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Can plastic mulch save water at night in irrigated croplands?

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ABSTRACT

Plastic mulching has been widely used in arid regions because it can decrease soil water evaporation and raise soil temperature. Previous studies, however, treated soil water evaporation under plastic mulch to be negligible, assuming that the plastic mulch can prevent water exchange between soil and atmosphere completely. In order to demonstrate validity of this assumption, experiments were conducted from 2014 to 2016 under irrigated maize (Zea mays) field in Northwest China, comparison experiments of soil water evaporation between mulched soil and the bare soil between mulches were carried out in two seed maize fields with different irrigation method, i.e. border irrigation under mulch (Site BM) and drip irrigation under mulch (Site DM), with micro-lysimeters placed under the plastic mulched soil and the bare soil between mulches to evaluate soil water evaporation of each experiment maize field. Our observations indicated that the soil water evaporation under plastic mulch (E_{ms}) was about 4.04–7.07% of the total evapotranspiration, among which E_{ms} in the daytime accounted for 3.58–5.37% of the total evapotranspiration and 0.99–2.10% of the total evapotranspiration in the nighttime. Thus E_{ms} was considered not to be negligible. For two experiment sites, soil water evaporation under bare soil between mulches (E_{bs}) was obviously higher than the soil water evaporation under plastic mulch (E_{ms}) in daytime, but the former was lower than the latter in the nighttime. At night, the mean soil temperature in the mulched soil was higher than that in the bare soil because of the warming effect of the plastic mulch. A soil-mulch-canopy-atmosphere model is used to consider the effects of the mulch, and the modeling results further support this finding. These results provide a new insight for understanding the effect of plastic mulch on water use efficiency.

1. Introduction

Plastic mulching is a critical technology for saving water in arid regions owing to its function in warming the soil, preserving soil moisture and increasing crop yield. As such, it has been extensively used in crop production such as wheat, maize, cotton, soybean and other crops in the world. In contrast with the traditional cultivation methods, plastic mulching changes the ground surface reflectance and water vapor transfer resistance, thereby altering surface water balance, energy balance and plant growth processes. However, the mechanism of plastic mulch water-saving effect remains uncertain. Thus, it is of great value to explore the influence from plastic mulching on soil water evaporation in order to optimize agricultural water resource management.

Until recently, numerous studies have been conducted to evaluate the effects of plastic mulching on water and energy transfer in farmland. Such studies have come to the following main conclusions: (1) Plastic mulching can reduce soil water evaporation and increase water use efficiency (Wang et al., 2001; Xie et al., 2005; Ramakrishna et al., 2006; Shen et al., 2012; Tiwari et al., 2016). (2) Plastic mulching enhances the surface radiation reflectance, thereby changing the water and energy balance in farmlands (Liakatas et al., 1986; Wilson et al., 2002; Heusinkveld et al., 2004; Bonachela et al., 2012; Yang et al., 2012; Jafari et al., 2012). (3) Plastic mulching can increase water vapor transfer resistance so that the soil water evaporation under plastic mulching can be assumed to be negligible in the model calculation (Yang et al., 2012; Li et al., 2013b; Wang et al., 2016). (4) The open-hole ratio on the plastic mulch has a vital impact on soil water evaporation under plastic mulching. The larger the ratio is, the smaller the water vapor transfer resistance will be, so that the water vapor will be easier to cross through plastic mulch to atmosphere (Li et al., 2003, 2005; Shi et al., 2013). However, these previous studies mainly focused on the effect of plastic mulch on evapotranspiration and crop growth, but paid little attention to the diurnal dynamic soil water evaporations of mulched and bare soils. The measurements of soil water evaporation under the mulched layer are seldom reported. Also, there are only few

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studies that compared the mulched soil water evaporation and the bare soil water evaporation. In some research conducted in mulched crop field, the researchers just ignored the soil water evaporation under mulch but adopted the soil water evaporation of bare soil between mulches as the all soil water evaporation throughout the crop field (Ding et al., 2013; Jiang et al., 2016). Moreover, no investigation has been made on the effect of plastic mulch on soil water evaporation during daytime or nighttime in arid croplands.

The micro-lysimeter weighing method is a direct method of measuring soil water evaporation and has been widely used in evaluating soil water evaporation under bare soil and canopy due to its small disturbance to surrounding soil, simple principle, handiness and cost-effectiveness (Liu et al., 2002; Mitchell et al., 2009; Cavanaugh et al., 2011; Zhao et al., 2015). Previous studies indicated that soil water evaporation measured by the micro-lysimeter weighing method obtained results consistent with those measured with other instruments (Matthias et al.,1986; Plauborg, 1995) and modeling methods (Li et al., 2013a; Zhao et al., 2015).

To explore the effect of plastic mulch on soil water evaporation during daytime or nighttime in arid croplands, micro-lysimeter weighing method was employed to evaluate evaporation under the mulched layer and bare soil layers under two typical irrigated seed maize field in arid regions: the border irrigation under mulched field and the drip irrigation under mulched field. The former is a traditional irrigation technology which has been widely applied in previous practical agricultural production, while the latter is a new irrigation technology combined drip irrigation and plastic mulch technology and has been widely applied in current practical agricultural production. Thus exploration of mechanism of the water and energy transfer process in the two croplands is of vital important in improving water use efficiency in arid regions. On this basis, the effect of plastic mulch on soil water evaporation was analyzed, as well as the “water saving effect” and control mechanism of plastic mulching were evaluated.

2. Materials and method

2.1. Experimental site and description

Three-year continuous experiments were conducted at Shiyanghe Experimental Station of China Agricultural University, located in Wuwei City, Gansu Province of northwest China (N 37°52′, E 102°50′, elevation 1581 m). The experimental site is located in a typical continental temperate climate zone with mean annual temperature of 8 °C, annual accumulated temperature (> 0 °C) of 3550 °C, mean annual pan evaporation of approximately 2000 mm, annual precipitation of 164 mm, the average annual sunshine duration of 3000 h. The groundwater table at the station is 40–50 m below the ground surface (Li et al., 2015, 2016a; Qin et al., 2016).

The comparison experiments were conducted at both border irrigation under mulch seed maize field (Site BM) and drip irrigation under mulch seed maize field (Site DM). Seeds of seeding maize field are divide into male maize seeds and female maize seeds. The two have minor difference from the point of genetic breeding. Male maize seeds are more conducive to the development of stamens in maize plants, while female maize seeds are more conducive to the growth of maize plants reproductive function. Professional semi-automated machines were applied to lay out plastic mulch, open holes and sow in the holes in both seed maize experiment fields. Male maize seeds and female maize seeds were sow in different holes with one line for male plants and several lines for female plants. However, both male maize seeds and female maize seeds were sown fixed distance apart within each row during the three years. One or two seeds were sow in one open-hole. While germination rates were different from each year, and in turn cause different planting density. Besides, when the professional semi-automatic machines open holes above the plastic mulch, the area of open-hole would have minor difference due to influence of artificial work. The plastic transparent mulch applied in both treatments was 8 μm thick with a shortwave transmissivity, reflectivity and absorptivity of 0.85, 0.10 and 0.05, respectively, and a longwave transmissivity of 0.74. The optical properties of the plastic mulch mentioned above were measured by spectrophotometer. And the plastic mulches were laid out along east to west with width of 1.2 m and, there is bare soil with width of 0.4 m between the two plastic mulches. Thus the ratio of the area of mulched soil and bare soil was 3:1.

Specifically, the border irrigation under mulch technology is a widely applied traditional agricultural irrigation technology which built ridges in the field and the field is split into many narrow and long plots, irrigation water from sub lateral canals flow into the plots along the long side of the plots, infiltration and wetting soil layer. Site BM is irrigated seed maize field under plastic mulch with an area of 400 m*200 m during 2014–2016. The field were sown in one-line male plants and four-line female plants in 2014–2015, while one-line male plants and seven-line female plants in 2016, respectively. Five seed rows were covered under one plastic mulch, both female and male seeds were sown 0.3 m apart within each row and the distance between seed rows under the same mulch was 0.25 m (Site BM, see in Fig. 1). Germination ratios were approximately 87%, 87% and 93% during 2014, 2015 and 2016, respectively. The average hole size was approximately 10.2–10.8 cm^2 and ratios of the total area of holes opened for seeding to the total plastic mulch area were 1.63%, 1.69% and 1.73% in 2014, 2015, 2016, respectively. Overall planting density was 108,000 plants ha^{-1} during 2014–2015 and 116,176 plants ha^{-1} in 2016. The soil at 1 m depth in the site is silty loam, with an average soil dry bulk density of 1.52 g cm^{-3} and volumetric soil water content at a field capacity (θ_{FC}) of 0.29 cm^3 cm^{-3} during 2014–2016.

The drip irrigation under mulch technology is a widely applied new agricultural irrigation technology which combined drip irrigation and plastic mulch technologies. Site DM is irrigated seed maize field under plastic mulch with an area of 2000 m*1000 m during 2014–2015, and 400 m*200 m in 2016. The field were sown in one-line male plants and seven-line female plants in 2014–2015, and one-line male plants and six-line female plants in 2016, respectively. Four seed rows were covered under one plastic mulch, both female and male seeds were sown 0.22 m apart within each row and the distance between seed rows under the same mulch was 0.30 m (Site DM, see in Fig. 1). Germination ratios were approximately 90%, 90% and 91% during 2014, 2015 and 2016, respectively. The average hole size was approximately 10.6–11.8 cm^2. Ratios of the total area of holes opened for seeding and the total plastic mulch area were 2.14%, 2.23% and 2.01% in 2014, 2015, 2016, respectively. Overall planting density was 112,500 plants ha^{-1} during 2014–2015 and 109,474 plants ha^{-1} in 2016. 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, with an average soil dry bulk density of 1.52 g cm^{-3}, averaged θ_{FC} of 0.30 cm^3 cm^{-3} in 2014, while the average soil dry bulk density and θ_{FC} is 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 has been reported in Qin et al. (2016).

2.2. Measurements and data collection

2.2.1. Soil evaporation

In our experiment, micro-lysimeters made of PVC tubes were applied to monitor soil water evaporation with the weighing method every day. The micro-lysimeter composed of inner and outer tubes, with the diameter of 11 cm for the outer tube and 10 cm for inner tube. The height of both tubes was 20 cm. The bottom of the inner tube was covered with nylon wire which was convenient for water vapor transfer in vertical direction. When installing the micro-lysimeters in the bare

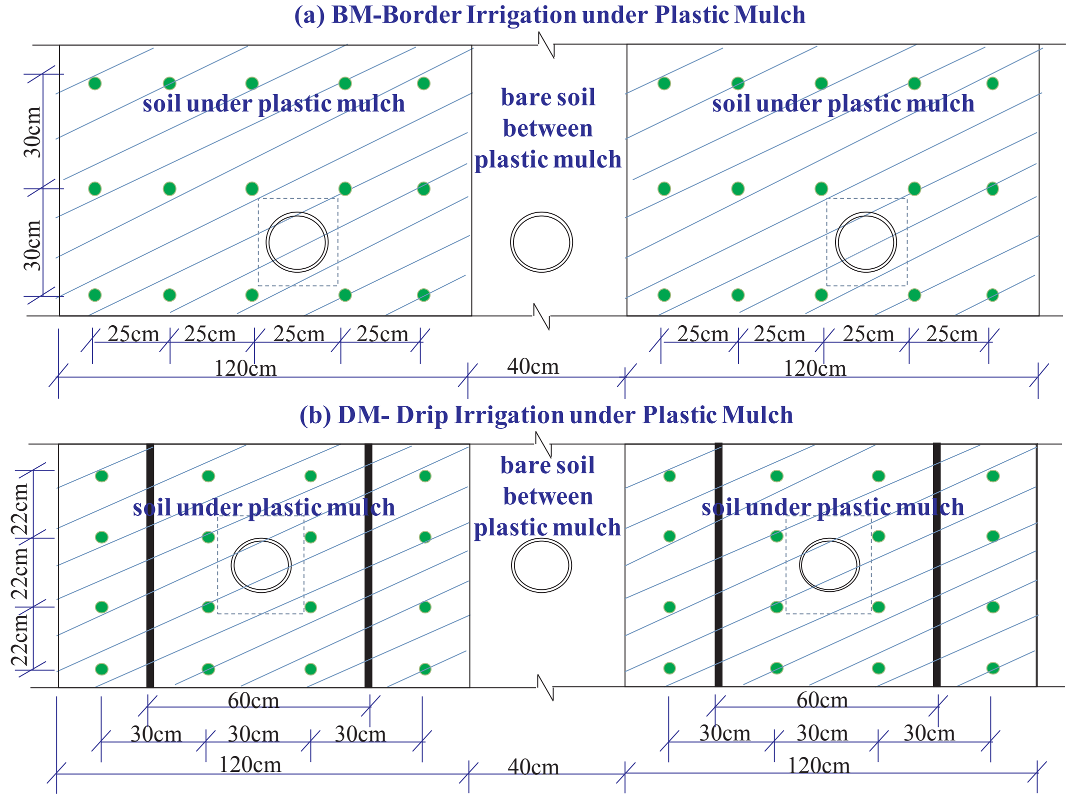

Fig. 1. Locations of the micro-lysimeters in the experiment. Site BM represents the border irrigation under plastic mulch field, while site DM represents the drip irrigation under plastic mulch field. Green dots represent the seeding holes and circular rings represents the micro-lysimeters.

soil, the inner tube was firstly drilled into the undisturbed soil in the installation location to ensure the homogeneity of soil water; then the inner tube was dig out as carefully as possible to minimize disturbance to surrounding soil; and then a piece of filter paper was placed inside the bottom of the inner tube and a piece of wire mesh was placed outside the tube to ensure the water and energy transfer in the vertical direction of soil; and finally both outer tube and inner tube were put into the soil and try to recover the soil. When installing the micro-lysimeter in plastic mulch, the first step was to uncover the plastic mulch and installed the micro-lysimeter. Then recovered the plastic mulch and trepanned in the plastic mulch with the same area as the bottom of micro-lysimeter. Finally sealed the hole with another small piece of plastic mulch to sustain original micro-meteorology under the mulch. The comparison experiments between soil water evaporation under mulch and that under bare soil were carried out in both BM and DM sites during 2014–2016.

The micro-lysimeter was installed between crops (under the mulch) and bare soil (between mulches) of the two sites (Fig. 1), with each site having 6 replications. The soil water evaporation at each micro-lysimeter was evaluated with the weighing method by an electronic scale (Mettler Toledo, PL6001-L, USA) with accuracy of 0.1 g at 7:30 AM and 19:30 PM every day, respectively, with the difference being the soil water evaporation of the daytime or nighttime. The micro-lysimeter under plastic mulch was placed to the original place after each weight measurement and a scotch tape was used to seal the plastic mulch, to ensure integrity of the hydrothermal environment. Before each weight measurement, the adhesive tape was torn off to take out the micro-lysimeter from the tank. Regular reinstallation of the micro-lysimeter was adopted to minimize the difference between soil moisture inside and outside the tubes (Yunusa et al., 2004). And comparison experiments of soil water evaporation under mulch between site BM (open-hole ratios were 1.63%, 1.69% and 1.73% in 2014, 2015 and 2016, respectively) and site DM (open-hole ratios were 2.14%, 2.23% and 2.01% in 2014, 2015 and 2016, respectively) before planting maize period were also carried out during 2015–2016 in order to investigate minor difference of open-hole ratios on soil water evaporation measurement. Results indicated that the differences of soil water evaporation under mulch between the two open-hole ratios were smaller (2015: $E_{ms1.69\%} = 1.01E_{ms2.23\%} + 0.02$, $R^2 = 0.93$, 10 observations; 2016: $E_{ms1.73\%} = 0.99E_{ms2.01\%} + 0.01$, $R^2 = 0.96$, 9 observations), thus the minor difference between the open-hole ratios has little effect on our soil water evaporation measurements. Besides, soil water evaporation in irrigation or precipitation events were not observed because the data during these period is inaccurate. Therefore, the averaged soil water evaporation values were computed using the measured values of observed dates during each growth period.

2.2.2. Meteorological data and eddy covariance system

All climatic parameters (listed in Table 1) needed to calculate evaporation by the MSW model and evapotranspiration were measured with eddy covariance system which located in central of each experiment site during 2014–2016.

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 experiment site (in 2014). While in DM experiment site (in 2014, 2015 and 2016) and in BM experiment site (in 2015 and 2016), the eddy covariance (EC) system consisted of a sonic anemometer/thermometer (model CSAT3), 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). 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 in 2016. And the radiation meter was installed at a 4.0 m height above the

Table 1
List of parameters used in MSW model.

Symbols	Implication	Value	Unit	Source
A	Total available energy		W m^{-2}	Measured by EC system
A_S	Available energy to the soil		W m^{-2}	Measured by EC system
c	Extinction coefficient of light attenaution	0.41	Dimensionless	Mo et al. (2000)
C_C	Canopy resistance coefficient		Dimensionless	Estimated
C_S	Coefficient for soil surface resistance		Dimensionless	Estimated
C_p	Specific heat of air	1013	J kg^{-1} °C^{-1}	Measured by EC system
d	Zero plane displacement		m	Brenner and Incoll (1997)
e_r	Water vapor pressure		kPa	Measured by EC system
ET	Evapotranspiration		mm d^{-1}	Measured by EC system
E_{bs}	Bare soil evaporation		mm d^{-1}	Measured by micro-lysimeter
E_{ms}	Mulched soil evaporation		mm d^{-1}	Measured by micro-lysimeter
λET	Latent heat flux		W m^{-2}	Measured by EC system
λE_{bs}	Latent heat flux from the bare soil		W m^{-2}	Estimated
λE_{ms}	Latent heat flux from the mulched soil		W m^{-2}	Estimated
λT	Latent heat flux from the crop		W m^{-2}	Estimated
f_m	Ratio of the mulched area to the total area	0.75	m^{-2} m^{-2}	Measured by EC system
G	Soil heat flux		W m^{-2}	Measured by EC system
G_{bs}	Bare soil heat flux		W m^{-2}	Measured by EC system
G_{ms}	Mulched soil heat flux		W m^{-2}	Measured by EC system
H	Sensible heat flux			Measured by EC system
H_c	Sensible heat flux from the canopy			Estimated
H_{ms}	Sensible heat flux from the mulched soil			Estimated
H_{bs}	Sensible heat flux from the bare soil			Estimated
h_C	Mean height of the crop canopy		m	Manual measurement
K	Eddy diffusion coefficient		m^{-2} s^{-1}	Shuttleworth and Wallace (1985)
K_h	Eddy diffusion coefficient at the top of canopy		m^{-2} s^{-1}	Shuttleworth and Wallace (1985)
k	Von Karman constant		Dimensionless	Shuttleworth and Wallace (1985)
LAI	Leaf area index		m^{-2} m^{-2}	Manual measurement
MSW	Adjust Shuttleworth-Wallace model			
n	Extinction coefficient of eddy diffusion	2.6	Dimensionless	Brustaert (1982)
n*	Attenuation coefficient for wind speed	2.5	Dimensionless	Choudhury and Monteith (1988)
PM_C	Founction of crop transpiration		W m^{-2}	Estimated
PM_S	Founction of soil evaporation		W m^{-2}	Estimated
R_n	Net radiation flux		W m^{-2}	Measured by EC system
R_{nc}	Net radiation flux absorbed by the canopy		W m^{-2}	Estimated
R_{ns}	Net radiation flux into the soil		W m^{-2}	Estimated
$r_a^a r_a^a$	Aerodynamic resistances from the reference height to in-canopy heat exchange plane height		s m^{-1}	Shuttleworth and Wallace (1985)
$r_a^s r_a^s$	Aerodynamic resistances from the reference height to soil surface		s m^{-1}	Shuttleworth and Wallace (1985)
$r_a^c r_a^c$	Aerodynamic resistances of the canopy to –in-canopy flow		s m^{-1}	Shuttleworth and Wallace (1985)
r_s^c	Canopy resistance		s m^{-1}	Shuttleworth and Wallace (1985)
$r_{smin}^c r_{s\,min}^c$	Minimum stomaltal resistance	20	s m^{-1}	Li et al. (2013a,b)
$r_s^m r_s^m$	Mulching resistance of the film mulch	1280	s m^{-1}	Estimated
$r_s^s r_s^s$	Soil surface resistance		s m^{-1}	Anadranistakis et al. (2000)
r_{smin}^s	Minimum soil surface resistance	100	s m^{-1}	Li et al. (2013a,b)
$r_b r_b$	Mean boundary layer resistance		s m^{-1}	Shuttleworth and Wallace (1985)
T_a	The mean temperature of air		°C^{-1}	Measured by EC system
T_c	The mean temperature of canopy		°C^{-1}	Measured by EC system
T_{bs}	The mean temperature of bare soil		°C^{-1}	Estimated
T_{ms}	The mean temperature of mulched soil		°C^{-1}	Estimated
T_r	The mean temperature of air at reference height		°C^{-1}	Measured by EC system
z	Referance height		m	Manual measurement
z_0	Roughness length			Brenner and Incoll (1997)
u*	Friction velocity		m s^{-1}	Measured by EC system
△	Slope of the saturation water vapor pressure versus temperature curve		kPa K^{-1}	Measured by EC system
γ	Psychrometric constant	0.055	kPa K^{-1}	Measured by EC system
ρ_a	Density of moist air	1.03	kg m^{-3}	Measured by EC system
θ	Soil water content		cm^3 cm^{-3}	Measured by EC system
θ_w	Wilting coefficient	0.11	cm^3 cm^{-3}	Manual measurement
θ_f	Field capacity	0.29	cm^3 cm^{-3}	Manual measurement

ground level during 2014–2015 and one meter above the canopy height in 2016. The soil moisture meters were installed distributed underground 0–1 m depth in 2014 and 2016, and 0–0.8 m depth in 2015. Soil heat flux (Gs) was measured at two points, bare soil between mulches and soil under mulch, by heat flux plates (model HFP01) installed at 5 cm below the ground surface. 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. 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 et al., 2000), (3) the frequency loss correction, (4) air density correction (Webb et al., 1980). Then the software evaluated the quality of EC data and the un-reliable data can be deleted based on the assessment of Eddy Pro 4.0. Additionally, the footprint of EC measurement was estimated by the software. The data which was 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). And the detailed meteorological, biological and agronomic measurements were reported in Qin et al. (2016).

2.3. The adjusted Shuttleworth-Wallace model (MSW) after considering the mulching effect on soil water evaporation

The Shuttleworth-Wallace model (Shuttleworth and Wallace, 1985) considers two layers for the surface energy and water budget, i.e., the soil water evaporation from the soil surface layer, and the transpiration from the canopy height to the reference height layer. However, the mulching effect on soil water evaporation is not accounted for in the model.

Li et al. (2013a) adjusted the original two-layer Shuttleworth-Wallace (SW) model after considering the mulching effect on soil water evaporation, and developed a three-transfer-pathway Shuttleworth-Wallace (MSW) model, and achieved high consistency when evaluating against the eddy covariance system measured evapotranspiration. The first pathway of the MSW model is between the canopy and the mulched soil surface, the second pathway between the canopy and the bare soil surface, and the third pathway is from the reference height above the crop to the canopy height. With the MSW model, the net radiation (R_n) is distributed into sensible heat (H), latent height (λET) and soil heat flux (G) through the soil-mulch-canopy-system. The total net radiation (R_n) is divided into the net radiation absorbed by the canopy (R_{nc}) and the soil (R_{ns}). Under the three-transfer-pathway model, the total latent heat (λET) is distributed into the latent heat from the canopy (λT), the bare soil (λE_{bs}) and the mulched soil (λE_{ms}), and the sensible heat (H) is distributed into the sensible heat from the canopy (H_c), the bare soil (H_{bs}) and the mulched soil (H_{ms}). The model diagram is shown in Fig. 2.

So the energy flux from the soil-mulch-canopy system can be given as follows:

$$R_n = R_{nc} + R_{ns} \quad (1)$$

$$\lambda ET = \lambda T + (1-f_m)\lambda E_{bs} + f_m \lambda E_{ms} \quad (2)$$

$$H = H_c + (1-f_m)H_{bs} + f_m H_{ms} \quad (3)$$

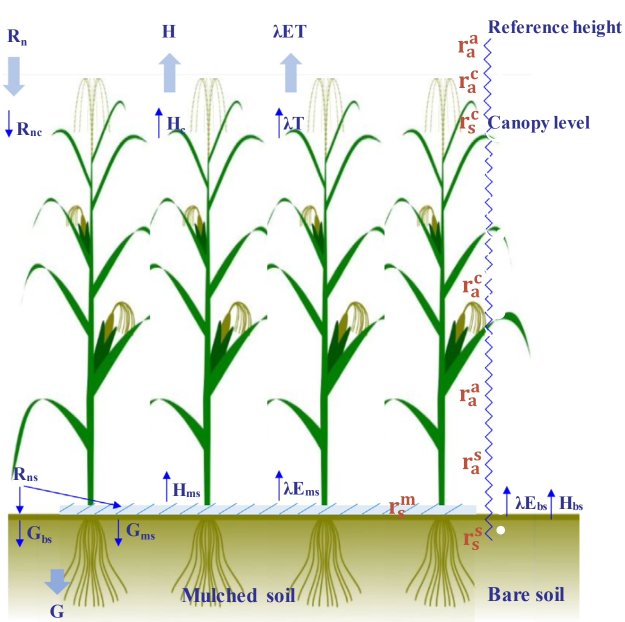

Fig. 2. Energy flux and schematic resistance network of the adjusted three-layer Shuttleworth-Wallace Model (MSW).

$$A = R_n-(1-f_m)G_{bs}-f_m G_{ms} \quad (4)$$

For the canopy layer,

$$R_{nc} = \lambda T + H_c \quad (5)$$

$$H_c = \frac{\rho C_p (T_c-T_r)}{r_a^c + r_a^a} \quad (6)$$

$$\lambda T = \frac{\rho C_p (e(T_{cm})^*-e_r)}{\gamma (r_a^c + r_a^a + r_s^c)}, \quad (7)$$

$$\lambda T + H_c = A_c \quad (8)$$

$$e(T_c)^*-e_r \approx \Delta(T_c-T_r) + VPD_r, \quad (9)$$

$$A_c = R_n-R_n EXP(-cLAI) \quad (10)$$

For the bare soil layer,

$$R_{ns} = \lambda E_{bs} + H_{bs} + G_{bs} \quad (11)$$

$$H_{bs} = \frac{\rho C_p (T_{bs}-T_r)}{r_a^s + r_a^a} \quad (12)$$

$$\lambda E_{bs} = \frac{\rho C_p (e(T_{bs})^*-e_r)}{\gamma (r_a^c + r_a^a + r_s^s)}, \quad (13)$$

$$\lambda E_{bs} + H_{bs} = A_{bs} \quad (14)$$

$$e(T_{bs})^*-e_r \approx \Delta(T_{bs}-T_r) + VPD_r \quad (15)$$

$$A_{bs} = R_{ns}-G_{bs} = R_n EXP(-cLAI)-G_{bs} \quad (16)$$

For the mulched soil layer,

$$R_{ns} = \lambda E_{ms} + H_{ms} + G_{ms} \quad (17)$$

$$H_{ms} = \frac{\rho C_p (T_{ms}-T_r)}{r_a^s + r_a^a} \quad (18)$$

$$\lambda E_{ms} = \frac{\rho C_p (e(T_{ms})^*-e_r)}{\gamma (r_a^c + r_a^a + r_s^s + r_s^m)}, \quad (19)$$

$$\lambda E_{ms} + H_{ms} = A_{ms} \quad (20)$$

$$e(T_{ms})^*-e_r \approx \Delta(T_{ms}-T_r) + VPD_r \quad (21)$$

$$A_m = R_{ns}-G_{ms} = R_n EXP(-cLAI)-G_{ms} \quad (22)$$

where $e(T_c)^*$ $e(T_{bs})^*$ and $e(T_{ms})^*$ are the saturated water vapor pressure (kPa) at temperature T_c, T_{bs} andT_{ms}, respectively.

Then T_{bs}, T_{ms}, E_{bs}, E_{ms} and ET can be calculated according to Eqs. (1)–(22),

$$T_{bs} = \frac{(R_n EXP(-cLAI)-G_{bs})-\rho C_p VPD_r/r(r_a^c + r_a^a + r_s^s)}{\rho C_p/(r_a^s + r_a^a) + \rho C_p \Delta/r(r_a^c + r_a^a + r_s^s)} + T_r \quad (23)$$

$$T_{ms} = \frac{(R_n EXP(-cLAI)-G_{ms})-\rho C_p VPD_r/r(r_a^c + r_a^a + r_s^s + r_s^m)}{\rho C_p/(r_a^s + r_a^a) + \rho C_p \Delta/r(r_a^c + r_a^a + r_s^s + r_s^m)} + T_r \quad (24)$$

$$E_{bs} = \frac{\rho C_p (\Delta(T_{bs}-T_r) + VPD_r)}{r(r_a^c + r_a^a + r_s^s)\lambda} \quad (25)$$

$$E_{ms} = \frac{\rho C_p (\Delta(T_{ms}-T_r) + VPD_r)}{r(r_a^c + r_a^a + r_s^s + r_s^m)\lambda} \quad (26)$$

$$T = \frac{\rho C_p (T_c-T_r)}{(r_a^c + r_a^a)\lambda} \quad (27)$$

$$ET = T + (1-f_m)E_{bs} + f_m E_{ms} \quad (28)$$

Aerodynamic resistances r_a^a and r_a^s can be calculated from the vertical wind profile in the field and are represented by the eddy diffusion coefficient (K) (Shuttleworth and Wallace,1985).

$$K = \begin{cases} ku^*(z-d)(z > h_c) \\ K_h exp[n(1-z/n)](0 < z < h_c) \end{cases} \quad (29)$$

where n is the extinction coefficient of the eddy diffusion, and can be calculated as follows (Brutsaert, 1982):

$$n = \begin{cases} 2.5(h_c < 1) \\ 4.25(h_c > 10) \end{cases} \quad (30)$$

And n can be determined by the liner interpolation when h_c is between 1 and 10.

In this study, K_h can be calculated as follows (Brtsaert, 1982):

$$K_h = ku^*(h_c-d) \quad (31)$$

Then the aerodynamic resistances r_a^a and r_a^s are expressed as (Shuttleworth and Wallace, 1985):

$$r_a^a = \frac{1}{ku^*}\ln\left(\frac{z-d}{h_c-d}\right) + \frac{h_c}{nK_h}\left\{exp\left[n\left(1-\frac{z_0+d}{h_c}\right)\right]-1\right\} \quad (32)$$

$$r_a^s = \frac{h_c exp(n)}{nK_h}\left\{\exp\left(\frac{-nz_0}{h_c}\right)-\exp\left[-n\left(\frac{z_0+d}{h_c}\right)\right]\right\}. \quad (33)$$

Here z_0 and d are functions of crop height and leaf area index, and can be determined as follows (Brenner and Incoll, 1997):

$d = 1.1h_c\ln(1 + X^{0.25})$, (34)

$$z_0 = \begin{cases} 0.01 + 0.3h_c X^{0.5}(0 < X < 0.2) \\ 0.3h_c(1-d/h_c)(0.2 < X < 1.5) \end{cases} \quad (35)$$

$$X = 0.07LAI \quad (36)$$

The aerodynamic resistances of the canopy to in-canopy flow r_a^c can be calculated as follows (Shuttleworth and Wallace, 1985):

$$r_a^c = \frac{r_b}{2LAI} \quad (37)$$

In the study, r_b was set as 50 s m^{-1} (Brisson et al., 1998).

Soil surface resistance (r_s^s) can be determined as follows (Anadranistakis et al., 2000):

$$r_s^s = r_{s\,min}^s f(\theta) \quad (38)$$

where $r_{s\,min}^s$ is assumed to approximately equal 100 s m^{-1} (Camillo and Gurney, 1986; Thompson et al., 1981). θ is the mean soil water moisture at 0–100 cm (cm^3 cm^{-3}) under continuous observation. And $f(\theta)$ can be expressed as (Thompson et al., 1981):

$$f(\theta) = 2.5\left(\frac{\theta_f}{\theta}\right)-1.5 \quad (39)$$

where θ_f is the mean filed capacity at 0–100 cm depth with a value of 0.29 cm^3 cm^{-3} in the study.

Canopy resistance (r_s^c)can be determined as follows (Shuttleworth and Wallace, 1985):

$$r_s^c = \frac{r_{ST}}{2LAI} \quad (40)$$

where r_{ST} is the mean stomatal resistance of the leaf and was set as 400 s m^{-1} here (Shuttleworth and Wallace, 1985), and when the soil was completely covered with the canopy, r_s^c was assumed to approximately equal 50 s m^{-1}.

r_s^m is the resistance of the film mulch which can be obtained when the simulated daily evapotranspiration (ET_{MSW}) has a good agreement with the measured daily evapotranspiration (ET_{EC}), and the value was 1280 s m^{-1}.

2.4. Evaluation of model performance

The performance of the adjusted Shuttleworth-Wallace model (MSW model) was assessed according to the liner regression between estimated (E_i) and observed (O_i) values of ET, E_{bs} and E_{ms}, respectively.

In the study, mean bias error (MBE), root mean square error (RMSE) and index of agreement (IA) were used to evaluate the performance of MSW model (Eberbach and Pala, 2005), and these statistical parameters are described as follows (Poblete-Echeverría and Ortega-Farias, 2009):

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(E_i-O_i) \quad (41)$$

$$RMSE = \left\{\frac{1}{n}\sum_{i=1}^{n}(E_i-O_i)^2\right\} \quad (42)$$

$$IA = 1-\frac{\sum_{i=1}^{n}(E_i-O_i)^2}{\sum_{i=1}^{n}||E_i-\bar{O}| + |E_i-\bar{O}||^2} \quad (43)$$

3. Results

3.1. Comparison of daily E_{ms} and E_{bs} under the two sites

The daily variation of soil water evaporation under the plastic mulch (E_{ms}) and the bare soil between mulches (E_{bs}) under the two sites during 2014–2016 are shown in Fig. 3. In order to reduce the influence of external interference on seed germination and increase the germination rate, regular soil water evaporation measurements were carried out after the seeds germination, and the germination period lasted for about one week. Thereby, the soil water evaporation values at the beginning one week were unobserved. Besides, there are some gaps in the graphics, which were because soil water evaporation during irrigation or precipitation events were not observed. Therefore, the averaged soil water evaporation values were computed using the measured values of observed dates during each growth period (Table 3). In the early growing stage, canopy coverage degree was extremely small, so both E_{ms} and E_{bs} were high especially after irrigation or rainfall. In the middle growing stage, the maize grew rapidly and the leaf area index increased rapidly, as such both E_{ms} and E_{bs} were lower than that at the beginning period except for several days right after irrigation or rainfall events. At the end of the growing stage, E_{ms} and E_{bs} were reduced due to less radiation at the surface soil from leaf interception, decreased air temperature, irrigation and rainfall. For the whole growth season, the daily E_{bs} under border irrigation and drip irrigation experiment sites were averagely higher than E_{ms} by 45% and 42% in 2014, 37% and 47% in 2015, and 54% and 47% in 2016, respectively (Table 2). Evapotranspiration under BM and DM experiment sites were 420.56 mm and 374.95 mm in 2014, 472.20 mm and 449.16 mm in 2015 and 513.84 mm and 449.94 mm in 2016, respectively. And the proportion of daily E_{bs} to ET_{EC} is about 10.66%~12.04% under site BM, and 7.96%~10.80% under site DM during 2014–2016. While the proportion of daily E_{ms} to ET_{EC} is about 6.34%~7.07% under site BM, and 4.4%~6.20% under site DM during 2014–2016 (Table 3).

Meanwhile, the data were separated into two groups to investigate the difference of the mulching effect on the soil water evaporation during the daytime and nighttime.

3.2. Comparison of daytime E_{ms} and E_{bs} under the two treatments

The seasonal variations of daytime E_{ms} and E_{bs} under the border and drip irrigation experiment sites during 2014–2016 are shown in Fig. 4 with greater difference in evaporation rate. The daytime E_{bs} under the both experiment sites were averagely higher than E_{ms} by 55% and 52% in 2014, 45% and 56% in 2015, and 61% and 54% in 2016, respectively (Table 2). The proportion of daytime E_{bs} to ET_{EC} is about 9.65%–10.60% under site BM, and 7.25%–9.52% under site DM during 2014–2016. Whereas, the proportion of daytime E_{ms} to ET_{EC} is about 5.02%–5.57% under site BM, and 2.72%–4.10% under site DM during 2014–2016. E_{bs} accounts for most part of daytime soil water

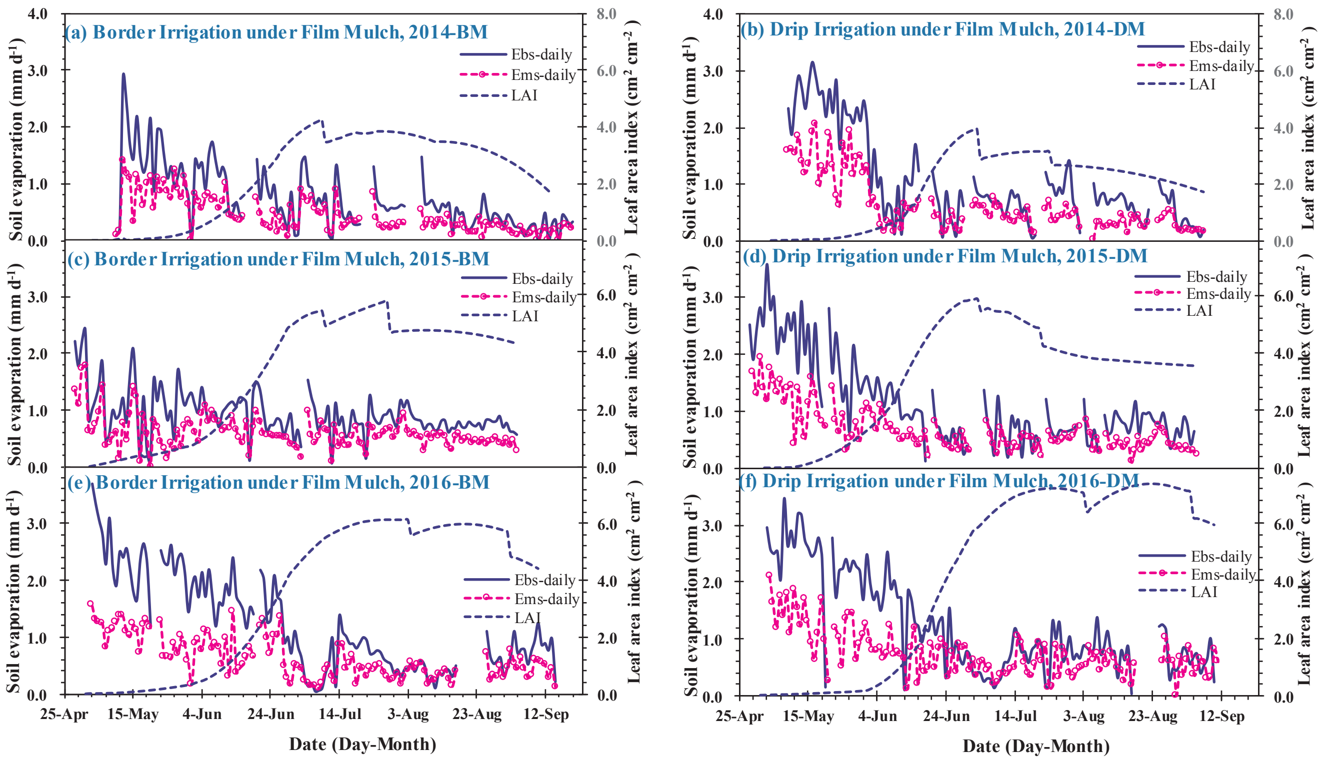

Fig. 3. Seasonal variation of **daily** evaporation of mulched soil (**E_{ms}**) and bare soil (**E_{bs}**) in the maize field during 2014–2016. In the middle crop stage, the LAI under both treatments decreased remarkably due to the earing event of the female maize and the cutting event of male maize.

Table 2
Comparison of the mulched soil evaporation (**E_{ms}**) with the bare soil evaporation (**E_{bs}**) in the maize field over daily, daytime and nighttime three periods during 2014–2016.

Sites	Periods	Regression equation	R^2	n
2014-BM	daily	E_{ms} = 0.55E_{bs}	0.47	140
	daytime	E_{ms} = 0.45E_{bs}	0.70	132
	nighttime	E_{ms} = 1.31E_{bs}	0.35	132
2014-DM	daily	E_{ms} = 0.58E_{bs}	0.80	124
	daytime	E_{ms} = 0.48E_{bs}	0.78	113
	nighttime	E_{ms} = 1.25E_{bs}	0.33	111
2015-BM	daily	E_{ms} = 0.63E_{bs}	0.65	131
	daytime	E_{ms} = 0.55E_{bs}	0.60	131
	nighttime	E_{ms} = 1.10E_{bs}	0.26	116
2015-DM	daily	E_{ms} = 0.53E_{bs}	0.62	131
	daytime	E_{ms} = 0.44E_{bs}	0.64	129
	nighttime	E_{ms} = 1.19E_{bs}	0.20	120
2016-BM	daily	E_{ms} = 0.46E_{bs}	0.62	121
	daytime	E_{ms} = 0.39E_{bs}	0.60	121
	nighttime	E_{ms} = 1.05E_{bs}	0.59	121
2016-DM	daily	E_{ms} = 0.53E_{bs}	0.52	124
	daytime	E_{ms} = 0.46E_{bs}	0.49	124
	nighttime	E_{ms} = 1.19E_{bs}	0.26	124

evaporation (Table 3). In BM experiment site, the average daytime bare soil temperature simulated by MSW model was 17.8 °C, compared to 25.7 °C of average daytime mulched soil temperature in 2014. And the two figures were 17.1 °C 26.7 °C in 2015, and 16.9 °C and 25.3 °C in 2016, respectively. While in DM experiment site, the average daytime bare soil temperature and daytime mulched soil temperature were 17.6 °C and 26.2 °C in 2014, 18.7 °C and 26.0 °C in 2015, 16.9 °C and 25.2 °C in 2016, respectively. On the soil under mulch, in the early growing stage of the maize, the soil was not covered by the crop canopy completely, so the mulch played an important role due to the high reflection of radiation. While with the growth of maize, the soil was covered by the canopy completely, so that the maize grew with a thicker canopy on the soil under mulch, and crop canopy intercepted more radiation, resulting in lower soil heat flux into the mulched soil (G_{ms}) than soil heat flux into the bare soil between mulches (G_{bs}) (Fig. 5).

Furthermore, in daytime, more soil heat flux into the bare soil between mulches and the bare soil temperature increased rapidly, but the average bare soil temperature was lower than that of mulched soil temperature. However, without the preservation from the transparent plastic mulch, substantive soil moisture of the bare soil layer evaporated, causing the daytime mean values of E_{bs} to be apparently higher than E_{ms}. The results indicated that the plastic mulch decreased the soil water evaporation by remarkably increasing the soil resistance. Simultaneously over the whole growth stage, the E_{bs} and E_{ms} with drip irrigation was slightly higher than border irrigation (Table 3), which was due to higher surface soil water content as a result of frequently irrigation events in drip irrigation under mulch experiment site.

3.3. Comparison of nighttime E_{ms} and E_{bs} under the two treatments

The nighttime E_{ms} and E_{bs} under the two experiment sites during 2014–2016 are shown in Fig. 6. In the whole growing stage, the mean value of nighttime evaporation under border irrigation ranged −0.05–0.35 mm d^{-1} in 2014, −0.2–0.26 mm d^{-1} in 2015 and −0.1–0.4 mm d^{-1} in 2016 (Fig. 6 a, c and e). Compared to the border irrigation, the nighttime evaporation under the drip irrigation ranged −0.1–0.4 1 mm d^{-1} in 2014, −0.06–0.4 mm d^{-1} in 2015 and −0.06–0.4 mm d^{-1} in 2016 (Fig. 6 b, d and f).

The nighttime mean value of E_{ms} under border irrigation and drip irrigation was averagely 31% and 25% higher than E_{bs} in 2014, 10% and 19% higher in 2015, 5% and 19% higher in 2016, respectively (Table 2), which was significantly different from the daytime evaporation of the mulched layer and the bare soil layer. The proportion of nighttime E_{bs} to ET_{EC} is about 0.93%-1.44% under site BM, and

Table 3
Comparison of the mulched soil evaporation (**E_{ms}**) with the bare soil evaporation (**E_{bs}**) in different maize growth stages during 2014–2016.

Sites	Growth stages	Period	Days	daily		daytime		nighttime		daily		daytime		nighttime	
				E_{bs}	E_{ms}	E_{bs}	E_{ms}	E_{bs}	E_{ms}	E_{bs}/ET_{EC}	E_{ms}/ET_{EC}	E_{bs}/ET_{EC}	E_{ms}/ET_{EC}	E_{bs}/ET_{EC}	E_{ms}/ET_{EC}
				(mmd^{-1})						%					
2014-BM	Seeding	4.25–6.10	47	1.31	0.76	1.18	0.58	0.13	0.18	36.83	21.37	33.27	16.73	3.56	4.64
	Shooting	6.11–7.09	29	0.74	0.45	0.65	0.28	0.09	0.17	7.57	4.41	6.60	2.77	0.97	1.64
	Heading	7.10–8.02	24	0.58	0.34	0.50	0.21	0.09	0.13	6.51	4.48	5.50	2.94	1.01	1.54
	Filling	8.03–9.04	33	0.49	0.25	0.39	0.11	0.10	0.13	8.04	3.69	6.84	2.04	1.20	1.65
	Maturity	9.05–9.20	16	0.25	0.15	0.21	0.08	0.03	0.07	6.26	3.83	5.17	1.76	1.09	2.07
	Whole	4.25–9.20	149	0.74	0.43	0.65	0.29	0.09	0.14	12.04	6.96	10.60	5.02	1.44	1.94
2014-DM	Seeding	4.27–6.08	43	2.08	1.21	1.88	0.94	0.20	0.26	34.68	19.91	31.61	15.75	3.07	4.16
	Shooting	6.09–7.03	25	0.76	0.43	0.66	0.26	0.10	0.18	9.85	5.89	8.77	3.81	1.08	2.08
	Heading	7.04–7.26	23	0.67	0.46	0.55	0.29	0.11	0.17	6.10	3.52	5.28	2.28	0.82	1.24
	Filling	7.27–8.19	24	0.74	0.35	0.63	0.19	0.12	0.16	6.96	3.58	5.53	1.71	1.43	1.87
	Maturity	8.20–9.07	19	0.44	0.28	0.37	0.13	0.08	0.14	10.95	6.60	9.43	3.58	1.52	3.02
	Whole	4.25–9.07	134	1.06	0.62	0.93	0.43	0.13	0.19	10.80	6.20	9.52	4.10	1.28	2.10
2015-BM	Seeding	4.15–6.05	52	1.18	0.73	1.08	0.56	0.11	0.17	24.05	15.04	21.90	11.77	2.15	3.27
	Shooting	6.06–7.04	29	0.89	0.60	0.77	0.43	0.12	0.17	10.22	7.06	8.96	5.16	1.26	1.90
	Heading	7.05–7.28	24	0.83	0.54	0.68	0.37	0.15	0.17	6.72	4.38	5.60	3.14	1.12	1.24
	Filling	7.29–8.25	28	0.80	0.54	0.69	0.41	0.10	0.12	8.44	5.70	7.37	4.39	1.07	1.31
	Maturity	8.26–9.16	22	0.74	0.43	0.66	0.34	0.08	0.09	12.39	7.14	11.05	5.72	1.34	1.42
	Whole	4.15–9.16	155	0.93	0.60	0.82	0.45	0.11	0.15	10.92	7.07	9.65	5.57	1.27	1.50
2015-DM	Seeding	4.26–6.09	45	1.96	1.02	1.72	0.77	0.24	0.25	26.06	13.63	22.96	10.41	3.10	3.22
	Shooting	6.10–7.03	24	0.73	0.47	0.62	0.29	0.11	0.18	6.00	3.85	5.14	2.44	0.86	1.41
	Heading	7.04–7.26	23	0.67	0.46	0.52	0.30	0.15	0.16	4.79	3.16	3.85	2.13	0.94	1.03
	Filling	7.27–8.19	24	0.71	0.46	0.55	0.26	0.16	0.21	5.42	3.60	4.23	2.06	1.19	1.54
	Maturity	8.20–9.04	16	0.72	0.43	0.57	0.28	0.15	0.15	6.44	3.85	5.14	2.48	1.30	1.37
	Whole	4.26–9.04	132	1.14	0.65	0.96	0.45	0.18	0.20	8.92	5.08	7.62	3.38	1.30	1.70
2016-BM	Seeding	4.15–6.07	54	2.28	1.00	2.17	0.80	0.12	0.20	31.73	16.13	30.14	13.47	1.59	2.66
	Shooting	6.08–7.08	31	1.24	0.63	1.15	0.49	0.10	0.14	12.70	7.02	11.58	5.46	1.12	1.56
	Heading	7.09–7.28	20	0.23	0.13	0.14	0.04	0.13	0.16	4.56	4.18	3.95	3.24	0.61	0.94
	Filling	7.29–8.26	29	0.42	0.35	0.36	0.24	0.07	0.11	6.14	4.05	5.61	3.17	0.53	0.88
	Maturity	8.27–9.16	21	0.72	0.42	0.56	0.27	0.16	0.15	8.66	7.01	6.14	4.73	2.52	2.28
	Whole	4.15–9.20	155	1.23	0.62	1.11	0.46	0.11	0.15	10.66	6.34	9.73	5.35	0.93	0.99
2016-DM	Seeding	4.20–6.03	45	2.40	1.21	2.27	1.01	0.12	0.21	26.26	11.50	24.91	9.21	1.35	2.29
	Shooting	6.04–7.01	28	1.28	0.71	1.15	0.54	0.12	0.17	4.81	2.47	4.44	1.95	0.37	0.52
	Heading	7.02–7.22	21	0.59	0.54	0.51	0.42	0.08	0.12	5.64	3.27	4.75	2.15	0.89	1.12
	Filling	7.23–8.23	32	0.77	0.53	0.69	0.41	0.07	0.12	3.13	2.58	2.65	1.82	0.48	0.76
	Maturity	8.24–9.04	12	0.69	0.56	0.48	0.37	0.21	0.19	8.24	4.87	6.50	3.21	1.74	1.66
	Whole	4.20–9.10	138	1.25	0.75	1.14	0.58	0.12	0.16	7.96	4.04	7.25	2.72	0.71	1.32

0.71%–1.28% under site DM during 2014–2016. While the proportion of daily E_{ms} to ET_{EC} is about 0.99%–1.94% under site BM, and 1.32%–2.10% under site DM during 2014–2016. Although compared to daytime soil water evaporation, nighttime soil water evaporation seems smaller, E_{ms} accounts for most part of nighttime soil water evaporation (Table 3).

In the BM experiment site, the average nighttime bare soil temperature simulated by MSW model was 11.7 °C compared to 13.7 °C of average mulched soil temperature in 2014. And the two figures were 11.8 °C 13.6 °C in 2015, and 12.1 °C and 13.8 °C in 2016, respectively. While in the DM experiment site, the average nighttime bare soil temperature and nighttime mulched soil temperature were 10.8 °C 13.1 °C in 2014, 11.8 °C and 13.9 °C in 2015, 11.9 °C and 13.2 °C in 2016, respectively.

This was mainly due to the fact that the soil started to release of heat to atmosphere under the effect of thermal gradient between the soil and the atmosphere during the nighttime. During this period, the soil heat flux under both bare soil between mulches and mulched soil decreased to negative value. As the heat of bare soil between mulches released even faster because of lacking preservation by the plastic mulch, the soil heat flux under bare soil surface between mulches (G_{bs}) was lower than that under mulched soil (G_{ms}) (Fig. 7), therefore the bare soil temperature decreased more rapidly.

The crop canopy above the soil become thicker with the crop growth. Then the micrometeorology factors between the plastic mulch and the crop mulch is dynamically verifying with the crop growth. On this condition, the dynamic variation of micrometeorology factors between plastic mulch and the crop canopy produce influence on water and energy transfer process and finally influence the crop growth. This influence was defined as coating effect in this study. During the nighttime, the longwave radiation released from the crop canopy would increase the effect of plastic mulch, resulting in the soil temperature under bare soil (T_{bs}) lower than that under mulch soil (T_{ms}) by 2–3 °C Moreover, the higher soil moisture under the mulch could also promoted the soil water evaporation through the open-holes of the mulch. Therefore, all above led to E_{ms} higher than E_{bs} during the nighttime. Due to the drip irrigation is conducive to the crop growth and the canopy coverage degree increase rapidly, the coating effect between the crop canopy and the mulched soil enhanced, so that the E_{bs} and E_{ms} under drip irrigation was slightly higher than border irrigation (Tables 2 and 3).

3.4. MSW-simulated bare soil water evaporation and mulched soil water evaporation

In order to understand the mechanism underlying these results, a sensitivity analysis was conducted. Though there are many input variables for the MSW model, most of them were determined by accurate measurement, with only aerodynamic resistances from the reference height to in-canopy heat exchange plane height (r_a^a), aerodynamic

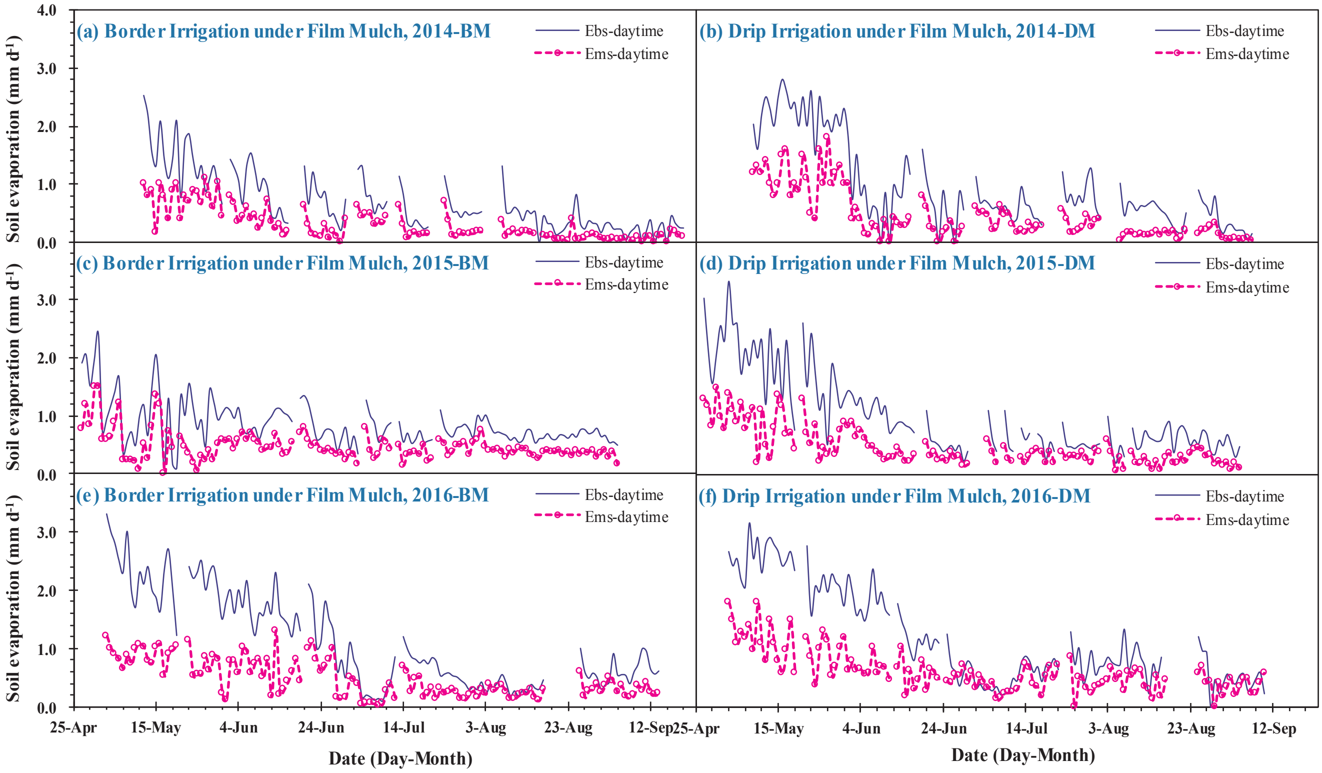

Fig. 4. Seasonal variation of **daytime** evaporation of mulched soil (**E_{ms}**) and bare soil (**E_{bs}**) in the maize field during 2014–2016.

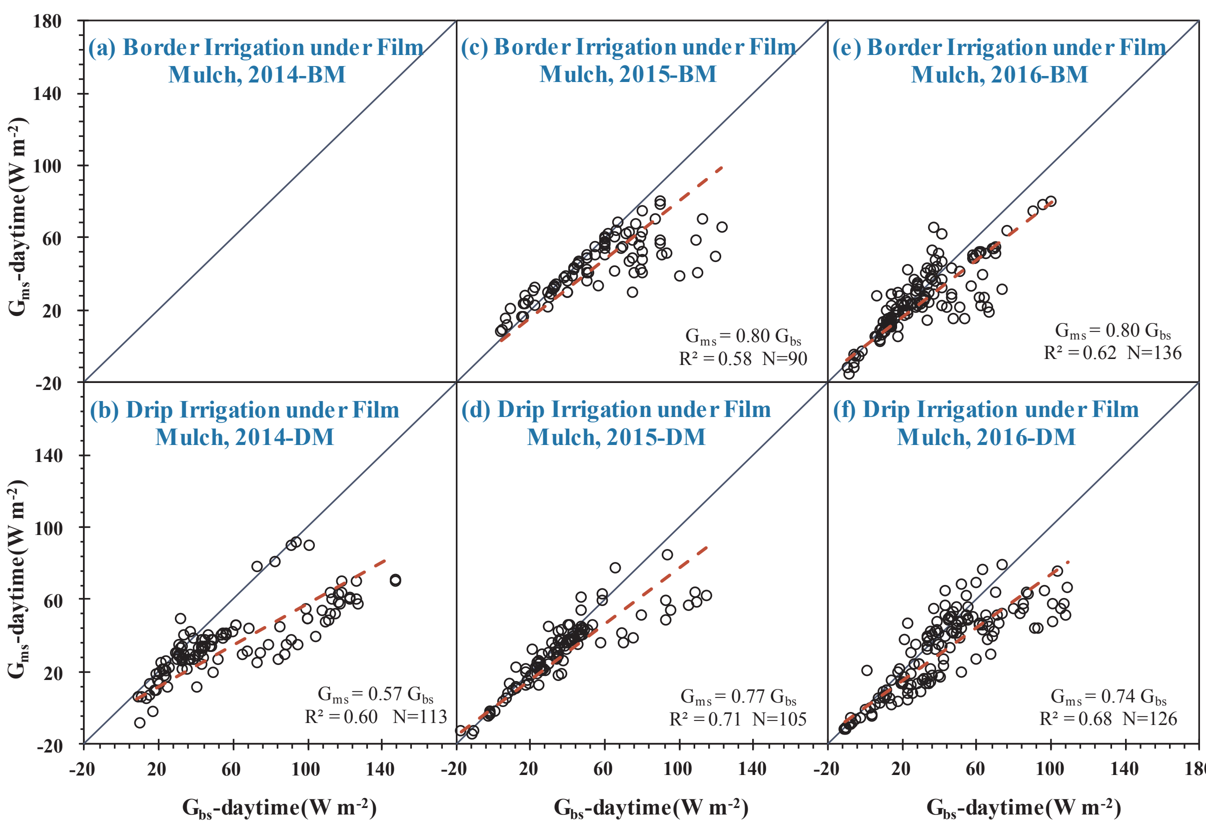

Fig. 5. Comparison of the **daytime** mulched soil heat flux (**G_{ms}**) with the bare soil heat flux (**G_{bs}**) in the maize field during 2014–2016. The missing soil heat flux data in 2014-BM mainly due to lack of observation.

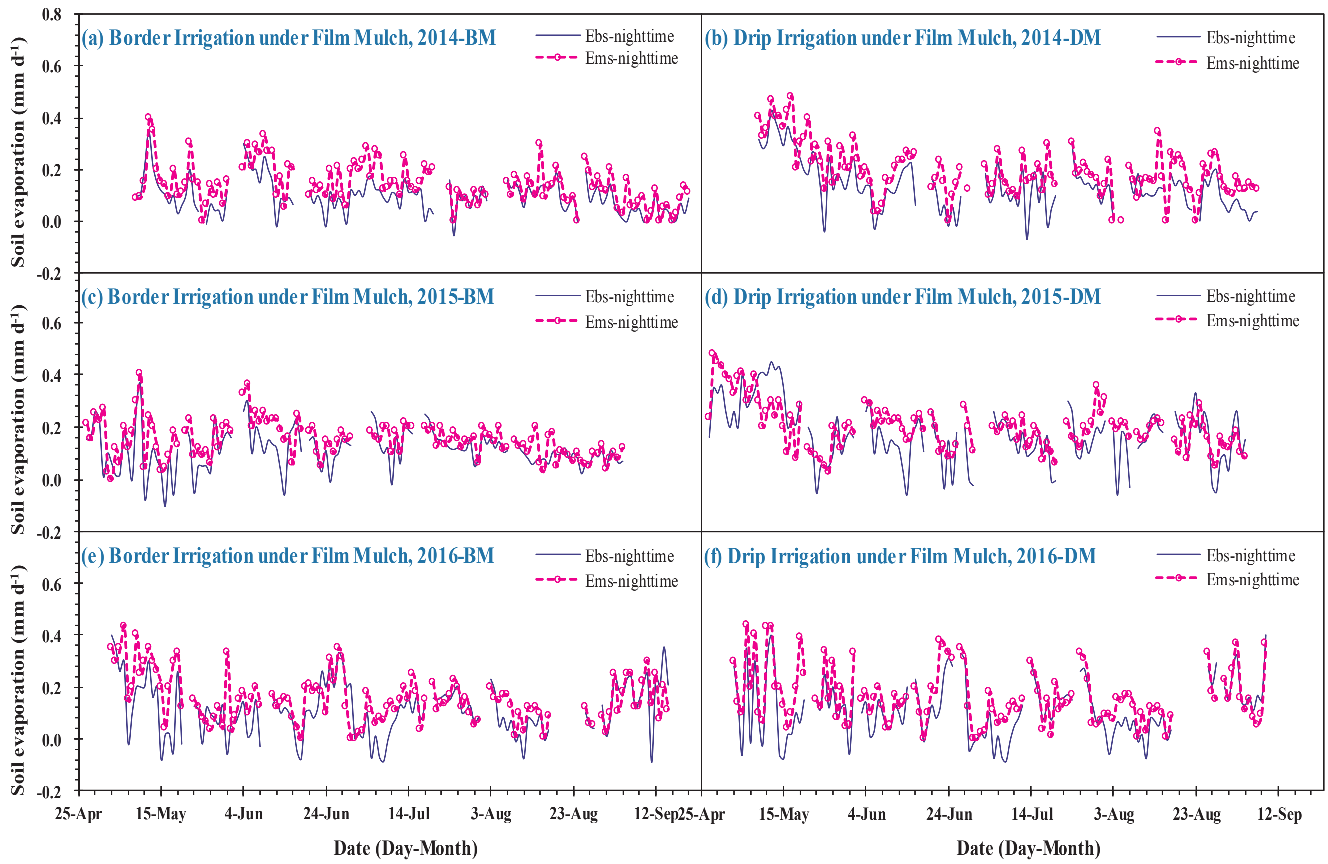

Fig. 6. Seasonal variation of **nighttime** evaporation of mulched soil (**E_{ms}**) and bare soil (**E_{bs}**) in the maize field during 2014–2016.

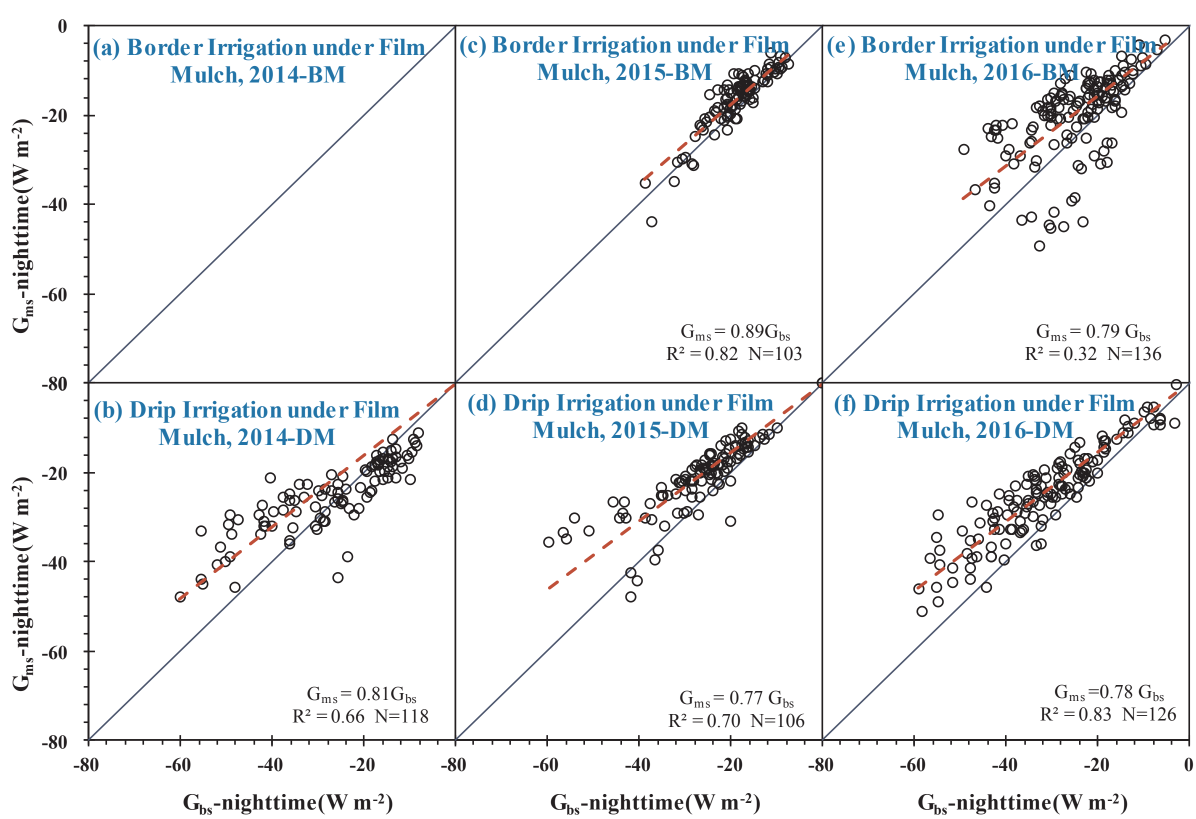

Fig. 7. Comparison of the **nighttime** mulched soil heat flux (**G_{ms}**) with the bare soil heat flux (**G_{bs}**) in the maize field during 2014–2016. The missing soil heat flux data in 2014-BM mainly due to lack of observation.

Table 4
Sensitivity analysis of the estimated mulched soil evaporation (**E_{ms}**), the bare soil evaporation (**E_{bs}**) and evapotranspiration (**ET**) by MSW model to uncertainties in resistance parameters.

Input variables	Sites	Year	Percentages of variation											
			daytime						nighttime					
			−10%			+10%			−10%			+10%		
			ET	E_{bs}	E_{ms}	ET	E_{bs}	E_{ms}	ET	E_{bs}	E_{ms}	ET	E_{bs}	E_{ms}
r_a^a	BM	2014	1.78	2.00	1.97	−1.59	−1.79	−1.74	8.82	8.68	9.79	−7.70	−7.58	−8.42
		2015	2.52	2.98	1.74	−2.21	−2.60	−1.52	8.56	8.75	8.96	−7.47	−7.65	−7.81
		2016	0.91	1.12	2.56	−0.81	−0.99	−2.25	10.71	10.59	11.81	−9.39	−9.28	−10.10
	DM	2014	0.27	0.65	1.95	−0.20	−0.55	−1.70	4.06	4.45	6.58	−3.63	−3.97	−5.73
		2015	0.63	0.65	2.14	−0.52	−0.54	−1.88	7.12	7.11	9.37	−6.31	−6.31	−8.07
		2016	0.79	0.97	2.65	−0.69	−0.85	−2.31	9.34	9.25	8.90	−8.17	−8.09	−7.62
r_a^s	BM	2014	4.00	−0.50	−0.01	−3.51	0.47	0.02	5.37	5.62	0.26	−4.75	−4.90	−0.23
		2015	6.80	0.95	0.01	−5.74	−0.89	0.00	5.29	9.56	0.32	−4.69	−8.16	−0.28
		2016	3.46	−0.27	0.09	−3.02	0.27	−0.08	5.95	5.48	0.83	−5.34	−4.94	−0.77
	DM	2014	4.39	−1.38	0.05	−3.76	1.31	−0.03	6.98	4.99	0.53	−6.21	−4.36	−0.47
		2015	2.86	−1.03	−1.89	−3.43	−0.06	−1.86	3.42	4.71	0.52	−3.08	−4.20	−0.49
		2016	4.19	−0.57	0.18	−3.65	0.53	−0.15	6.13	4.80	0.53	−5.45	−4.27	−0.49
r_a^c	BM	2014	−1.45	−1.48	0.49	1.40	1.43	−0.47	−1.46	−1.44	0.81	1.43	1.41	−0.79
		2015	−2.23	−2.29	0.33	2.17	2.23	−0.32	−1.79	−1.75	1.05	1.74	1.71	−1.02
		2016	−0.70	−0.82	0.47	0.67	0.80	−0.45	−1.13	−1.18	0.74	1.10	1.15	−0.72
	DM	2014	−0.83	−0.97	0.38	0.80	0.94	−0.37	−0.70	−0.79	0.68	0.68	0.77	−0.67
		2015	−1.54	−1.54	−1.48	0.46	0.44	−2.26	−0.98	−0.94	0.66	0.96	0.92	−0.64
		2016	−0.57	−0.74	0.36	0.55	0.72	−0.35	−1.46	−1.45	0.66	1.43	1.42	−0.65
r_s^c	BM	2014							−3.72	−3.68	1.53	3.51	3.47	−1.45
		2015	−4.03	−4.10	1.97	3.84	3.91	−1.87	−4.36	−4.29	2.10	4.13	4.06	−1.98
		2016	−1.70	−1.98	2.34	1.57	1.83	−2.18	−2.13	−2.20	0.86	2.02	2.09	−0.81
	DM	2014	−1.60	−1.83	2.04	1.50	1.72	−1.93	−1.72	−1.94	1.82	1.62	1.82	−1.72
		2015	−2.47	−2.46	0.09	1.30	1.27	−3.74	−2.48	−2.37	1.21	2.34	2.24	−1.14
		2016	−6.00	8.75	−3.62	−10.31	12.35	−7.51	−2.69	−2.68	0.88	2.57	2.56	−0.84
r_s^s	BM	2014	3.67	−0.21	0.11	−3.40	0.19	−0.10	3.66	−0.18	0.05	−3.35	0.16	−0.04
		2015	1.37	−0.02	0.02	−1.33	0.02	−0.02	3.40	−0.05	0.04	−3.17	0.05	−0.03
		2016	4.49	−0.39	0.30	−4.05	0.35	−0.27	3.38	−0.37	0.10	−3.11	0.34	−0.09
	DM	2014	2.25	−0.21	0.13	−2.13	0.20	−0.12	3.70	−0.24	0.06	−3.41	0.22	−0.06
		2015	3.74	−0.93	−1.67	−4.36	−0.19	−2.06	5.14	−0.32	0.21	−4.56	0.28	−0.18
		2016	2.96	−0.46	0.25	−2.75	0.42	−0.23	1.76	−0.19	0.04	−1.68	0.18	−0.03
r_s^m	BM	2014	−0.42		0.27	0.71		−0.45	−0.55		0.14	0.50		−0.13
		2015	−0.15		0.14	0.13		−0.13	−0.09		0.04	0.09		−0.04
		2016	−0.49		0.38	0.42		−0.33	−1.15		0.31	1.08		−0.29
	DM	2014	−1.60		0.35	0.48		−0.30	−0.76		0.26	0.71		−0.24
		2015	−1.82		−1.11	2.30		−2.20	−0.98		0.60	0.88		−0.54
		2016	−4.50		−5.05	4.30		−5.97	−0.59		0.14	0.57		−0.14

resistances from the reference height to soil surface (r_a^s), aerodynamic resistances of the canopy to in-canopy flow (r_a^c), the canopy resistance (r_s^c), soil surface resistance (r_s^s) and the mulching resistance of the film mulch (r_s^m) these six resistance parameters estimated, so we only focused on the sensitivity of model towards these six resistance parameters (Table 4). Results indicate that the model was very sensitive to the variation in aerodynamic resistances from the reference height to soil surface (r_a^s), the canopy resistance (r_s^c) and soil surface resistance (r_s^s) when applied to calculation of evapotranspiration (ET), bare soil water evaporation (E_{bs}) and mulched soil water evaporation (E_{ms}) during both daytime and nighttime. While the model was more sensitive to the variation in aerodynamic resistances from the reference height to in-canopy heat exchange plane height (r_a^a) when computing the nighttime ET, E_{bs} and E_{ms} compared to the daytime ET, E_{bs} and E_{ms}. The model was also sensitive to the mulching resistance of the film mulch (r_s^m) when simulating the daytime ET and E_{ms}.

Evapotranspiration measured by eddy covariance system (ET_{EC}) was adopted to validate the Modified Shuttleworth-Wallace model (MSW) (Table 5). The results indicated that during the daytime, the bare soil water evaporation was higher than mulched soil, but lower than the mulched soil during the nighttime, which was consistent with the measured results (Figs. 8, 9).

The results could be attributed to the following two factors: (1) Thermal driving. During the daytime, the crop canopy intercepted more net radiation, and the plastic mulch reflected more net radiation compared to the bare soil, so that the heat flux into the bare soil was more than the mulched soil. While during the nighttime, the longwave radiation released from the crop canopy above the mulched soil would increase the warming effect of the plastic mulch. The thicker the crop canopy is, the more remarkable coating effect on plastic mulch. (2) Moisture driving. Soil moisture under the plastic mulch was obviously higher than the bare soil. But during the daytime, the atmosphere evaporation capacity is strong, and bare soil between mulches would have higher evaporation potential than the mulched soil because the bare soil between mulches directly exposure to the atmosphere without the protection of plastic mulch.

Under sufficient irrigation conditions, there will be upper migration when the surface bare soil layer moisture decreases. While during the nighttime, the atmosphere evaporation capacity decreases, the higher soil moisture and temperature under the plastic mulch promote the soil water evaporation through the open-hole of the plastic mulch.

Table 5
Statistic results of the mulched soil evaporation (**E_{ms}**), the bare soil evaporation (**E_{bs}**) and evapotranspiration (**ET**) estimated using the modified Shuttleworth-Wallace (**MSW**) model in comparison with that measured by micro-lysimeter and eddy covariance (**EC**) in the maize field during 2014–2016.

Sites	Periods	Regression equations	R^2	n	MBE(mmd^{-1})	RMSE(mmd^{-1})	IA
2014-BM	daytime	$E_{bs\ MSW} = 1.15E_{bs\ LYS}$	0.48	132	0.18	0.45	0.83
		$E_{ms\ MSW} = 0.92E_{ms\ LYS}$	0.19	132	0.03	0.17	0.91
		$ET_{MSW} = 1.09ET_{EC}$	0.70	149	0.47	1.11	0.91
	nighttime	$E_{bs\ MSW} = 1.15E_{bs\ LYS}$	0.12	132	0.03	0.09	0.66
		$E_{ms\ MSW} = 0.97E_{ms\ LYS}$	0.28	132	0.00	0.10	0.76
		$ET_{MSW} = 1.05ET_{EC}$	0.37	129	0.09	0.49	0.77
2014-DM	daytime	$E_{bs\ MSW} = 1.69E_{bs\ LYS}$	0.71	113	0.53	0.79	0.77
		$E_{ms\ MSW} = 0.92E_{ms\ LYS}$	0.92	113	0.02	0.24	0.88
		$ET_{MSW} = 1.10ET_{EC}$	0.77	134	0.51	1.09	0.97
	nighttime	$E_{bs\ MSW} = 1.51E_{bs\ LYS}$	0.38	111	0.05	0.22	0.57
		$E_{ms\ MSW} = 1.42E_{ms\ LYS}$	0.36	111	0.06	0.24	0.61
		$ET_{MSW} = 1.02ET_{EC}$	0.31	134	0.15	0.57	0.80
2015-BM	daytime	$E_{bs\ MSW} = 0.93E_{bs\ LYS}$	0.30	131	-0.01	0.31	0.71
		$E_{ms\ MSW} = 0.81E_{ms\ LYS}$	0.20	131	-0.05	0.17	0.71
		$ET_{MSW} = 1.20ET_{EC}$	0.65	155	0.95	1.23	0.92
	nighttime	$E_{bs\ MSW} = 0.89E_{bs\ LYS}$	0.18	116	0.00	0.06	0.69
		$E_{ms\ MSW} = 0.88E_{ms\ LYS}$	0.14	116	-0.01	0.07	0.78
		$ET_{MSW} = 1.10ET_{EC}$	0.14	155	0.19	0.43	0.82
2015-DM	daytime	$E_{bs\ MSW} = 1.38E_{bs\ LYS}$	0.75	129	0.37	0.74	0.80
		$E_{ms\ MSW} = 1.01E_{ms\ LYS}$	0.48	129	0.05	0.26	0.87
		$ET_{MSW} = 1.19ET_{EC}$	0.64	132	1.16	1.42	0.91
	nighttime	$E_{bs\ MSW} = 1.14E_{bs\ LYS}$	0.25	120	0.04	0.15	0.72
		$E_{ms\ MSW} = 1.34E_{ms\ LYS}$	0.32	120	0.03	0.18	0.69
		$ET_{MSW} = 1.07ET_{EC}$	0.61	132	0.03	0.53	0.84
2016-BM	daytime	$E_{bs\ MSW} = 1.67E_{bs\ LYS}$	0.89	121	0.68	1.08	0.79
		$E_{ms\ MSW} = 1.02E_{ms\ LYS}$	0.39	121	0.06	0.26	0.86
		$ET_{MSW} = 1.18ET_{EC}$	0.75	155	1.04	1.54	0.92
	nighttime	$E_{bs\ MSW} = 1.19E_{bs\ LYS}$	0.09	121	0.07	0.19	0.52
		$E_{ms\ MSW} = 1.30E_{ms\ LYS}$	0.26	121	0.04	0.17	0.65
		$ET_{MSW} = 0.97ET_{EC}$	0.49	155	-0.01	0.27	0.80
2016-DM	daytime	$E_{bs\ MSW} = 2.12E_{bs\ LYS}$	0.80	124	0.94	1.96	0.61
		$E_{ms\ MSW} = 0.73E_{ms\ LYS}$	0.54	124	-0.13	0.29	0.87
		$ET_{MSW} = 1.22ET_{EC}$	0.63	138	1.13	1.43	0.91
	nighttime	$E_{bs\ MSW} = 0.96E_{bs\ LYS}$	0.05	124	0.03	0.14	0.65
		$E_{ms\ MSW} = 1.01E_{ms\ LYS}$	0.34	124	0.01	0.13	0.79
		$ET_{MSW} = 1.10ET_{EC}$	0.58	138	0.11	0.33	0.88

4. Discussions

4.1. Why E_{ms} was lower than E_{bs} during daytime in the maize field?

Results indicate that the mulched soil water evaporation (E_{ms}) was significantly lower than the bare soil water evaporation (E_{bs}) during daytime under either BM or DM experiment sites from 2014 to 2016 (Fig. 4, Table 3). The main reason was that plastic mulch significantly increased the water transfer resistance and severely limited the water vapor exchange between the mulched soil and atmosphere (Yang et al., 2012). Furthermore, the transparent plastic mulch increased the surface reflectance (Ham and Kluitenberg, 1994; Tarara and Ham, 1999; Wang et al., 2011), and lowered the ground net radiation (Fan et al., 2017) compared to the non-mulched soil in daytime during early growing stages when the soil was not covered completely. Thus plastic mulch remarkably restricted the soil water evaporation and saved water during daytime, which is in line with previous studies (Ramakrishna et al., 2006; Dahiya et al., 2007; Wang et al., 2009).

4.2. Why E_{ms} was higher than E_{bs} during nighttime in the maize field?

In contrast to previous studies, three-year continuous experiment results indicate that the E_{ms} was higher than E_{bs} during nighttime in the maize field under the both experiment sites (Fig. 6, Table 3). These implicated that the plastic mulch promoted the soil water evaporation during the nighttime and more soil water evaporated from the mulched soil. These were mainly caused by the coating effect between the crop canopy and the mulched soil

In the nighttime, air temperature dropped sharply, while the long-wave radiation from mulched soil to atmosphere was retarded by the plastic mulch. Besides, the crop canopy above the soil was just like a coat which enhanced the warming effect of plastic mulch. And the enhanced effect increased with develop of the crop canopy. As the crop canopy developing, the bare soil between mulches would be covered by the crop canopy. Even so, the crop canopy above the mulched soil is thicker than that above the bare soil between mulches during the whole crop growth period. Therefore, the enhanced effect from the crop canopy on mulched soil is stronger than that on bare soil between mulches. As a result, the mulched soil heat reserve was higher than the bare soil, which is consistent with previous studies (Tarara, 2000; El-Shaikh and Fouda, 2008; Cao et al, 2012; Li et al, 2016b).

Previous studies confirmed the water-saving effect of plastic mulch but did not quantify the time scale of such effect. In this study, the data were separated into two groups to investigate the difference of the mulching effect on soil water evaporation during the daytime and nighttime. During the daytime, the proportion of E_{bs} to ET_{EC} was about 7.25%–10.60% during 2014–2016, while the proportion of E_{ms} to ET_{EC} was about 2.72%–5.57% during 2014–2016. However, during the nighttime, the proportion of E_{bs} to ET_{EC} was about 0.71%-1.44% during 2014–2016, while the proportion of E_{ms} to ET_{EC} was about 0.99%–2.10% during 2014–2016.

E_{bs} accounts for most part of daytime soil water evaporation, while

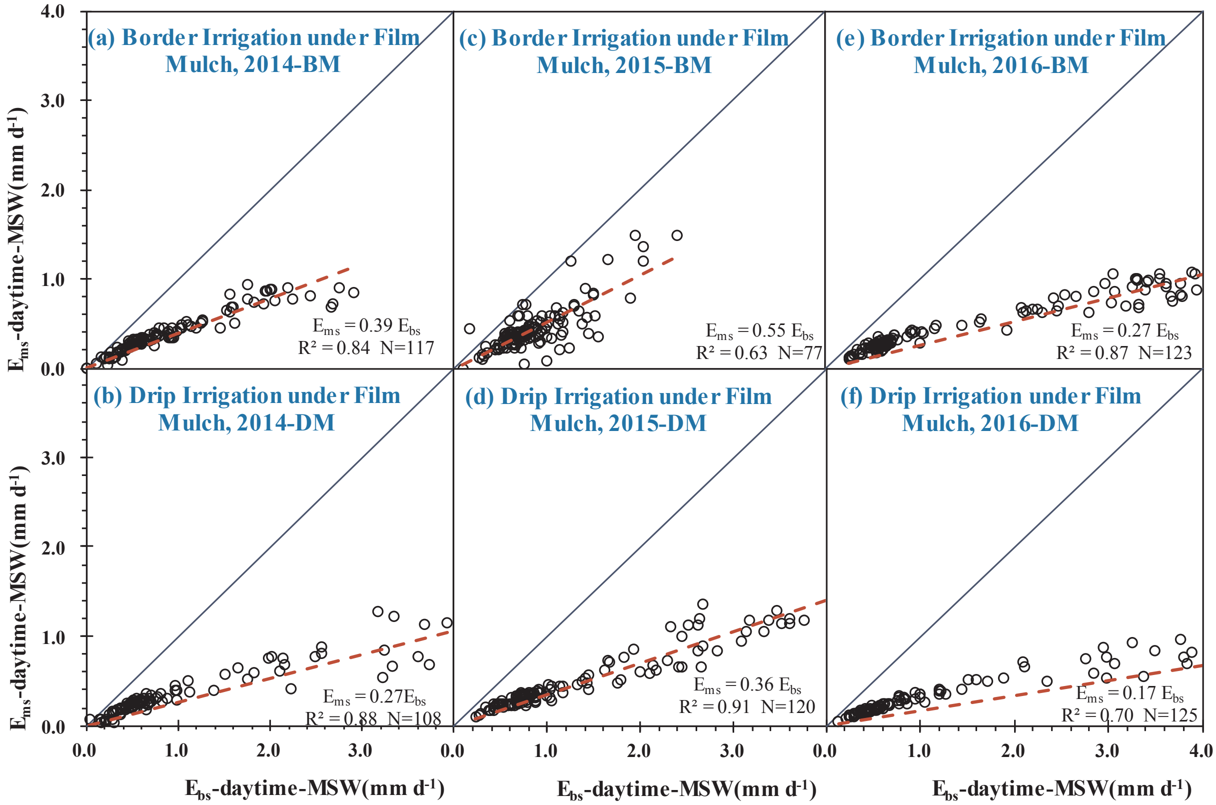

Fig. 8. Comparison of the **daytime** mulched soil evaporation (**E_{ms}**) with the bare soil evaporation (**E_{bs}**) estimated by the Modified Shuttleworth-Wallace model (MSW) in the maize field during 2014–2016.

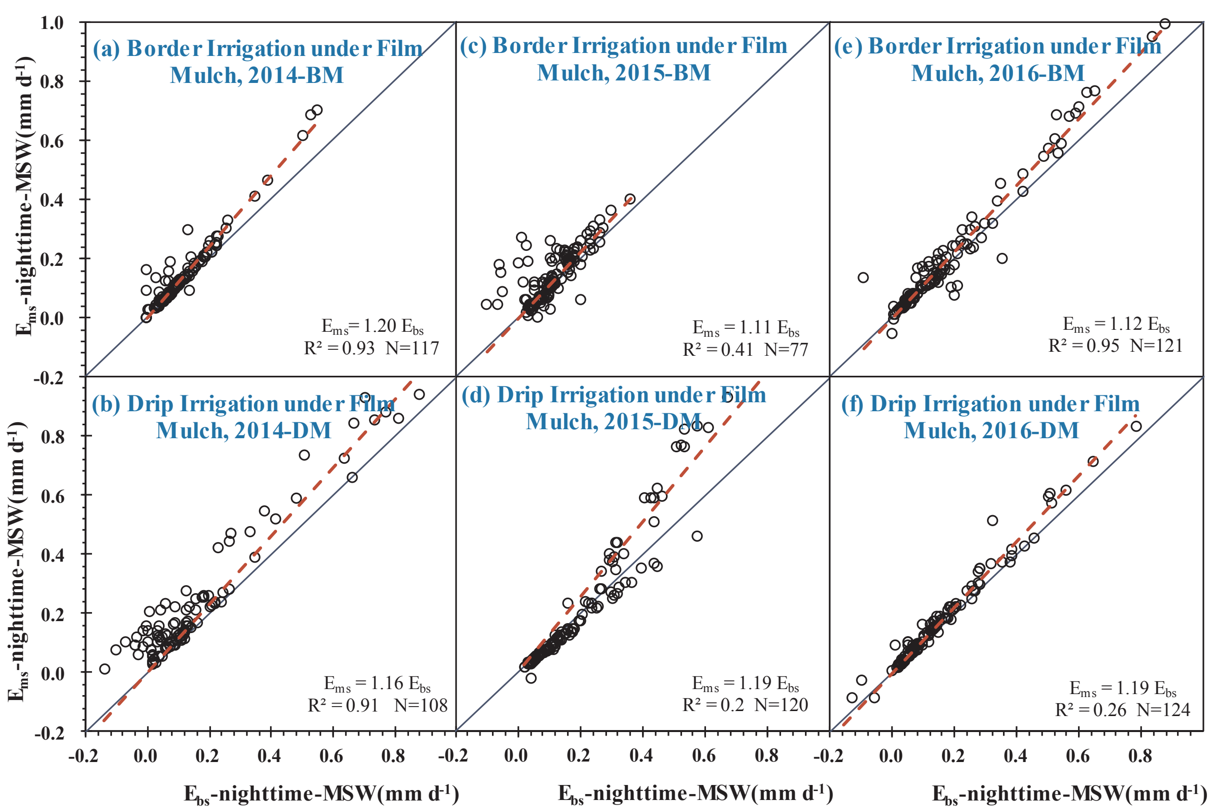

Fig. 9. Comparison of the **nighttime** mulched soil evaporation (**E_{ms}**) with the bare soil evaporation (**E_{bs}**) estimated by the Modified Shuttleworth-Wallace model (MSW) in the maize field during 2014–2016.

E_{ms} accounts for most part of nighttime soil water evaporation (Table 3). We confirmed that the water-saving effect of plastic mulch occurred mainly during daytime, and the warming effect occurred mainly during nighttime. This finding is helpful for understanding the effect of plastic mulch on water use efficiency.

5. Conclusion

Previous studies have demonstrated that plastic mulch can reduce soil water evaporation, but rarely consider the mulching effect on soil water evaporation and energy transfer process. In this study, three-year continuous field experiments were conducted to contrast soil water evaporation between mulched soil and bare soil using micro-lysimeters during daytime and nighttime. On this basis, we expected to reveal the effect of plastic mulch on soil water evaporation and energy transfer process. Based on the long-term measured data, we found that daytime E_{bs} was averagely higher than E_{ms} by 45%-61%, while the nighttime E_{ms} was averagely 5%-31% higher than E_{bs} during 2014–2016. Also, a soil-mulch-canopy-atmosphere model was used to consider the effects of the mulch, and the model results further support this finding. Therefore, the plastic mulch decreased the soil water evaporation in the daytime but promoted the soil water evaporation in the nighttime.

Our study indicated that water-saving effect of the plastic mulch mainly occurred in the daytime, while the plastic mulch promoted the soil water evaporation in the nighttime. Furthermore, we found that the crop canopy plays an important role in water and energy transfer process between the soil and the atmosphere. Therefore, the coating effect was proposed for which could enhance the effect of plastic mulch, such as increasing water transfer resistance in the daytime and promoting warming effect in the nighttime.

These provided a new insight for understanding the effect of plastic mulch on soil water evaporation. However, the energy transfer process between the plastic mulch and the crop canopy and the interactive relationship between coating effect and crop growth still need to be further studied.

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