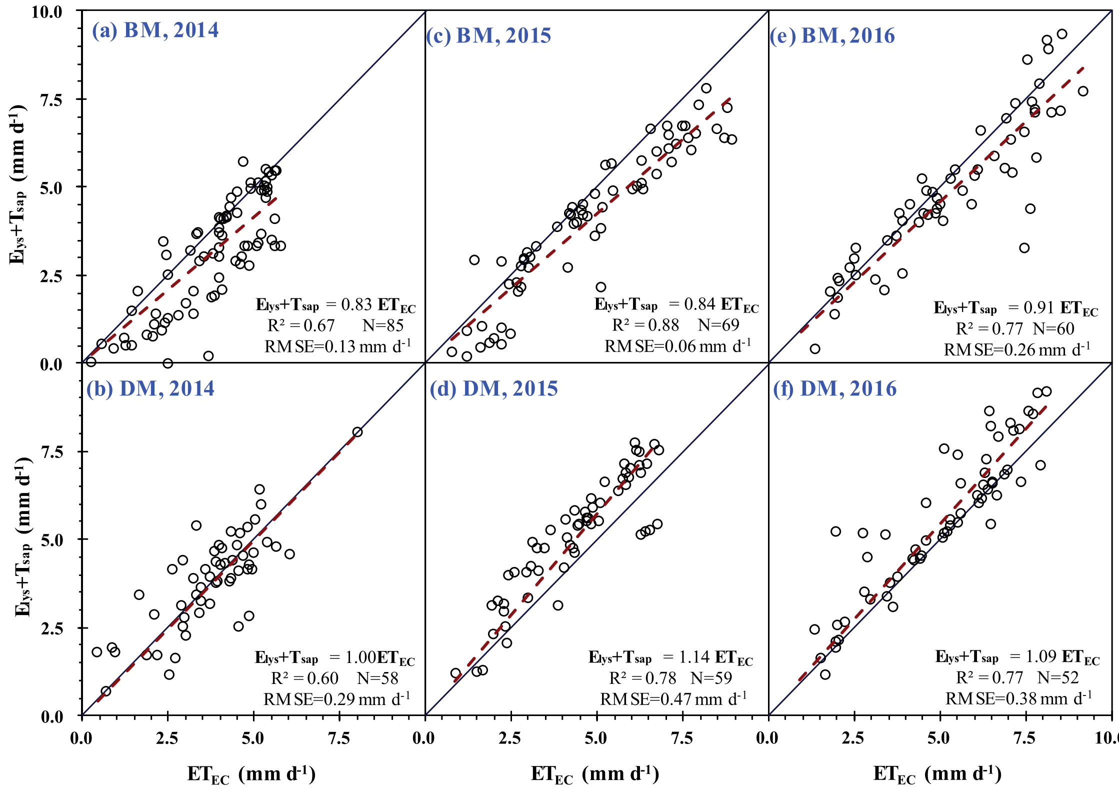

Fig. 2. Comparison of daily evapotranspiration (**$E_{lys}+T_{sap}$**) composed of evaporation (**E_{lys}**) measured by micro-lysimeter and transpiration (**T_{sap}**) measured by sap flow with daily evapotranspiration (**ET_{EC}**) measured by eddy covariance system in the maize field under treatment **BM** (**a, c, e**) and **DM** (**b, d, f**) during 2014–2016.

3. Results

3.1. Comparison of EC-observed ET (ET_{EC}) and E + T at the two sites

Fig. 2 shows the daily comparison between the EC-observed ET (ET_{EC}) and the sum of evaporation measured by micro-lysimeter and crop transpiration measured by sap flow (T_{sap} + E_{lys}). Crop transpiration was calculated as a weighted average using the planting ratio between male and female plants under border irrigation under mulch treatment (BM) and drip irrigation under mulch treatment (DM) during the observation period in 2014–2016. Under the two treatments, the growing period of male parents was 30–60 d shorter than that of female parents due to later sowing time and earlier being cut off from the seed maize field.During the sap flow observation period, the average values of ET_{EC}, T_{sap} and E_{lys} under BM treatment were 3.84, 3.41 and 0.43 mm d^{-1} in 2014; 5.04, 4.18 and 0.86 mm d^{-1} in 2015; and 4.94, 4.39 and 0.55 mm d^{-1} in 2016, respectively. Under the DM treatment, the average values of ET_{EC}, T_{sap} and E_{lys} were 3.65, 3.44 and 0.21 mm d^{-1} in 2014; 4.68, 4.31 and 0.37 mm d^{-1} in 2015; and 4.84, 4.54 and 0.30 mm d^{-1} in 2016, respectively. During the sap flow observation period in 2014–2016, the average values of evapotranspiration under DM treatment were lower than those under BM treatment by 0.19, 0.56 and 0.10 mm d^{-1}, respectively. However, the average transpiration values under DM treatment were greater than those under BM treatment by 0.03, 0.12 and 0.15 mm d^{-1}, respectively, and the average evaporation values under DM treatment were lower than those under BM treatment by 0.22, 0.24 and 0.25 mm d^{-1}, respectively. Under the DM treatment, more water consumption was used to the plant transpiration.

After forcing the energy balance to be closed, the maize field evapotranspiration measured using the eddy covariance (EC) system (ET_{EC}) was compared to the sum of transpiration (the transpiration by the female (T_{f_sap}) and male plants (T_{m_sap}) was added proportionally) measured by sap flow system and soil evaporation (E_{lys}) measured by micro lysimeter. Fig. 2 indicates that E_{lys} + T_{sap} was close to ET_{EC} during the observation period in 2014–2016. The regression was not significantly different from line 1:1, with a root mean square error (RMSE) of 0.06-0.47 mm d^{-1} in both treatments during three years, indicating a good agreement between the measured ET by two approaches. Thus, the EC system can be used as a standard in the calculation of water vapour closure in the studied maize field.

3.2. Transpiration data fitting and interpolation at the two sites

However, since the plant stems in the early growth stage of maize are too thin for sap flow observation, the transpiration data in this stage were extended by interpolation to quantify the water consumption from the transpiration of male and female plants over the entire growing period. The ET_{EC} value was taken as the standard and used for the water vapour closure correction of the plant transpiration measured from the sap flow (Flow 32-k) according to the parent planting proportions and the soil evaporation measured by the micro-lysimeter during the same period.

The plant transpiration values (T_m and T_f) after correcting for water vapour closure under the BM and DM treatments over 2014–2016 were first made Person analysis with biological factors and meteorological factors and finally finding that T_m and T_f were significant correlation with leaf area index (LAI_m and LAI_f), surface temperature (T_s), water vapour deficit (VPD), net radiation (R_n) and average soil moisture content (θ) at 0–80 cm depth (Table 4). And nonlinear regression analysis between T_m and T_f under both BM and DM treatments were made with the above influencing factors, and get the following empirical regression equations (Eq. (1)–(4)) for female plant transpiration (T_f) and male plant transpiration (T_m) under the BM and DM treatments.

(1) Transpiration of female parent plants under BM during 2014–2016:

Table 4
Correlation between female plants transpiration **(T_f)** or male plants **(T_m)** and biological factors and meteorological factors over the whole growth stages under treatment **BM** and **DM** during 2014–2016. For * represents $P < 0.05$, and ** represents $P < 0.01$.

Treatments		Biological factors		Meteorological factors			
		LAI_f ($cm^2\,cm^{-2}$)	LAIm(cm2 cm − 2)	SWC ($cm^3\,cm^{-3}$)	Ts (°C)	VPD (Kpa)	Rn (W m−2)
BM	T_f	0.385**		0.319**	0.360**	0.428**	0.636**
	T_m		0.515**	0.628**	0.227*	0.374**	0.519**
DM	T_f	0.200**		0.150*	0.429**	0.536**	0.713**
	T_m		0.248*	0.470**	0.621**	0.715**	0.833**

$$T_f = -0.082LAI_f^2 + 0.849LAI_f + 0.03T_s^2 - 0.041T_s + 0.720VPD^2 - 1.48VPD + 0.001R_n^2 - 0.01R_n + 52.705\theta^2 - 14.042\theta + 0.531 \quad (7)$$

(2) Transpiration of male parent plants under BM during 2014–2016:

$$T_m = -0.127LAI_m^2 + 1.784LAI_m - 0.005T_s^2 + 0.078T_s + 0.479VPD^2 - 1.371VPD + 0.01R_n^2 - 0.006R_n + 323.002\theta^2 - 189.704\theta + 25.762 \quad (8)$$

(3) Transpiration of female parent plants under DM during 2014–2016:

$$T_f = -0.045LAI_f^2 + 0.791LAI_f + 0.01T_s^2 - 0.590T_s + 0.642VPD^2 - 1.148VPD + 0.01R_n^2 - 0.02R_n - 308.845\theta^2 + 213.852\theta - 30.241 \quad (9)$$

(4) Transpiration of male parent plants under DM during 2014–2016:

$$T_m = 0.07LAI_m^2 - 0.03LAI_m - 0.01T_s^2 + 0.47T_s - 2.143VPD^2 + 6.282VPD + 0.01R_n^2 - 0.03R_n + 17.00\theta^2 + 22.37\theta - 18.71 \quad (10)$$

Then the empirical equations in Eq. (7)–(9) were used for interpolation and extension of the data series to fill in the beginning period of growth to obtain female plant transpiration and male plant transpiration for the entire growing period. After fitting, female plant transpiration and male plant transpiration were added to the micro-lysimeter-observed soil evaporation for the same term according to the planting proportion to obtain the total ET, which was compared with ET_{EC} with consistency index of 0.99 under both treatments during 2014–2016, respectively, and the results were good consistent (Table 5).

3.3. Comparison of the transpiration between BM and DM treatments

ET_{EC} was taken as the standard and used for the water vapour closure correction of soil water evaporation, female plant transpiration and male plant transpiration, respectively. Seasonal variations of E_s, T_f and T_m during the entire growth period under both treatments in 2014–2016 are shown in Fig. 3. A comparison of water vapour closure-corrected daily E_s, T_f and T_m values over all of the growth stages and their respective ratios against ET_{EC} over the entire growing period under the BM and DM treatments in 2014–2016 is shown in Table 6.

The female average daily transpiration rate under DM treatment was higher than that under BM treatment by 0.19, 0.23 and 0.21 mm d^{-1} during 2014, 2015 and 2016, respectively. The values for male plants varied due to the different removal times of male plants in the growing period. Fig. 4 (a) depicts the comparison of average daily transpiration rate weighted by planting ratio between the BM field and DM field. The average daily transpiration rates in the DM field were higher than the transpiration rates in the BM field by 2%, 8% and 7%, respectively.

The ratios of the total female plant transpiration amount against the total evapotranspiration ($\Sigma T_f/\Sigma ET_{EC}$) under the DM treatments were higher than the ratios under the BM treatments by 0.10, 0.08 and 0.02 during 2014, 2015 and 2016, respectively. Additionally, the planting ratios under the DM treatment were higher than the planting ratios under the BM treatment by 0.05, 0.05 and −0.02 during 2014–2016, respectively. Even though seed maize plants grew with different planting ratios, the female transpiration amount under DM treatment was generally higher than that under BM treatment, and the promoting effect of female transpiration under DM treatment was greater than the effects increased by the different planting ratios. In brief, female plants under DM treatment generally grew with a higher transpiration rate.

3.4. Comparison of transpiration by female and male plants under both treatments

In the early growth stage, the transpiration rate of female plants was higher than that of male plants under both treatments due to their earlier seed time. However, male plants grew faster, with a rapidly increased transpiration rate, which gradually reduced the transpiration rate difference between the female and male plants during the vigorous growth stages (Fig. 3). Although the fruits of male maize plants cannot be used as commercial seeds, they were sometimes left to grow longer even after the pollination period to be processed for feedstuff or fertilizer. Finally, the male plants were removed before the female plant harvest to avoid mixture with the female plants.

Considering the entire growing period, female plants grew longer than male plants by 18, 67 and 45 d under BM treatments during 2014–2016, respectively. The corresponding values under the DM treatments which were 56, 57 and 36 d, respectively. During the entire female plant growth period, the average daily female transpiration rates were 2.80, 2.97 and 3.26 mm d^{-1} under BM treatments during

Table 5
Comparison of daily evapotranspiration measured by eddy covariance **(ET_{EC})** with the sum of interpolated transpiration of female plants **(T_f)**, male plants **(T_m)** and soil evaporation **(E_s)** in the seed maize field under treatment **BM** and **DM** during 2014–2016.

Treatments		Regression equation	R^2	n	MBE (mmd^{-1})	RMSE (mmd^{-1})	IA
2014	BM	$4/5T_f + 1/5T_m + E_s = 0.90ET_{EC}$	0.62	49	0.18	0.84	0.99
	DM	$7/8T_f + 1/8T_m + E_s = 0.90ET_{EC}$	0.57	54	0.17	0.94	0.99
2015	BM	$4/5T_f + 1/5T_m + E_s = 0.92ET_{EC}$	0.67	48	−0.24	1.55	0.99
	DM	$7/8T_f + 1/8T_m + E_s = 0.97ET_{EC}$	0.66	49	−0.06	0.89	0.99
2016	BM	$7/8T_f + 1/8T_m + E_s = 1.02ET_{EC}$	0.66	39	−0.38	1.26	0.99
	DM	$6/7T_f + 1/7T_m + E_s = 0.99ET_{EC}$	0.59	42	−0.23	1.08	0.99

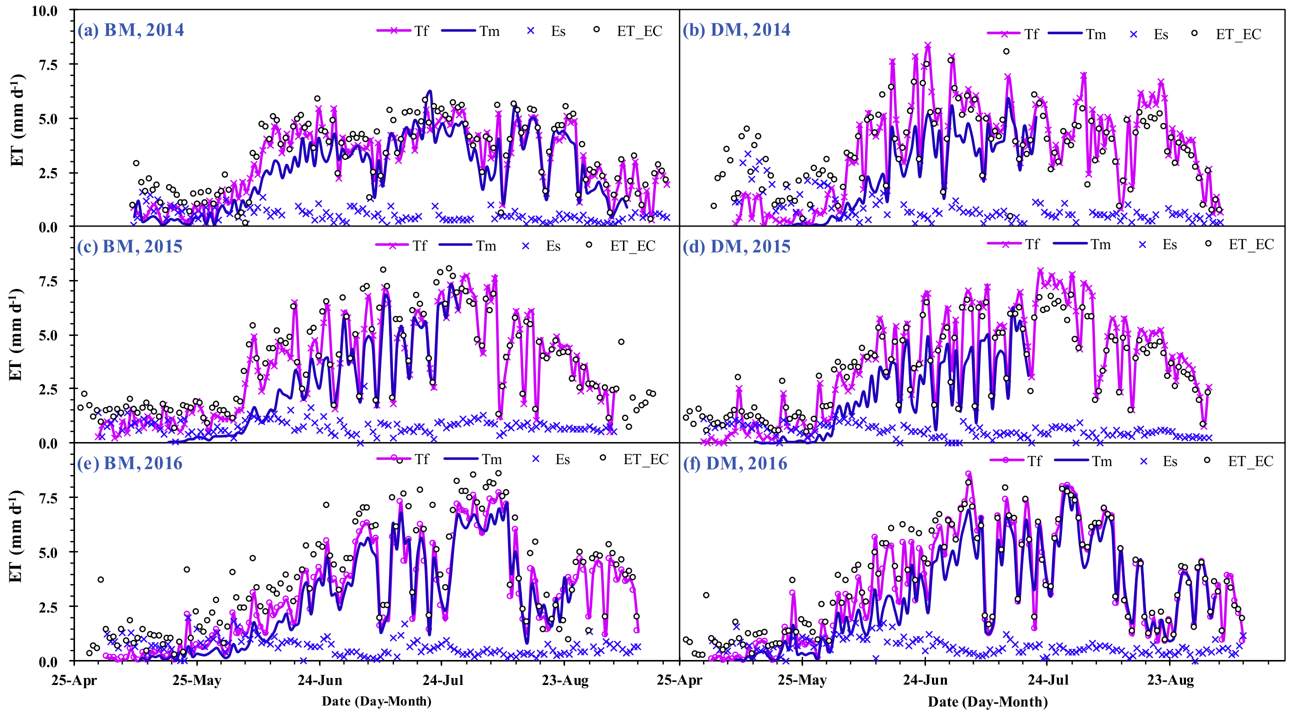

Fig. 3. Seasonal variation of water-vapour-closure corrected daily transpiration of female plants (**T_f**), male plants (**T_m**), evaporation (**E_s**) and evapotranspiration measured by eddy covariance system (**ET_{EC}**) in the maize field under **BM** treatment (**a, c, e**) and **DM** treatment (**b, d, f**) during 2014–2016.

Table 6
Comparison of daily transpiration of female plants (**T_f**) and male plants (**T_m**) over the whole growth stages in the seed maize field under treatment **BM** and **DM** during 2014–2016.

Treatments		Plants	Period	Days	T_f (mmd^{-1})	T_m (mmd^{-1})	ET_{EC} (mmd^{-1})	$\Sigma T_f/\Sigma ET_{EC}$	$\Sigma T_m/\Sigma ET_{EC}$	$\Sigma E_s/\Sigma ET_{EC}$
2014	BM	I_{female}	4.25 – 9.20	149	2.80			0.69		
		II_{male}	5.03 – 9.10	131		2.33			0.13	
		Whole	**4.25 – 9.20**	**149**	**2.65**		**3.27**	**0.81**		**0.19**
	DM	I_{female}	4.27 – 9.07	134	2.99			0.78		
		II_{male}	5.08 – 7.24	78		2.29			0.05	
		Whole	**4.27 – 9.07**	**134**	**2.76**		**3.33**	**0.83**		**0.17**
2015	BM	I_{female}	4.15 – 9.16	155	2.97			0.72		
		II_{male}	5.02 – 7.28	88		2.75			0.10	
		Whole	**4.15 – 9.16**	**155**	**2.69**		**3.28**	**0.82**		**0.18**
	DM	I_{female}	4.26 – 9.04	132	3.19			0.81		
		II_{male}	5.06 – 7.19	75		2.52			0.05	
		Whole	**4.26-9.04**	**132**	**2.98**		**3.47**	**0.86**		**0.14**
2016	BM	I_{female}	4.15-9.20	158	3.26			0.76		
		II_{male}	5.12-9.01	113		3.07			0.07	
		Whole	**4.15 – 9.20**	**159**	**3.10**		**3.73**	**0.83**		**0.17**
	DM	I_{female}	4.20 – 9.10	144	3.47			0.78		
		II_{male}	5.16 – 8.31	108		3.45			0.10	
		Whole	**4.20 – 9.10**	**144**	**3.35**		**3.81**	**0.88**		**0.12**

2014–2016, respectively, which were higher than the male transpiration rates by 0.47, 0.22 and 0.19 mm d^{-1} in 2014, 2015 and 2016, respectively. Under the DM treatments, the average daily female transpiration rates were 2.99, 3.19 and 3.49 mm d^{-1} during 2014–2016, respectively, which were higher than the male transpiration rates by 0.70, 0.67 and 0.02 mm d^{-1} in 2014, 2015 and 2016, respectively (Table 6).

Comparisons of transpiration rates between female and male plants were performed, and the results are shown in Fig. 4 **(b)**. Female plant transpiration rates were higher than male plant transpiration rates by 14%, 20% and 9% under BM treatment during 2014–2016, respectively. Under the DM treatment, female plant transpiration rates exceeded male plant transpiration rates by 24%, 32% and 14% during 2014–2016, respectively. Among the comparisons of transpiration rates between female plants and male transpiration rates under the two treatments during 2014–2016, comparisons under the BM treatment in 2015 and comparisons under the DM treatment in 2014 and 2015 were obviously different from the other three comparisons, with higher differences. With the later removal of male plants, the smaller difference was between the female plant transpiration rate and the male transpiration rate. Additionally, the ratios of the total male plant transpiration amount against the total evapotranspiration ($\Sigma T_m/\Sigma ET_{EC}$) to the total female plant transpiration amount against the total evapotranspiration ($\Sigma T_f/\Sigma ET_{EC}$) were generally lower than the planting ratios under both treatments during 2014–2016. In other words, female plants grow with a higher transpiration rate than the male plants. And increasing transpiration of female plants would result in an increased harvest of seed maize, which favours achieving the farmers' production aims according to the local agricultural management.

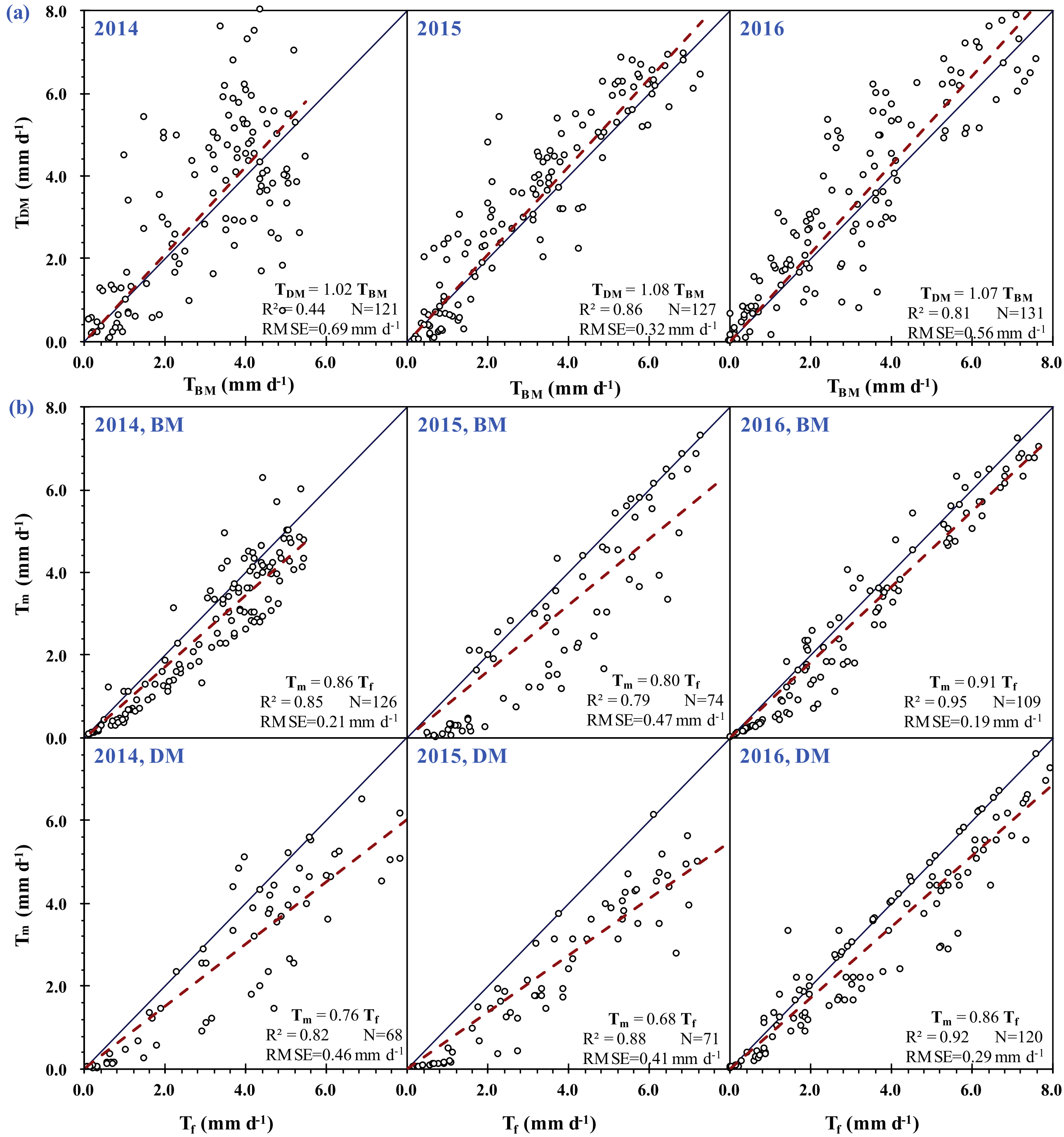

Fig. 4. Comparison of daily transpiration between the border irrigation under mulch field (**T_{BM}**) and drip irrigation under mulch field (**T_{DM}**) and comparison of daily female plants transpiration (**T_f**) and male plants transpiration (**T_m**) under both treatments during 2014–2016.

4. Discussion

4.1. The transpiration rate under the DM treatment was higher than that under the BM treatment

An analysis of the three-year continuous experimental results indicates that transpiration rates under the DM treatment were generally higher than transpiration rates under the BM treatment under the local agricultural management conditions during 2014–2016 (Figs. 3 and 4 and Table 6). The reasons were mainly attributed to the favourable soil moisture environment and higher canopy surface temperature provided by the DM treatment (Fig. 5). In this circumstance, crops grow with a rapid transpiration rate. Previous research has indicated that DM could provide a more suitable moisture and nutrient environment for plant growth, thereby promoting plant growth, increasing water use efficiency (Alenazi et al., 2015; Bai et al., 2015; Hou et al., 2010; Ibarra et al., 2007; Miyauchi et al., 2012; Qin et al., 2016; Yi et al., 2011), and better facilitating the accumulation of dry matter and nutrients to increase the yield of seed maize.

4.2. Difference in transpiration between male and female seed maize plants

The male plants in the early stage were undersized and had a lower LAI and a much lower transpiration rate than the female parents due to the later seed time. However, the male parents grew quickly, and their transpiration rate increased rapidly, gradually decreasing the difference

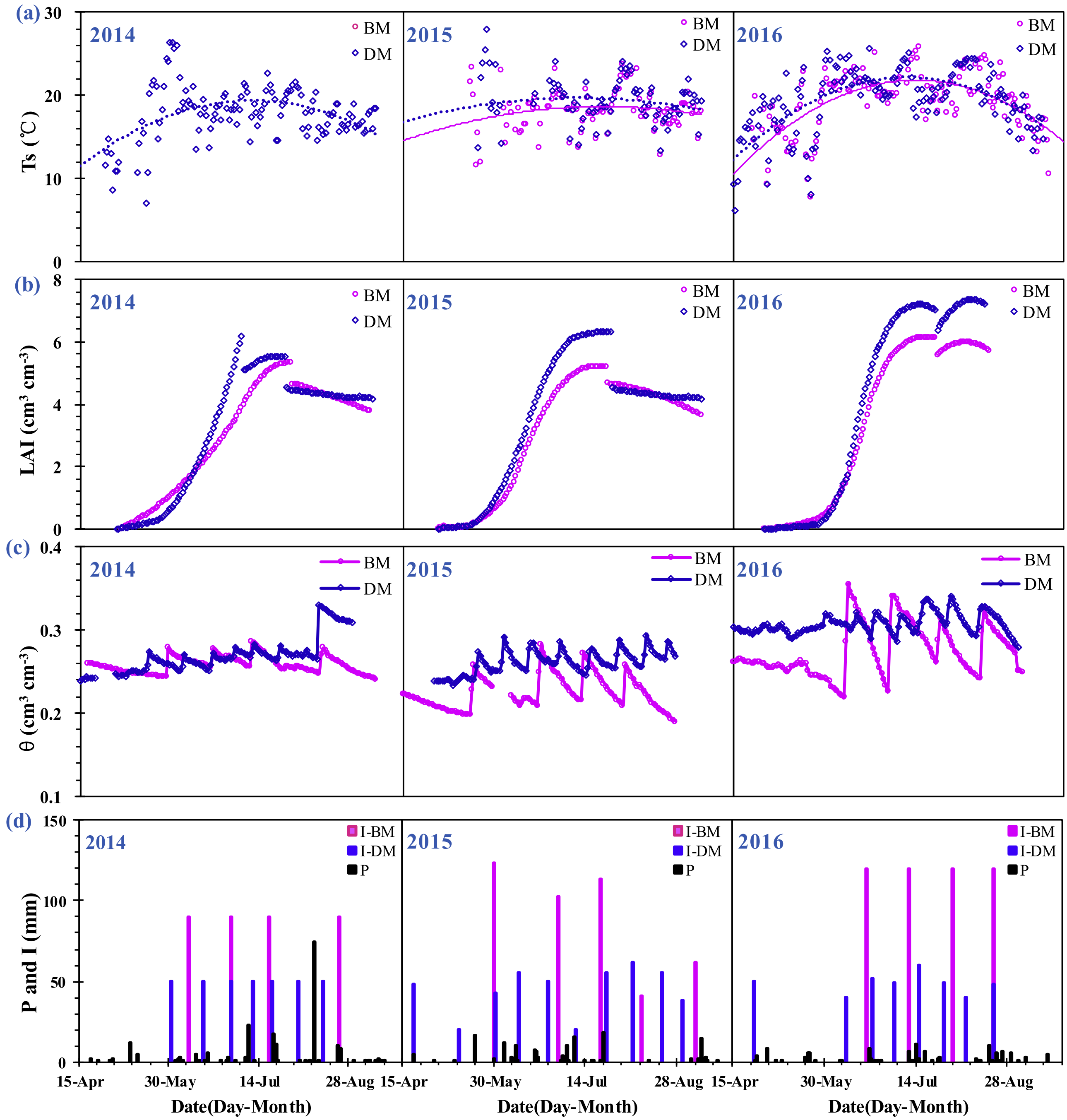

Fig. 5. Seasonal variation of surface temperature **(T_s)**, leaf area index **(LAI)**, soil water content **(θ)** and precipitation and irrigation **(P and I)** under both BM treatment and DM treatment during 2014–2016. For first gap in DM treatment in (b, 2014) due to detasseling of female plants by automation machinery, while other gaps due to removal of male plants.

in transpiration rate between the female plants and the male plants. Even the male transpiration rate matched that of the female plants during the late growth stage, as indicated in Fig. 3. The later was the removal of the male plants, the smaller was the difference in the transpiration rate between the female plants and the male plants (Fig. 4 and Table 6).

The reason for the above finding may be, on the one hand, that the female plants had a weakened upward growth ability after emasculation but in turn underwent compensatory growth in reproduction (Hilbert et al., 1981; Jiang et al., 2016; McNaughton, 1983; Neilsen and Pinkard, 2003; van Staalduinen and Anten, 2005). On the other hand, the reason may be that the coating effect between the taller female plants and the mulched soil accelerated the growth of plants by preventing male seedlings from burning due to excessive heat in the daytime and from freezing at night. In addition, the taller female plants produced shade, which required the male plants to grow faster to obtain the sunlight needed for survival.

4.3. Difference in crop transpiration between seed maize and grain maize

In seed maize field, female and male plants have different growth characteristics over the whole growth stages due to the earlier sowing date of female plants and earlier elimination date of male plants. In the vigorous growth stage, both the male and female plants stabilized, having essentially the same transpiration rate (Fig. 3).

To date, a substantial amount of researches have been conducted on

Table 7
Overview of publications regarding ET partitioning **(ET = E + T)** with measurements for at least two components.

No.	Location	Coordinate	Climate	Experiment time	Species	Planting density	Scheduling	Mulching proportion	Methods	ET (mm)	T (mm)	T/ET (%)	E/ET (%)	LAI_{max} ($cm^2 cm^{-2}$)	Source
1	Ecosystem Research in the Bornhoved Lakes region, Northern Germany	54°06′ N, 10°15′ W	marine,-humid-temperate climate	1995	Grain maize	8.75 pm^{-2}			ET(BREB methord), E(Microlysismeter), T(g_s scaled)			77-116	0-22	2.5	Herbst et al. (1996)
2	USDAARS research laboratory, Texas, USA	35°2′ N, 102°1′ W		1989	Grain maize		Sprinker Irrigation		ET(Lysismeter), E (Microlysismeter), T(Sap flow)			48-74	28-58		Thompson et al. (1997)
3	the Roza Unit of the Washington State University IAREC,Washingt-on,USA	46°15′ N, 119°45′ W		1993	Grain maize	8.6 pm^{-2}	Furrow irrigation		ET(BREB methord), E(Microlysismeter), T(Sap flow)				20-35	5.4	Jara et al. (1998)
4	the Unit of Bioclimatology INRA, Grignon, French			1993-1994	Grain maize				ET(BREB methord), T(Sap flow)			88-90		4	Bethenod et al. (2000)
5	Luancheng Experimental Station, North China Plain	37°50′ N, 114°40′ E		1996	Grain maize		Suffcient Irrigation	0	ET (Weighting lysimeter), E (Micro-lysimeter)	434.2		69.7	30.3	4.7	Liu et al. (2002)
6	the Irrigation Experment Station,Yangling, China	34°20′ N, 108°24′ E	semi-arid zone	1987-1997	Grain maize	8 pm^{-2}		0	ET (Weighting lysimeter), E (Micro-lysimeter), T(ET-E)	424	313.9	74.0	26.0	5.5	Kang et al. (2003)
7	University of Nebraska-Lincoln West Central Research and Extension Center,USA	41°1′ N, 100°8′ W	semiarid climate	2003-2004	Grain maize		Sprinker Suffcient Irrigation	0	Dual crop coefficient precedure	702.4 (2003) 757.4 (2004)			32.5 33.4		Payero et al. (2006)
8	the Arid Land Research Center, Tottori University, Japan	35°32′ N, 134°13′ E		2004	Grain maize	4-8 pm^{-2}			ET (Weighting lysimeter), E (Micro-lysimeter)	304.82(4pm^{-2}) 326.56(6pm^{-2}) 369.37(8pm^{-2})	201.18(4pm^{-2}) 236.95(6pm^{-2}) 286.09(8pm^{-2})	66 (4pm^{-2}) 73 (6pm^{-2}) 77 (8pm^{-2})		2.59(4pm^{-2}) 3.59(6pm^{-2}) 5.01(8pm^{-2})	Tahiri et al. (2006)
9	the Experimental Station of the Arid Land Research Center, Tottori University, Japan	35°32′ N, 134°13′ E		2005	Grain maize	4 pm^{-2}	Sprinker Irrigation		ET(Weighting lysimeter), T(Biomass ralation), E(ET-T)			25-58	45-63		Zeggaf et al. (2008)
10	Western U.S. Corn-Belt,Kansas, Nebraska,USA	37–45° N, 92 − 105°W	Continental temperate climate	2003–2007	Grain maize		Fully Irrigated		Hybrid-Maize model	613-623			7-34		Grassini et al. (2009)
11	University of Nebraska Agricultural Research and Development	41°09′54.2″ N, 96°58′35.9″ W		2001-2005	Grain maize		Center pivot irrigation		ET(Eddy conerience system)	502-586				4.9 − 6.4	Suyker and Verma (2009)

(continued on next page)

Table 7 (*continued*)

No.	Location	Coordinate	Climate	Experiment time	Species	Planting density	Scheduling	Mulching proportion	Methods	ET (mm)	T (mm)	T/ET (%)	E/ET (%)	LAI_{max} ($cm^2 cm^{-2}$)	Source
	Center, eastern Nebraska.USA														
12	the Blaustein Institutes for Desert Research, Sede Boqer Campus of Ben-Gurion University of the Negev, Israel	31°08′ N, 34°53′ E	Mediterranea-n climate	2007	Grain maize		Furrow/ Drip irrigation	0	ET(Water balance methord), T(Biomass ralation), E(ET-T)			61–63	37–39		Zegada and Berliner (2011)
13	OPE3 research site operated by the USDA Agricultural Research Service, Maryland, USA			2008	Grain maize				ET(Eddy conerience system) Flux partitioning procedure			70-80		3	Scanlon and Kustas (2012)
14	Department of Agricultural Engineering,UFS-M, Santa Maria, Brazil.	29°41′24″ S, 53°48′42″ W	Subtropical humid climate	2010-2011	Grain maize	6.5 pm^{-2}	Sprinker Irrigation	0.9	Dual crop coefficient precedure	479-502	450-463		6-8		Martins et al. (2013)
							Drip irrigation			272-365	241-331		8-9		
15	the Irrigation Experiment Station of the IWHR at Daxing, China	35°32′ N, 134°13′ E	Sub-humid climate	2007–2009	Grain maize	8 pm^{-2}			ET(Eddy conerience system), Dual crop coefficient precedure	333.1 (2008)	216.9 (2008)		35 (200-8)		Zhang et al. (2013)
										373.3 (2009)	207.0 (2009)		45 (200-9)		
16	Quinta da Lagoalva de Cima, located in Alpiarça, Ribatejo, Portugal.	39°16′ N, 8°33′ W	Mediterranea-n climate	2010–2012	Grain maize	82000 pha^{-1}	Center pivot Sprinker Irrigation		SIMDualKc model				18-29		Paredes et al. (2014)
17	the Experimental Station of the IRRI in Los Baños, Laguna, The Philippines	14°8′49.72″ N, 121°15′58.1-0″ E (2011)		2011-2012	Grain maize	70000 pha^{-1} (2011)	Center pivot surfficient irrigation		ET(Eddy conerience system), Dual crop coefficient precedure	469 (mean)		66-74	26–34	5.2 (2011)	Alberto et al.(2014)
		14°18′43.26″ N, 121°15′54.9-4″ E (2012)				75000 pha^{-1} (2012)								5.3 (2012)	

grain maize across the world, but little work has been focused on seed maize. Table 7 lists the observation methods of ET, soil evaporation and plant transpiration by maize in the main maize production regions worldwide and some quantitative results. Most findings indicate that without mulching treatment, water consumption due to plant transpiration accounted for 60%-80% of the total ET and that due to soil evaporation accounted for 20–40% of the total ET. Several studies found that soil evaporation accounted for less than 10% or more than 60% of the total ET, which was caused by differences in irrigation methods. Mulching greatly reduced soil evaporation (Ding et al., 2013; Martins et al., 2013; Zegada-Lizarazu and Berliner, 2011), promoted plant growth and increased water use efficiency. However, the total ET varied significantly depending on the climatic region and physiographic characteristics of the research region.

In our study, the seed maize plants had lower plant heights, thinner stalks, a higher plant density and a shorter growing period than the plants in the above grain maize studies. Under the mulching treatment, soil evaporation in border irrigation treatment accounted for 17%-19% of the total water consumption, and 12%-17% of the total water consumption in drip irrigation treatment, which is lower than the mean level for grain maize. This result was attributed to the reduced soil evaporation by mulching and higher plant density. Similar to the findings of most studies on grain maize, plant transpiration by seed maize is an important contributor to total water consumption, accounting for 81%-83% under BM treatment and 83%-88% under DM treatment. However, female plants accounted for 85–94% of the total transpiration, which is effective transpiration, while male plants accounted for only 6–15% of the total, which is useless transpiration for seeds production above the seed maize field. In fact, this useless water consumption could be smaller in principle by decreasing the planting ratio, as long as there were enough male plants to adequately fertilize the female plants. Thus, the smaller of the planting ratio and the earlier removal of the male plants, the higher the water use efficiency would be obtained in the seed maize field.

5. Conclusions

Three-year continuous experiments using EC, thermal balance sap flow and micro-lysimeter measurements were conducted to reveal the difference in transpiration rate between the BM field and DM field and the water consumption rates of female plants and male plants under both treatments, and we further investigated the difference in transpiration rates between seed maize and grain maize. The following three conclusions were drawn: (1) DM treatment provided favourable soil moisture and higher canopy surface temperature environment conditions for the crop, which promoted rapid growth with the higher transpiration rate of the crop. The transpiration rates under the DM treatment were 2–8% higher than transpiration rates under the BM treatment under the local agricultural management conditions. (2) Generally, the female plant transpiration rate exceeded the male plant transpiration rate by 9–20% in the BM field and 14–32% in the DM field. However, the coating effect between the first seeded and taller female plants and the mulched soil accelerated the growth of male plants by preventing male seedlings from burning due to excessive heat in the daytime and from freezing at night, so that male parents grew rapidly with a high transpiration rate and gradually decreased the difference in transpiration rates between the female plants and male plants. (3) The seed maize fields in the present study have a smaller proportion of soil evaporation and a higher plant density than those in other grain maize field studies around the world. Decreasing the planting ratio and removing the male plants earlier would increase the water use efficiency in seed maize fields due to the useless transpiration between reproduction and the final seed production by the male plants.

Agricultural microclimate environmental conditions have a marked impact on crop growth, and the different growth conditions of female plants and male plants in the seed maize field would influence the energy transfer process above the cropland and further influence the estimations of crop transpiration and water consumption. Accordingly, when estimating the total plant transpiration and water consumption, the influence of male plants should be considered. However, it is difficult to effectively distinguish between the parent plants of seed maize using existing models. An in-depth study on the regulation of transpiration and water consumption by female and male seed maize plants will play a vital role in the establishment and improvement of models.

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