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Evapotranspiration measurement and estimation using modified Priestley–Taylor model in an irrigated maize field with mulching

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ABSTRACT

Accurate measurement or estimation of crop evapotranspiration (ET) is important to develop exact irrigation scheduling and reasonably use water resources. ET of an irrigated maize field mulched with plastic film was measured using eddy covariance technique over two growing seasons in an arid region of northwest China. A modified Priestley–Taylor (PT) model was developed, incorporating the effect of leaf area, soil moisture, mulching fraction and leaf senescence on ET. The model was parameterized by field measurements in 2008 and validated by those in 2009. Results indicate that diurnal variation of ET was bell-shaped curve for all the growing stages. During the two growing seasons, total ET was 503.1 and 562.4 mm, and mean daily ET 3.47 and 3.54 mm d^{-1}, respectively. ET was mainly controlled by solar radiation, and significantly affected by influential factors below the thresholds, which were leaf area index of 3.0 m^2 m^{-2}, and soil relative extractable water of 0.5, and canopy conductance of 20 mm s^{-1}, respectively. A good agreement was found between ET estimated by the modified PT model with observations, with linear slope of 0.99 and R^2 of 0.94 and 0.96 for half-hourly and daily time scale, respectively. Thus the modified PT model can be used to estimate ET or quantify the effect of controlling factors on ET in similar agricultural fields.

1. Introduction

More than 90% of water used in agriculture is lost by soil evaporation and crop transpiration (Rana and Katerji, 2000). Thus accurate measurement or estimation of crop evapotranspiration (ET) is important to develop exact irrigation scheduling and reasonably use water resources (Kang et al., 2008). However, direct measurement of ET is difficult, cost and not available in many regions, so different models are developed to estimate ET (Stannard, 1993; Sumner and Jacobs, 2005; Utset et al., 2004). ET is significantly affected by weather condition, crop species, irrigation scheduling and field management (e.g. surface mulching) (Allen et al., 1998; Kang et al., 2003; Tolk et al., 1998; Zhao et al., 2010). Therefore, determination of major factors affecting ET is needed to provide information to establish the ET model.

The Priestley and Taylor (PT) model is a simplification of Penman equation (Agam et al., 2010; Priestley and Taylor, 1972; Utset et al., 2004). In this model, ET is a product of the equilibrium evaporation (ET_{eq}) and PT coefficient (α), where ET_{eq} can be obtained from meteorological data (net radiation, soil heat flux, and air temperature). The successful use of PT model depends on accurate determination of α (De Bruin, 1983; Pereira and Villa Nova, 1992; Priestley and Taylor, 1972). De Bruin (1983) developed the PT coefficient model as a function of surface resistance. Pereira and Villa Nova (1992) showed that α was linearly related to sensible heat flux at either hourly or daily time scales. In addition, some studies indicated that α = 1.26 could be applied to many vegetated areas (Brutsaert, 1982; Lhomme, 1997; Parlange and Katul, 1992). Conversely, other studies indicated that α was not constant over whole growing season and varied greatly with crop species, soil moisture availability and climate condition (Lei and Yang, 2010; Pereira, 2004). They suggested that the main factors controlling α included leaf area index (LAI), vapor pressure deficit (VPD) and soil moisture content (θ). However, a unique functional form for the response of α to the factors has not been defined yet.

Maize is one of main food crops in Shiyanghe basin of arid region in northwest China, where has larger population density and higher exploitation of water resources (Kang et al., 2008). Because of low precipitation in this region, water requirement of maize is mainly supplied by irrigation. To reduce soil evaporation in the field, ground is mulched with plastic film, which is a well established management strategy (Hou et al., 2010). Many studies indicated that plastic mulching not only reduced water loss from soil evaporation, but also accelerated crop development in the early stage by increasing soil temperature and controlling weed, which would enhance crop yield (Allen et al., 1998; Hou et al., 2010).

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Table 1
Crop management and irrigation scheduling over the whole growing seasons of maize in 2008–2009.

Year	Sowing date	Emergence date	Harvest date	Irrigation scheduling	
				Irrigation date	Irrigation quota (mm)
2008	May 2	May 11	September 25	June 12	100
				July 7	100
				July 27	100
				August 23	95
2009	April 21	May 1	September 28	June 15	105
				July 6	105
				July 29	105
				August 20	105

Irrigation water amount was measured by pump meter in each event.

However, fewer attempts have been made to investigate long-term variation in ET and its controlling factors with this management practice.

In this study, to investigate the variability and magnitude of ET and the controlling factors, ET of an irrigated maize field with mulching was measured by eddy covariance technique over the whole growing seasons in 2008 and 2009. Leaf area, meteorological factor and soil water content were also measured. After incorporating the effects of leaf area, soil moisture, ground mulch and leaf senescence on ET, a modified PT model was developed to estimate ET.

2. Materials and methods

2.1. Study area

The experiments were conducted at Shiyanghe Experimental Station for Water-saving in Agriculture and Ecology of China Agricultural University, located in Gansu Province of northwest China (N 37°52′, E 102°50′, altitude 1581 m) during 2008–2009. The site has high sunlight hours with a mean annual sunshine duration over 3000 h, mean annual temperature of 8 °C and frost-free days of 150 d. The region is limited in water resources with a mean annual precipitation of 164 mm and a mean annual pan evaporation of 2000 mm measured by a cylinder Class A evaporation pan with a diameter of 120.7 cm and a depth of 25.0 cm. Average groundwater table is below 30 m.

Spring maize was sown in the experimental field with a north-south length of 700 m and a west-east width of 300 m on May 3 2008 and April 21 2009, and harvested on September 25 2008 and September 28 2009. Plastic film was mulched with the width of 100 cm and bare soil of 65 cm between two plastic films. Maize was sown in hole of 5.0 cm diameter under plastic film, with a row spacing of 50 cm and a plant spacing of 23.8 cm, so the planting density was approximately 76,300 plants ha^{-1}. Actual mulching fraction was about 0.5 for the two years. The experimental soil is light sandy loam texture, with a dry bulk density of 1.45 g cm^{-3}, field capacity (θ_F) of 0.32 cm^3 cm^{-3} and wilting point (θ_W) of 0.10 cm^3 cm^{-3} at the 0–100 cm layer. The irrigation regime and crop management are listed in Table 1. The different growing stages were divided by our local visual observations of maize development characteristics and phenology, combined with changes of maize height and leaf area (Allen et al., 1998; Xu et al., 2002).

2.2. Evapotranspiration measurements

Evapotranspiration was measured using an eddy covariance system, which was installed in the center of maize field. The eddy covariance (EC) system consists of a fast response 3D sonic anemometer, a Krypton hygrometer and a temperature and humidity sensor. The sensors were installed at a 3.5 m height above ground level. Net radiation (R_n) was measured by a net radiometer which was installed at a height of 3.5 m. Two soil heat fluxes were installed below 8.0 cm soil depth under the plastic film and the bare soil, respectively. Temperature above the soil heat flux plates was measured with thermocouples at depths of 2.0 cm and 6.0 cm in line with each soil heat flux plate, and soil moisture at 0–10.0 cm was measured by an EnviroSMART soil moisture reflectometer. Surface soil heat flux is estimated by correcting the heat flux at 8.0 cm for heat storage above the transducers; the storage above 8.0 cm is determined from changes in soil temperature and volumetric moisture content above the heat flux transducers. The instrumentation and fluxes correction was described in Ding et al. (2010).

Soil evaporation (E_s) was measured by micro-lysimeters in 2009 (Ritchie, 1972). Eight micro-lysimeters cylinders, made from PVC tubes with a diameter of 10 cm and height of 20 cm, were installed within bare soil between two plastic films. The cylinders were weighted in the evening every day by the electric scale with the precision of 0.1 g. The micro-lysimeters were reinstalled within one day after each irrigation and heavy rain.

2.3. Other measurements

Solar radiation, precipitation, air temperature, relative humidity and wind speed were measured with a standard automatic weather station at a height of 2.0 m above the ground. Volumetric soil moisture at root zone (0–100 cm) was measured with eight PVC access tubes at the experimental field using portable device Diviner 2000 (Sentek Pty. Ltd., Australia). Measurements were made at an interval of 10 cm with maximal soil depth of 100 cm at intervals of 3–5 days. Extra samplings were conducted before and after irrigation events, and after rainfall. The measurements were calibrated by oven drying method. Interpolation is applied between consecutive irrigations to determine the θ at each day of the growing season.

Ten maize plants were randomly selected to measure leaf length and width at intervals of approximately 10 days during the growing period. Leaf area was calculated by summing rectangular area of each leaf (product of leaf length and maximum width) multiplied by a factor of 0.74, which was obtained by analyzing the ratio of rectangular area to real area, measured by an AM300 (ADC BioScientific Ltd., UK). Leaf area index (LAI) is defined as maize green leaf area per unit area (Allen et al., 1998). Continuous LAI was obtained by fitting observations with the days after sowing (DAS) using a single equation ($\mathrm{LAI} = a \cdot t^b \exp(-r \cdot t)$, where t is DAS, r is rate of LAI change with the value of 0.077 d^{-1}, a and b are fitted coefficients) (Hashimoto, 1990).

Maize leaf chlorophyll content (C_c) was measured by SPAD-502 meter (Konica Minolta Optics, Inc., Japan). SPAD readings, which are relative values of chlorophyll content and dimensionless, were taken three times during the growing season in 2009, at the shooting stage (June 30), filling stage (August 20), and maturity stage

(September 20), respectively. Twenty SPAD readings taken were averaged each time. The mean SPAD readings at the three times were 50.2, 53.6 and 37.5, respectively.

2.4. Parameter calculation and data analysis

To minimize the interaction of environmental factors, analysis of the relationship between ET and soil moisture and VPD was performed using a boundary line analysis, which was designed to select top dependent variable (y) points for each independent variable (x) range and describe the relationship when other factors were removed or reduced (Schafer et al., 2000). The upper boundary line was derived by: (1) partitioning x into different classes (see below), (2) calculating mean and standard deviation (SD) of y in each x interval, (3) removing y outliers ($P < 0.05$, Dixon's test), (4) selecting the y data falling above mean plus one SD and (5) averaging the selected y data when the number of remaining y being greater than five for each x interval to prevent x intervals with too little information from affecting the relationship (Schafer et al., 2000). In step (2), x was respectively referred to soil moisture (θ) and vapor pressure deficit (VPD). θ was separated into twelve classes (ten classes from 0.19 to 0.29 cm^3 cm^{-3} at the interval of 0.01 cm^3 cm^{-3}, one class below 0.19 cm^3 cm^{-3} and one class above 0.29 cm^3 cm^{-3}), and VPD was partitioned into nine classes (seven classes from 0.8 to 3.6 kPa at the interval of 0.4 kPa, one class below 0.8 kPa and one class above 3.6 kPa). Soil relative extractable water (REW) is defined as:

$$\mathrm{REW} = \frac{\theta - \theta_W}{\theta_F - \theta_W} \quad (1)$$

where θ is soil water content in 0–1.0 m soil (cm^3 cm^{-3}), θ_F is field capacity (cm^3 cm^{-3}) and θ_W is wilting point (cm^3 cm^{-3}). In this study, REW of 50% is referred as the threshold of crop water stress (Lei and Yang, 2010; Monteith and Unsworth, 2008; Suyker and Verma, 2008).

In order to understand canopy conductance (g_c) effect on ET, the relationship was analyzed according to the observations. g_c is calculated by inverting the Penman–Monteith equation as (Allen et al., 1998):

$$g_c = \frac{\gamma \lambda ET g_a}{\Delta(R_n - G) + \rho c_p g_a \mathrm{VPD} - \lambda ET(\Delta + \gamma)} \quad (2)$$

where ρ is air density (kg m^{-3}), c_p is specific heat of dry air at constant pressure (J kg^{-1} K^{-1}), λ is the heat of water vaporization (J kg^{-1}), Δ is the slope of the saturation vapor pressure curve (kPa °C^{-1}), γ is psychrometric constant (kPa °C^{-1}), $R_n - G$ is the available energy (W m^{-2}), and VPD is vapor pressure deficit (kPa). g_a is aerodynamic conductance (mm s^{-1}) and estimated as follows (Monteith and Unsworth, 2008):

$$g_a = \left(\frac{u}{u_*^2} + 6.2u_*^{-2/3}\right)^{-1} \quad (3)$$

where u is mean wind velocity (m s^{-1}) and u_* is friction velocity (m s^{-1}) measured by the EC system.

2.5. Modified Priestley–Taylor approach

Priestley–Taylor (PT) equation for actual bulk ET (λET) is expressed as:

$$\lambda ET = \alpha_b \cdot \lambda ET_{eq} = \alpha_b \frac{\Delta}{\Delta + \gamma}(R_n - G) \quad (4)$$

where α_b is so-called actually bulk PT coefficient and is a variable according to different underlying surfaces, and λET_{eq} is equilibrium evaporation (W m^{-2}). λET can be partitioned as soil evaporation (λE_s) and crop transpiration (λT_c):

$$\lambda ET = \lambda E_s + \lambda T_c \quad (5)$$

λE_s and λT_c can be calculated according to the obtained available energy, respectively, expressed as:

$$\lambda E_s = \alpha_s \frac{\Delta}{\Delta + \gamma}(R_{ns} - G) \quad (6)$$

$$\lambda T_c = \alpha_c \frac{\Delta}{\Delta + \gamma} R_{nc} \quad (7)$$

where R_{ns} and R_{nc} are net radiation obtained by soil surface and intercepted by crop canopy (W m^{-2}), respectively; α_s and α_c are soil evaporation coefficient and crop transpiration coefficient, respectively. R_{ns} and R_{nc} are respectively given by:

$$R_{ns} = \tau R_n \quad (8)$$

$$R_{nc} = (1 - \tau)R_n \quad (9)$$

$$\tau = \exp(-\kappa \mathrm{LAI}) \quad (10)$$

where τ is the fraction of net radiation transmission reached soil surface; κ, canopy extinction coefficient of radiation, is dependent on foliage orientation and solar zenith angle, 0.45 for this study (Campbell and Norman, 1998). α_s and α_c are respectively given by:

$$\alpha_s = f_{sw}(1 - f_m)\alpha_{s0} \quad (11)$$

$$\alpha_c = f_{cw}(1 - f_s)\alpha_0 \quad (12)$$

where f_{sw} and f_{cw} are the factor of soil water stress for soil evaporation and crop transpiration, respectively; f_m is fraction of ground mulched by plastic film, 0.5 measured in this study; f_s is fraction of leaf senescence, defined as the difference between unit and the ratio of chlorophyll content at the maturity stage ($C_{c,m}$) to that at the filling stage ($C_{c,f}$), i.e. $(1.0 - C_{c,m}/C_{c,f})$. The ratio of $C_{c,m}/C_{c,f}$ was 0.7, indicating $f_s = 0.3$, which was regarded as constant at the maturity stage of maize in 2009. α_{s0} are values of α_s under energy-limited conditions where available soil water was ample and there was no water limited. Thus, evaporation was only controlled by energy received in the surface. α_0, 1.26, is the reference Priestley–Taylor coefficient (Morgan et al., 2003; Priestley and Taylor, 1972). The α_{s0} was same as α_0 when the soil is wet and bare ($\tau = 1$), and gradually approached unity as LAI increases (Tanner and Jury, 1976), i.e.

$$\alpha_{s0} = \begin{cases} 1.0 & \tau \le \tau_c \\ \alpha_0 - \dfrac{(\alpha_0 - 1)(1 - \tau)}{1 - \tau_c} & \tau > \tau_c \end{cases} \quad (13)$$

where τ_c is a critical value of τ at which canopy cover is sufficient for α_{s0} approaching unity, 0.55 for this study (Morgan et al., 2003). For surface soil evaporation, f_{sw} is given by Deardorff (1977):

$$f_{sw} = \begin{cases} S_e & S_e < 0.75 \\ 1.0 & S_e \ge 0.75 \end{cases} \quad (14)$$

where S_e is effective surface saturation in 0–10 cm soil; $S_e = (\theta_g - \theta_r)/(\theta_s - \theta_r)$, where θ_g, θ_r (0.04 in this study) and θ_s (0.36 in this study) denote measured, residual and saturated water content in 0–10 cm soil depth (cm^3 cm^{-3}), respectively. f_{cw} is calculated by an exponential increase to maximum function:

$$f_{cw} = \min(1.0,\ m_1 + m_2(1 - \exp(-m_3 \mathrm{REW}))) \quad (15)$$

where m_1, m_2 and m_3 are empirical coefficients fitted by the observations based on the nonlinear relationship between ET and REW < 0.5 as shown in Fig. 5c using least squares method, with the values of −8.26, 9.26 and 10.15 in this study.

Soil heat flux (G) is described as a fraction of net radiation reached soil surface (R_{ns}) to develop an analytical expression of α_b (Choudhury et al., 1987):

$$G = f_G R_{ns} \quad (16)$$

where f_G is fraction of G to R_{ns}, with a value of 0.35 obtained by the observed G and calculated R_{ns} for this study, which was similar with Choudhury et al. (1987) in a wheat field.

Formulae of α_b can be derived as follows. Firstly, substituting Eqs. (8), (9), (11), and (12) into Eqs. (6) and (7). Then inserting Eqs. (4), (6) and (7) into Eq. (5). Thirdly, G was substituted by Eq. (16), τ substituted by Eq. (10), and R_n was eliminated. Finally, the analytical formulae of α_b can be written as:

$$\alpha_b = \frac{f_{cw}(1-f_s)\alpha_0 - [f_{cw}(1-f_s)\alpha_0 - f_{sw}(1-f_m)(1-f_G)\alpha_{s0}]\exp(-\kappa \mathrm{LAI})}{1 - f_G \exp(-\kappa \mathrm{LAI})} \quad (17)$$

The parameters, θ_F, θ_w, m_1, m_2, and m_3 in f_{cw}, θ_r and θ_s in f_{sw}, f_G, f_m and f_s were obtained by the observations. The input variables in Eq. (4) included R_n, G, LAI, θ_g and θ.

3. Results and discussion

3.1. Hydrometeorological condition and leaf area

Meteorological conditions were similar for two years (Fig. 1a and b). Mean seasonal T_a was 19.1 and 18.1 °C, VPD 1.36 and 1.20 kPa, total R_n 1480.7 and 1507.9 MJ m^{-2} and total precipitation 78.0 and 118.8 mm for 2008 and 2009, respectively (Table 2).

Soil moisture content (θ) at the 0–100 cm layer varied greatly over whole growing season. The variability of θ depended on irrigation scheduling (irrigation quota and timing) (Table 1). Soil moisture content had a peak value after irrigation and reduced gradually till next irrigation (Fig. 1b). 50% of REW (soil relative extractable water) is often referred as the threshold of crop water stress (Lei and Yang, 2010; Monteith and Unsworth, 2008; Suyker and Verma, 2008). Before irrigation event at the shooting stage of maize (June 12) in 2008, there were 9 days of θ below the threshold.

Leaf area index (LAI) showed a clear "one peak" pattern over the whole growing season in both years (Fig. 1c), with peak values of 4.5 and 5.4 m^2 m^{-2} and mean LAI of 2.7 and 3.1 m^2 m^{-2} (Table 2), respectively in 2008 and 2009. Previous studies indicated that maize height and LAI would reduce when suffering water deficit during the early growing stage (Allen et al., 1998; Kang et al., 2000). As shown in Fig. 1b, maize suffered from remarkable water deficit before the first irrigation event in 2008, thus LAI was reduced.

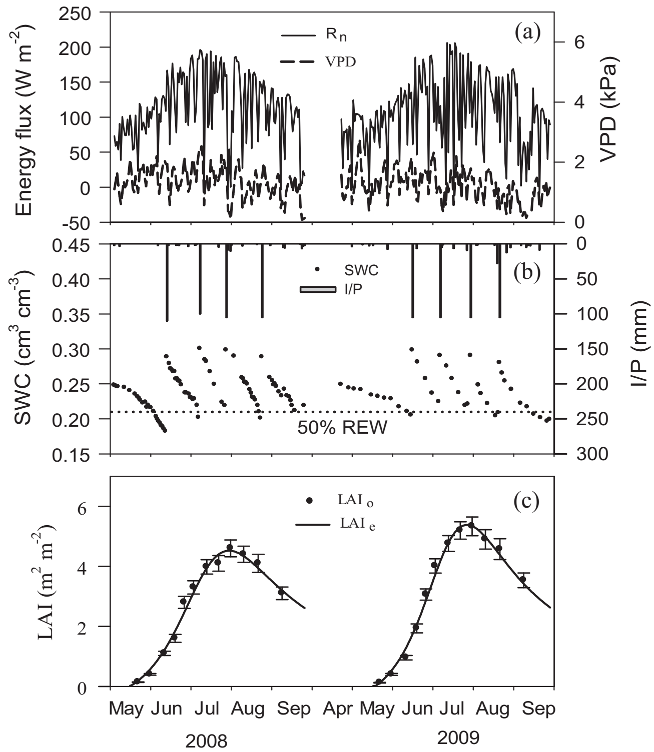

Fig. 1. Seasonal variation of (a) net radiation (R_n) and vapor pressure deficit (VPD), (b) averaged soil water content (SWC) at the 0–1.0 m layer, (c) leaf area index (LAI) over the whole growing seasons of maize in 2008 and 2009. Irrigation (I) and rainfall (P) are included. Soil relative extractable water (REW) of 50% is referred as the threshold of crop water stress, below which crop development will be constrained. LAI_o is observed value and LAI_e is estimated value.

3.2. Variation of evapotranspiration

Diurnal variation of ET was bell-shaped curve for different growing stages in both years (Fig. 2). Mean half-hourly ET increased between 07:00 and 08:00, peaked between 12:00 and 14:00 and decreased to the stabilization between 19:00 and 20:00. During the nighttime, half-hourly ET was nearly zero over whole growing stage.

Seasonal variation of daily ET was similar for both years (Fig. 3). Daily ET increased rapidly from less than 1.0 mm d^{-1} at the seedling stage to 8.0–9.0 mm d^{-1} at the heading stage. Subsequently daily ET decreased to about 2.0 mm d^{-1} at the maturity stage. Maximum daily ET was 7.92 and 9.14 mm d^{-1} in 2008 and 2009, respectively, which was close to the peak values of 8.0 mm d^{-1} observed in irrigated maize field in North Dakota (Al-Kaisi et al., 1989), but still

Table 2
Summaries of evapotranspiration (ET), net radiation (R_n), air temperature (T_a), vapor pressure deficit (VPD), precipitation (P), and leaf area index (LAI) over the whole growing seasons of maize in 2008 and 2009.

Year	Growing stage	Period	Total ET (mm)	Mean ET (mm d^{-1})	Total R_n (MJ m^{-2})	Mean T_a (°C)	Mean VPD (kPa)	Total P (mm)	Mean LAI (m^2 m^{-2})
2008	Seedling	5.3–5.30	38.3	1.37	214.8	17.0	1.40	6.0	0.3
	Shooting	5.31–7.7	145.0	3.82	440.4	20.8	1.62	16.4	2.0
	Heading	7.8–7.24	95.9	5.64	242.7	22.0	1.59	4.6	4.1
	Filling	7.25–9.6	183.1	4.16	450.0	19.1	1.21	27.2	4.0
	Maturity	9.07–9.24	40.9	2.27	132.8	16.2	0.88	23.8	2.9
	Whole	5.3–9.24	503.1	3.47	1480.7	19.1	1.36	78.0	2.7
2009	Seedling	4.22–6.5	66.3	1.47	332.1	16.0	1.29	17.0	0.4
	Shooting	6.6–7.9	161.8	4.76	369.3	20.2	1.43	12.8	2.6
	Heading	7.10–8.3	145.9	5.84	277.2	21.3	1.38	18.4	5.2
	Filling	8.4–9.10	152.2	4.00	400.1	18.0	1.13	58.8	4.2
	Maturity	9.11–9.27	36.2	2.13	129.2	15.4	0.81	11.8	2.9
	Whole	4.22–9.27	562.4	3.54	1507.9	18.1	1.20	118.8	3.1

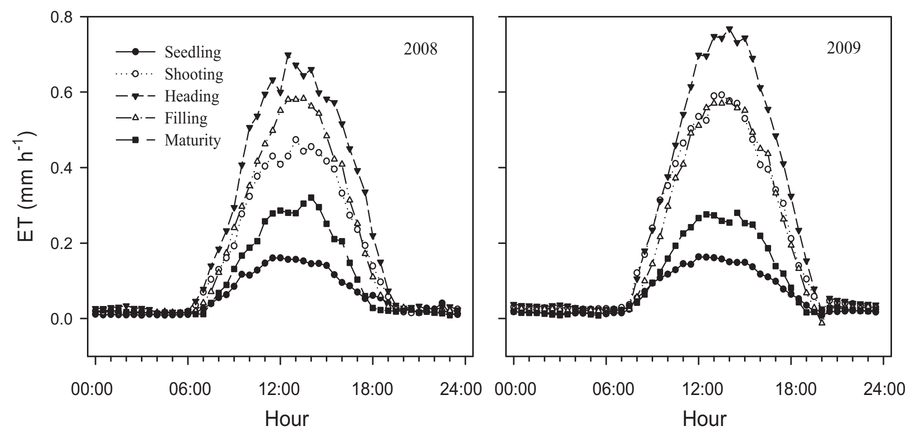

Fig. 2. Diurnal variation of average half-hourly ET at each growing stage of maize in 2008 and 2009.

lower than those for two irrigated maize hybrids in the hot, dry and windy High Plain of Texas (Howell et al., 1998), where peak value ranged from 13.0 to 14.0 mm d^{-1}. Table 2 shows that ET totals were 503.1 and 562.4 mm over the whole growing stage, with mean daily ET of 3.47 and 3.54 mm d^{-1} in 2008 and 2009. And total ET per LAI was 186.3 mm (503.1/2.7) in 2008 and 181.4 mm (562.4/3.1) in 2009. Although the difference of total ET between two years was about 10%, the difference of total ET per LAI was less than 3%, suggesting that inter-annual difference of ET was primarily related to LAI.

ET totals of the whole growing season for the two years in this study were within the range of water use (288–841 mm) for maize fields with full irrigation reported by other researchers (Table 3). However, daily mean ET from sowing to harvest of the study in the study was comparable with the results from other studies with plastic or straw mulching, yet significantly lower than others without mulching (Table 3). Doss et al. (1970) found that total ET of maize with completely plastic mulching were lower by 25.4–29.2% for different years compared to that without mulching under furrow irrigation at the southeastern US. In another rain-fed maize field, Zhou et al. (2009) reported that partly (f_m = 0.7) and whole mulching with plastic film reduced total ET by 11.1% and 16.6%, respectively comparing with that without mulching. Although we did not have any data from non-mulching field, researches on tomatoes in the same site showed that ET of field with drip irrigation and plastic mulching was lower than that without mulching, by 10.1% and 11.9% for 2006 and 2007, respectively (Hou et al., 2010).

One of the main reasons for ET reduced by mulching was that the proportion of soil evaporation (E_s) was reduced. In our study, E_s measured by micro-lysimeters varied from 0.02 to 1.56 mm d^{-1} during the growing season of 2009 (Fig. 3). Average ratio of E_s to ET was 10.1%, which was much lower than ratios from non-mulching maize field reported by other researchers with 26.0% and 30.3% (Kang et al., 2003; Liu et al., 2002).

3.3. Controlling factors of ET

Half-hourly and daily ET variations were primarily determined by solar radiation energy (Fig. 4), with linear slope of 0.66 (R^2 = 0.73) and 0.86 (R^2 = 0.69) in Fig. 4. This suggests that maize ET was mainly controlled by radiation energy or available energy, which laid a foundation to select PT model to estimate ET. The equilibrium evaporation rate (ET_{eq}) represented the amount of surface available energy obtained (Monteith and Unsworth, 2008). Thus the ratio of ET/ET_{eq}, i.e. measured PT coefficient (α_m), was selected as normalized ET to quantify the relationship between ET and other environmental and physiological factors.

The α_m increased quickly with the increased LAI when LAI < 3.0 m^2 m^{-2} and varied slightly when LAI > 3.0 m^2 m^{-2} (Fig. 5a), indicating that LAI of 3.0 m^2 m^{-2} can be used as the threshold affecting ET. Al-Kaisi et al. (1989) also suggested that LAI of 3.0 m^2 m^{-2} can be used as critical value affecting ET for a given crop. Full coverage of canopy led to no relative increase of energy intercepted by the canopy when LAI > 3.0 m^2 m^{-2} (Allen et al., 1998), so greater leaf area did not significantly increase ET (Suyker and Verma, 2008). Moreover, some values of α_m were less than though LAI was around 3.0 m^2 m^{-2} at the maturity stage (downward triangles in Fig. 5a). Because canopy senescence and the decline of physiological function led to stomatal closure at the maturity stage, ET rate decreased drastically. Steduto and Hsiao (1998) also showed that leaf senescence significantly decreases ET. Thus, the effect was taken into consideration in the modified PT model as leaf senescence fraction (f_s).

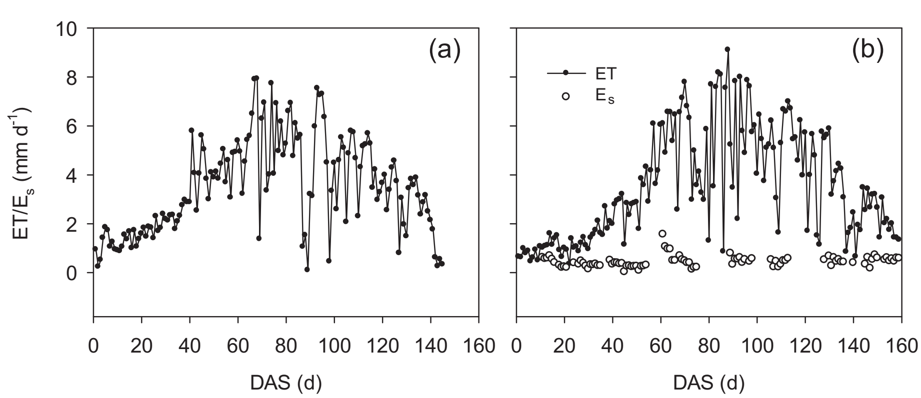

Fig. 3. Seasonal variation of ET and soil evaporation (E_s) against days after sowing (DAS) over the whole growing seasons of maize in 2008 (a) and 2009 (b).

Table 3
Review of total evapotranspiration (ET) and mean daily ET of maize over the whole growing season under irrigation condition.

Total ET (mm)	Mean ET ($mm\,d^{-1}$)	Mulch or not[a]	Measurement method	Location and climate	References
503	3.47	PM	Eddy covariance	Northwest arid region, China	This study
562	3.54	PM	Eddy covariance	Northwest arid region, China	This study
378	3.89	PM	Water balance	South humid region, USA	Doss et al. (1970)
288	3.00	PM	Water balance	South humid region, USA	Doss et al. (1970)
476	2.96	PM	Eddy covariance	Northwest arid region, China	Li et al. (2008)
376	3.54	SM	Water balance	North semi-humid region, China	Zhang et al. (2011)
381	3.60	SM	Water balance	North semi-humid region, China	Zhang et al. (2011)
396	3.74	SM	Water balance	North semi-humid region, China	Zhang et al. (2011)
544	3.34	SM	Eddy covariance	Midwest humid region, USA	Suyker and Verma (2008)
578	3.59	SM	Eddy covariance	Midwest humid region, USA	Suyker and Verma (2008)
506	5.21	NM	Water balance	South humid region, USA	Doss et al. (1970)
406	4.24	NM	Water balance	South humid region, USA	Doss et al. (1970)
741	4.84	NM	Lysimeter	Arid to humid regions, USA	Howell et al. (1998)
841	5.13	NM	Lysimeter	Arid to humid regions, USA	Howell et al. (1998)
424	4.01	NM	Lysimeter	Northwest semi-humid region, China	Kang et al. (2003)
573	4.09	NM	Lysimeter	North semi-arid region, China	Li et al. (2003)
423	4.14	NM	Lysimeter	North semi-humid region, China	Liu et al. (2002)
587	5.48	NM	Lysimeter	South semi-humid region, USA	Tolk et al. (1998)
616	4.16	NM	Bowen ratio-energy balance method	Northwest arid region, China	Zhao et al. (2010)

[a] PM, SM and NM represent plastic film mulching, straw mulching and not mulching, respectively.

Fig. 5b shows that α_m increased significantly with the increased canopy conductance (g_c) when $g_c < 15–20\,mm\,s^{-1}$ and almost remained constant when $g_c > 20\,mm\,s^{-1}$, which is in agreement with previous studies (Lei and Yang, 2010; Monteith and Unsworth, 2008; Suyker and Verma, 2008). McNaughton and Spriggs (1986) indicated that canopy conductance affects *ET* when $g_c < 16\,mm\,s^{-1}$. Therefore, like g_c, α_m can also be used to indicate the physiological response to changing environment.

The coefficient α_m was sensitive to REW when REW < 0.5 (Fig. 5c), which was similar to the previous studies (Lei and Yang, 2010). The nonlinear relationship between ET and REW < 0.5 was used to obtain the parameters (m_1, m_2, and m_3) in Eq. (15). The lack of α_m dependency on VPD was shown in Fig. 5d. Agam et al. (2010) indicated that α_m was constant for agricultural crops when VPD ranges from 0 to 4.0 kPa. A theoretical study also indicated that α_m is relatively insensitive to small changes in VPD (Eichinger et al., 1996).

3.4. ET estimation using the modified PT model

A good agreement was found between the observed ET and estimates by the modified PT coefficient model, with linear slope of 0.99 and R^2 of 0.94 ($P < 0.01$) (Fig. 6a). The root mean square error (RMSE) and relative error (RE) were 39.1 $W\,m^{-2}$ and −4.5%, respectively. Compared to half-hourly ET estimates (Fig. 6a), daily ET estimated by the modified PT model presented an enhanced agreement with observations, with linear slope of 0.99 and R^2 of 0.96 ($P < 0.001$) (Fig. 6b). These results suggest that the modified PT model could accurately estimate evapotranspiration of irrigated maize with mulching in the arid region of northwest China for either half-hourly or daily time scale, while daily ET is considered important to develop precision irrigation scheduling (Allen et al., 1998; Kang et al., 2003). Sumner and Jacobs (2005) noted that the PT method can provide better estimation of pasture ET in Florida, where α_b is a function of LAI and solar radiation. Stannard (1993) also presented that the PT approach was better than the PM approach in estimating ET of sparsely vegetation in the semiarid area of Colorado, where α_b was a function of LAI and soil evaporation loss.

We also validated the modified PT model performance with ET measured by eddy covariance systems in 2010 under a different mulching fraction (f_m) of 0.6. We found that the model could well reproduce the observed ET, with linear slope of 1.01 and R^2 of 0.93 (data not shown). These results further suggest that the model was a robust tool to estimate ET under different mulching regimes. We want to point out that actually mulching fraction does not vary much between years because local growers tend to adopt the same management practices each year.

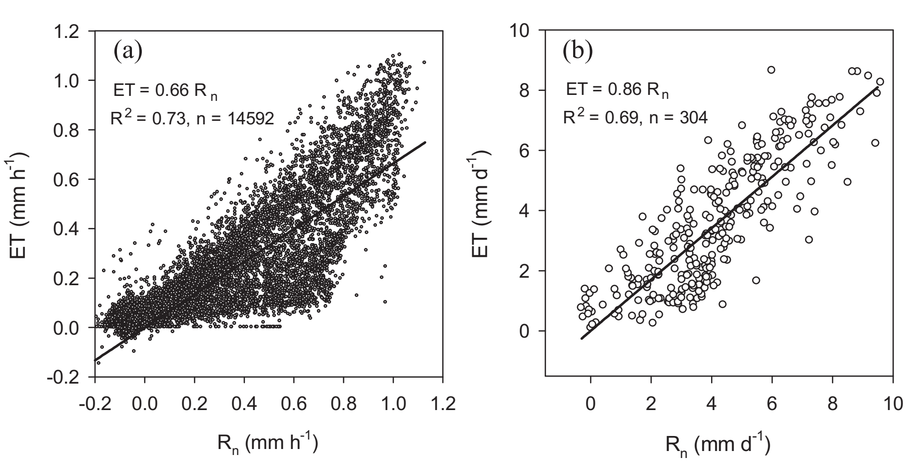

Fig. 4. The relationship between measured ET and net radiation (R_n) in the two years, (a) half-hourly values, and (b) daily values.

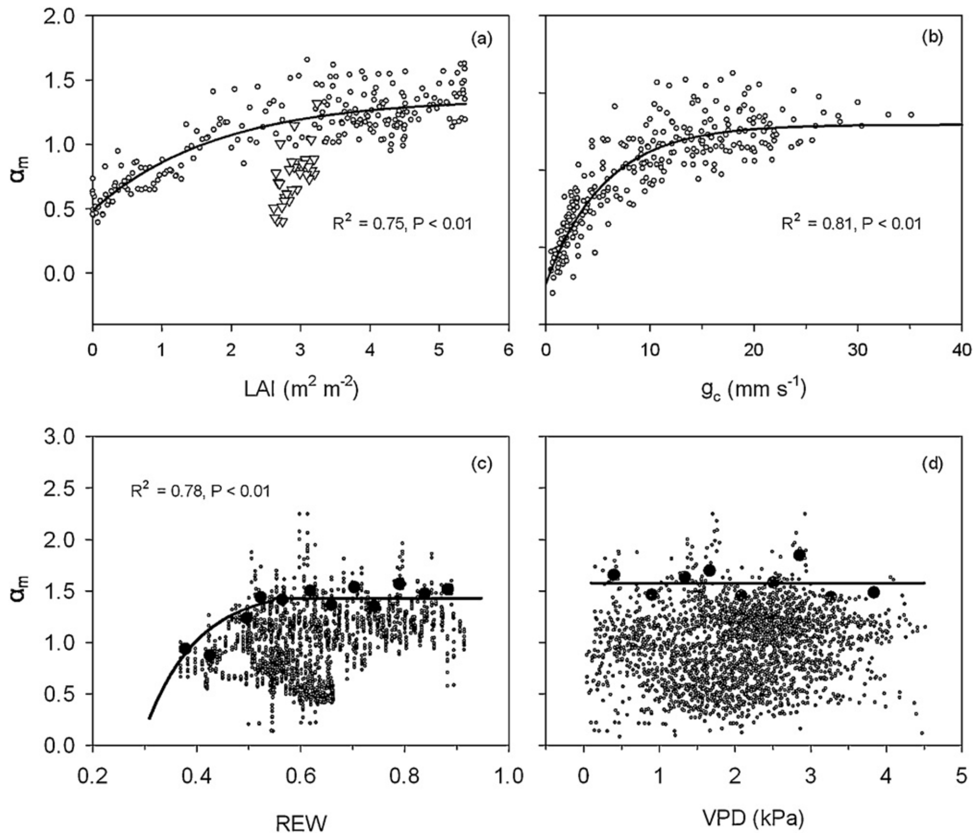

Fig. 5. Relationship between mean midday (10:00–15:00) bulk Priestley–Taylor coefficient measurements (α_m) and influencing factors over the whole growing seasons in 2008 and 2009. Solid lines are fit curves. In (a), downward triangles (▽) represent data at the maturity stage when maize leaves were senescing. In (b), g_c is canopy conductance inverted by Penman–Monteith equation with observations. In (c) and (d), REW is soil relative extractable water at the 0–100 cm depth; VPD is saturation vapor pressure deficit; closed circles (●) represent the results of boundary line analysis at different REW and VPD levels.

ET estimates by the modified PT model with f_m = 0.0 and f_m = 1.0 were higher and lower, respectively, than those with f_m = 0.5. The differences were evident during the seedling stage, the first half of shooting stage and the second half of maturity stage, but little during the middle part of the season (Fig. 7), which were consistent with previous studies (Doss et al., 1970; Hou et al., 2010). The ET totals were 507.5 and 589.1 mm under full and no mulching, respectively, i.e. total ET reducing by 13.8%, which was close to previous reported value of 16.6% (Zhou et al., 2009). This suggests that the modified PT model in this study can well capture the effect of changes in mulching fraction on ET over the whole growing season of maize, especially during the growing stages where soil surface was not fully covered by crop canopy.

For simulations conducted, ET with f_m = 0.0 and 1.0 was obtained with the input variables, such as R_n and LAI, parameterized as the same as those of f_m = 0.5, which might be imprecise and compromise the results. Previous studies has shown that different plastic

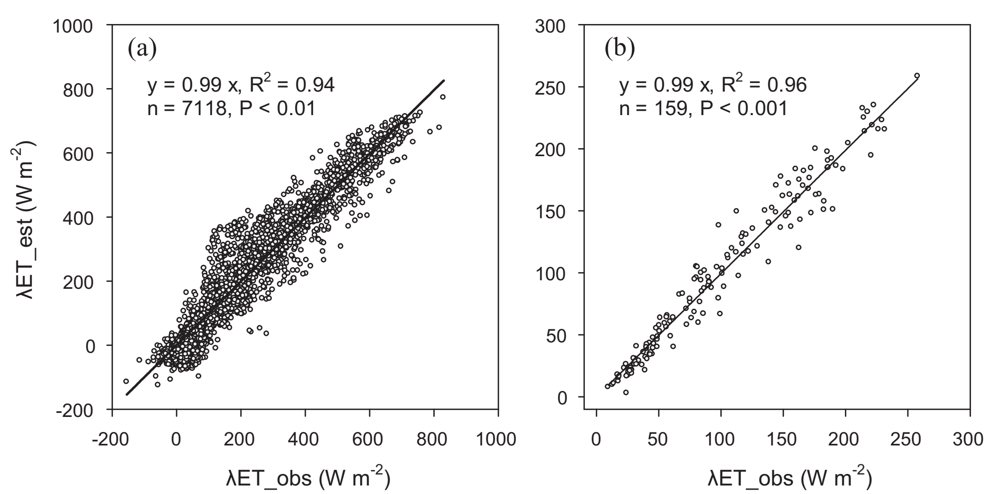

Fig. 6. Comparison between estimated ET (λ_{ET_est}) by the modified Priestley–Taylor model versus observed ET by eddy covariance (λ_{ET_obs}) over the whole growing season of maize in 2009, (a) half-hourly values and (b) daily values.

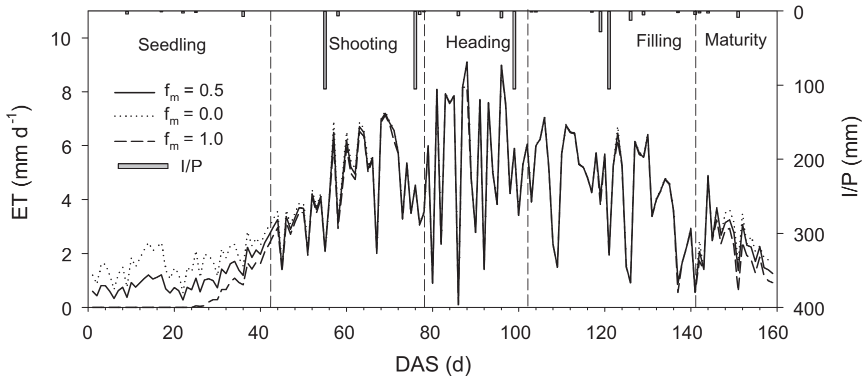

Fig. 7. Seasonal variations of daily ET calculated by the modified Priestley–Taylor model in different mulching fraction (f_m) against days after sowing (DAS) over the whole growing season of maize in 2009. The f_m = 0.5 is the actually observed value in this study, and f_m = 0.0 and 1.0 represent no and full plastic film mulching. I/P represent irrigation and precipitation amounts.

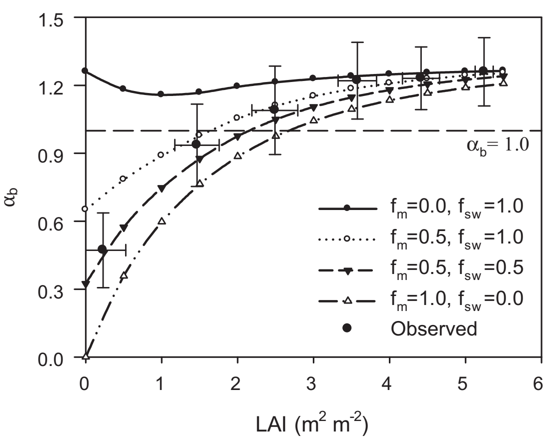

Fig. 8. Relationship between bulk Priestley–Taylor coefficient (α_b) and leaf area index (LAI). The curve lines represent analytical results calculated by Eq. (17) in different fractions of ground mulched by plastic film (f_m = 0.0, 0.5, 1.0) under different soil surface moisture conditions (f_{sw} = 0.0, 0.5, 1.0, representing extremely dry soil, dry soil and wet soil, respectively). Mean observed values of α_b and LAI are shown with one standard deviation within a LAI interval of 1.0 $m^2\,m^{-2}$. The α_b = 1.0 are shown with dashed line.

mulching fraction would produce complex changes in crop microclimate environment and energy transfer due to different optical properties and temperature in soil surface (Tarara, 2000). Therefore, using observed data of those input variables is recommended for better results when applying the modified PT model to estimate in different mulching regimes.

From Eq. (11), soil evaporation is affected by surface available energy, mulching fraction and surface soil moisture content. The modified PT coefficient model can be used to quantify the effect of those factors on soil evaporation and ET. We assumed that maize was transpiring at the potential rate (α_c = 1.26), which is reasonable since maize was not stressed in most of growing stages (Fig. 1b). Different surface soil water regimes (f_{sw} = 0, 0.5, 1.0) and different mulching fractions (f_m = 0, 0.5, 1.0) were selected to calculate the variability of α_b under different LAI (Fig. 8). Under the same condition of surface soil moisture (f_{sw} = 1.0), α_b decreased by 13.2% when f_m increased from 0 to 0.5. Under the same mulching fraction (f_m = 0.5), α_b decreased by 8.5% when f_{sw} decreased from 1.0 to 0.5. The α_b decreased significantly when LAI < 3.0 $m^2\,m^{-2}$, i.e. soil surface was not fully covered by canopy. The theoretical analysis suggests that when LAI was similar, α_b was lower with higher mulching fraction and/or lower soil moisture regime, which is consistent with previous experimental results (Allen et al., 1998; Hou et al., 2010). Observed α_b values were clustered between the curve of f_m = 0.5, f_m = 0.5 and f_{sw} = 0.5, and f_{sw} = 1.0 (Fig. 8), which is agreement with the fact that actual f_m = 0.5 and f_{sw} between 0.5 and 1.0 in 2008 and 2009.

4. Conclusions

Diurnal variation of ET was bell-shaped curve for all the growing stages. During the two growing seasons, total ET was 503.1 and 562.4 mm, and mean daily ET 3.47 and 3.54 mm d^{-1}, respectively. Plastic film mulching could reduce soil evaporation and ET. ET was mainly controlled by radiation energy, and was significantly influenced by LAI (<3.0 $m^2\,m^{-2}$), soil relative extractable water (<0.5), and canopy conductance (< 20 mm s^{-1}).

The modified Priestley–Taylor (PT) model was validated with ET measured by eddy covariance systems under different mulching fractions for either half-hourly or daily time scale. Thus the modified PT model can be used to estimate ET or quantify the effect of controlling factors on ET in similar agricultural fields.

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