Comparison of three evapotranspiration models in a rain-fed spring maize field in the Loess Plateau, China

Xiang Gao a,b,†, Fengxue Gu a, Daozhi Gong a, Weiping Hao a, Jianmin Chu b and Haoru Li a

Key Laboratory of Dryland Agriculture, Ministry of Agriculture and Rural Affairs of the People’s Republic of China, Beijing 100081, China
Key Laboratory of Tree Breeding and Cultivation of National Forestry and Grassland Administration, Research Institute of Forestry, Chinese Academy of Forestry, Beijing 100091, China

Abstract

Accurate estimates of the rain-fed field evapotranspiration (ET) in the Loess Plateau of Northwest China is critical for predicting hydrologic processes, crop yield formation, and climate change. We simulated the ET variation in a rain-fed spring maize field in the eastern Loess Plateau using the Penman-Monteith (PM), Shuttleworth-Wallace (SW), and modified Priestley-Taylor (PTm) models. Then we compared their results with the observed ET using the eddy covariance (EC) method. Generally, the diurnal variation in estimated ET from the three models was similar to that of observed ET by the EC method. However, the PM model significantly underestimated ET. The ET estimates obtained from the SW and PTm models were approximately equal to the observed ET by the EC method. Considering the PTm model’s simplicity, we finally recommend it for rain-fed spring maize fields in the Loess Plateau. After precipitation, the estimated ET from the three models was significantly smaller than measured ET by the EC method, especially the PM model. After a frost, all three models failed to reflect the dramatic decrease in crop transpiration, and thus significantly overestimated ET.

Key words: Modified Priestley-Taylor model, Penman-Monteith model, Rain-fed spring maize, Shuttleworth-Wallace model, The Loess Plateau

1. Introduction

Evapotranspiration (ET), which returns about 60–70% of terrestrial precipitation to the atmosphere (Feng et al., 2016), is a critical component of the energy balance and hydrologic cycle. ET is closely related to biological activity and dry matter accumulation, providing raw material for photosynthesis (Gao et al., 2017). ET also affects precipitation; the associated latent heat flux has a critical impact on surface temperatures, and further plays a key role in regional climate change (Jung et al., 2010). Thus, ET estimates are required for a wide range of research fields, including hydrologic processes, crop yield formation, and climate change. Due to complex interactions among the land, plants, and atmosphere, ET is difficult to quantify (Xu and Singh, 2005).

There are several methods for calculating ET, including the Penman-Monteith (PM) (Zhang et al., 2008; Zhou et al., 2019), Shuttleworth-Wallace (SW) (Li et al., 2011; Gong et al., 2019), and Priestley–Taylor (PT) models (Zhang et al., 2008; Ding et al., 2013). In the PM model, the underlying surface is considered as a single homogeneous layer; this model is popular due to its relative simplicity (Monteith, 1965; Zhang et al., 2008) and accuracy in densely vegetated canopies (Rana and Katerji, 2000). The SW model is a direct approach to ET estimation that distinguishes between crop transpiration and soil evaporation; its theoretical basis is the PM model (Zhang et al., 2008). The SW model is especially good at estimating ET of clumped crops and row crops (Zhang et al., 2008). The Penman equation is simplified to the PT model by Priestley and Taylor (1972), in which ET is a product of the PT coefficient (α) and equilibrium evaporation. Thus, accurate determination of α determines the PT model’s precision. Ding et al. (2013) divided α into two parts, for the soil and plant surface, respectively, and successfully applied the modified PT (PTm) model to estimate ET in an irrigated maize field. Evaluating the applicability of different ET models in diverse ecosystems is an important research goal.

The Loess Plateau’s area is 6.238 × 10^4 km² in Northwestern China; 30% of its surface is cropland (Ma et al., 2019). The rain-fed field is dominant on the Loess Plateau. About 40% of the total rain-fed fields in China are distributed across the plateau (Gao et al., 2018), and spring maize (Zea mays L.) is the predominant crop in this region (Gao et al., 2017). Accurate ET estimation for rain-fed spring maize fields plays a key role in improving rainfall use efficiency, estimating crop yield, and quantifying hydrologic processes in this region. However, previous studies have mainly focused on ET model evaluation for irrigated fields in agricultural ecosystems (Zhang et al., 2008; Gong et al., 2019), with little attention to rain-fed fields (Feng et al., 2016). Therefore, it is essential to determine which models can be used to estimate ET in rain-fed fields in the Loess Plateau.

To determine the optimum model for estimating ET in the rain-fed spring maize field in the Loess Plateau, we compared ET estimates produced by the PM, SW, and PTm models. We
used the rain-fed spring maize field ET data collected by the eddy covariance (EC) method to evaluate the three models’ applicability.

2. Materials and Methods

2.1 Experimental station

The study was carried out at the Shouyang Scientific Observing and Experimental Station of the Dryland Agriculture and Agro-environment, located in the eastern Loess Plateau (37°45′N, 113°12′E; altitude, 1,202 m), from May 10 to September 30, 2011. The climate belongs to a typical semi-arid temperate continental monsoon climate. There is seasonal variation in mean annual precipitation of 474.5 mm, a mean annual temperature of 8.2 °C, and a frost-free period of 150 days annually (Gao et al., 2017). The experimental soil is sandy–loamy, containing 54.9% sand, 29.5% silt, and 15.6% clay. The soil bulk density is 1.34 g cm⁻³, and the volumetric water content of wilting humidity (θw) and field capacity (θf) are 0.10 cm⁻³ and 0.37 cm⁻³, respectively. Spring maize was sown around May 1 with a plant spacing of 0.3 m and a row spacing of 0.5 m. The root distribution of spring maize was mainly in the 0–100 cm soil layers during the experiment.

An open-path EC system and environmental monitoring sensors were installed on a 6-m-tall tower, which was erected near the center of a spring maize field at the Shouyang station. Table 1 provides detailed information on those instruments. The EC system height was adjusted to maintain a relative height of 1.3 m above the crop canopy. The fetch extended about 140 m from the tower in the upwind direction. The EC system was connected to a data logger (model CR3000, Campbell Scientific Inc.). This data logger was also used to store relative air humidity (HR), net radiation (RN), air temperature (T), and soil heat flux (G) data. Soil water content, precipitation (P), and photosynthetically active radiation (PAR) data were collected by another data logger (model CR3000, Campbell Scientific Inc.). The green leaf area index (GLAI) and total leaf area index (TLAI) were observed every 6–10 days using a crop canopy analyzer (model CI-110, CID Bio-Science Inc., Camas, WA, USA). The total leaf area includes a green leaf area and a dead leaf area. Crop height (h,) ranged from 0 to 2.79 m, was measured manually at the same time.

2.2 Eddy covariance method

According to Li et al. (2008), ET is calculated by EC method as follow:

$$\lambda ET = \rho \lambda w' q'$$  (1)

where λ stands for the latent heat of vaporization (J kg⁻¹), ET signifies the evapotranspiration (kg m⁻² s⁻¹), ρ represents the air density (kg m⁻³), w'q' denotes the covariance between fluctuations of humidity q' (kg kg⁻¹) and vertical wind speed w' (m s⁻¹).

We used flux data processing software (EddyPro 5, Li-COR Inc.) for quality control and to correct the ET data measured by the EC system. The quality control of ET data includes basic tests, statistical tests, and tests on the fulfillment of theoretical requirements (Foken et al., 2004). Correcting the ET data includes the coordinate rotation by the planar fit method (Wilczak et al., 2001), spectral loss correction (Moore, 1986), and density fluctuations correction (Webb et al., 1980). According to the software footprint analysis, if >70% of the 30-min flux footprint overlapped in the area of interest, the data were used for further analysis. Otherwise, the data were rejected. For missing ET data, we used the linear equation to fill the short gaps (≤2 h), and the mean diurnal variation method (Falge et al., 2001) to fill the long gaps (>2 h). The gap-filled ET data were used in the comparison between the EC observation and water balance observation. We used the observed ET data in the rest of the analysis.

Table 1. List of measured items and instruments at the Shouyang station.

| Observations                  | Height/depth | Model, manufacturer         | Accuracy | Data logging |
|-------------------------------|--------------|-----------------------------|----------|-------------|
| H₂O fluctuation               | 1.3 m above canopy | LI-7500, Li-COR Inc., Lincoln, NE, USA⁺ | ±1%      | 30 min avg.³ |
| Wind speed (u₀) friction velocity (u₀) | 1.3 m above canopy | CSAT3, Campbell Scientific Inc., Logan, UT, USA⁺ | ±0.01 m/s | 30 min avg. |
| Net radiation (Rn)            | 4 m          | CNR4, Kipp & Zonen B.V., Delft, Netherlands | <10%     | 30 min avg. |
| Soil heat flux (G)            | 2 cm         | HFP01SC, Hukseflux B.V, Delft, Netherlands | ±2%      | 30 min avg. |
| Air temperature (T_air) relative humidity (HR) | 4 m         | HMP45C, Vaisala Co., Ltd., Helsinki, Finland | ±0.2 °C/3% | 30 min avg. |
| Photosynthetically active radiation (PAR) | 4 m | LI190SB, Li-COR Inc. | ±1%      | 30 min avg. |
| Precipitation (P)             | 4 m          | TE525, Texas Electronics Inc., Dallas, TX, USA⁴ | ±0.1 mm  | 30 min avg. |
| Soil water content            | 10, 20, 30, 40, 50, 70, and 100 cm | EnviroSmart, Sentek Pty. Ltd., Stepney, SA, Australia⁺ | ±1.8%    | 30 min inst.⁵ |

Note:⁺ eddy covariance system consisted of a 3D sonic anemometer (CSAT3) and an infrared H₂O/CO₂ gas analyzer (LI-7500).
³30 min interval average of samples taken at 10 s sampling interval.
⁴instantaneous value of 10 s sampling interval at 30 min record interval.
⁵calibrated by a manual rain gauge.
⁶calibrated by oven drying method.

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2.3 Water balance method

According to Li et al. (2008), the rain-fed spring maize field ET is also calculated by water balance (WB) method, as follow:

\[ ET = I + P + Q_s - R - D_s - \Delta W \]  

where \( I \) signifies the irrigation (mm), \( P \) stands for the precipitation (mm), \( Q_s \) denotes the contribution from soil water under root zone (mm), \( R \) represents the surface runoff (mm), \( D_s \) stands for the deep drainage (mm). \( \Delta W \) represents the change of water storage in the root zone (mm), calculated as:

\[ \Delta W = W_{i1} - W_{i2} \]  

where \( W_{i1} \) and \( W_{i2} \) represent the average water content in root zone at time \( t_1 \) and \( t_2 \), respectively.

In the rain-fed cropland, \( I \) is 0. The \( R \) and \( D_s \) were neglected in this study because the rain-fed spring maize field was flat, and the \( P \) was not intensive. And \( Q_s \) was also neglected in this study as the water table was over 20 m deep in this region.

2.4 Evapotranspiration model

2.4.1 The PM model

The PM model is given by Monteith (1965) as follow:

\[ \lambda ET = \frac{A (R_e - G)}{\rho C_p D} \left( 1 + \left( \frac{r_c}{r_s} \right)^4 \right) \]  

where \( \lambda \) signifies the slope of saturation vapor pressure curve (kPa °C\(^{-1} \)); \( C_p \) signifies the specific heat of the air (J kg\(^{-1} \) °C\(^{-1} \)); \( D \) denotes the water vapor deficit (kPa); \( \gamma \) signifies the psychrometric constant (kPa °C\(^{-1} \)); \( r_c \) represents the aerodynamic resistance (s m\(^{-1} \)); and \( r_s \) stands for the surface canopy resistance (s m\(^{-1} \)); given by Jarvis (1976) as follow:

\[ r_c = \frac{r_{s\text{min}}}{LAI \cdot \Pi \cdot F_i (X_i)} \]  

where \( r_{s\text{min}} \) stands for the minimum stomatal resistance (120 s/m), calculated according to Qu et al. (2013), \( LAI_s \) denotes the effective \( GLAI \), calculated as follow:

\[ LAI_s = \begin{cases} GLAI & \text{GLAI} < 2 \\ 2 & 2 \leq \text{GLAI} \leq 4 \\ \text{GLAI/2} & \text{GLAI} > 4 \end{cases} \]  

The \( X_i \) represents an environmental variable, \( F_i (X_i) \) signifies the stress function of \( X_i \), and \( F_i (X_i) \) ranges from 0 to 1. The \( F_i (X_i) \) is evaluated as follow:

\[ F_1 (PAR) = \left( \frac{PAR}{1100} \right) \left( \frac{1100 + a_1}{PAR + a_1} \right) \]  

\[ F_2 (T_a) = \left( \frac{(T_a - T) (T_a - T) (T_a - a_3)}{(a_1 - T) (T_a - a_1) (a_2 - T)} \right) \]  

\[ F_3 (D) = e^{-a_1 D} \]  

\[ F_4 (\theta) = \begin{cases} 1 & \theta \geq \theta_w \\ \theta - \theta_w & \theta < \theta \theta_w, \theta < \theta_w \\ 0 & \theta < \theta_w \end{cases} \]  

where \( \theta \) is the actual soil moisture in the root zone (cm\(^3\) cm\(^{-3} \)). \( T_l \) and \( T_u \) represent the lower and upper-temperature thresholds, respectively, beyond which the transpiration rate is considered 0. The values of \( a_1, a_2, \) and \( a_3 \), obtained by a multivariate nonlinear fitting method using the observed \( r_s \), are 49.02, 20.65, and 0.25, respectively. The observed \( r_s \) was derived from the rearranged PM model using observed ET and meteorological data.

The \( r_s \) is given by Perrier (1975 a,b) as follow:

\[ r_s = \frac{\ln((z-d)/(b_1-d)) \ln((z-d)/z_0)}{k/u} \]  

where \( z \) represents the reference height (m), \( d \) denotes the zero plane displacement (m), \( z_0 \) stands for the roughness length of the crop relative to momentum transfer (m), \( k \) represents the von Karman constant, and \( u \) stands for the wind speed at the reference height (m s\(^{-1} \)).

2.4.2 The SW model

The SW model is given by Shuttleworth and Wallace (1985) as follow:

\[ \lambda ET = \lambda E + \lambda T = C_s \lambda PM + C_p \lambda SW \]  

where \( C_s \lambda PM = \Delta A + \gamma \left[ 1 + r_s^f (r_s^d + r_s^p) \right] \)  

\[ C_p \lambda SW = \frac{\Delta A + \gamma \left[ 1 + r_s^f (r_s^d + r_s^p) \right]}{1 + \left[ R_{sw} \cdot R_{sw}^a \cdot R_{sw}^b \cdot R_{sw}^c \cdot R_{sw}^d \right]} \]  

where \( E \) stands for soil evaporation (mm), \( T \) represents crop transpiration (mm), \( r_s^f \) and \( r_s^d \) denote canopy and soil surface resistance (s m\(^{-1} \)), respectively; \( r_s^p \) signifies the boundary layer resistance in the canopy (s m\(^{-1} \)); \( r_s^f \) and \( r_s^d \) represent the aerodynamic resistances from the soil surface to canopy source height and from that height to the reference level (s m\(^{-1} \)), respectively; \( A_{sw} \) and \( A_{sw} \) signify the available energy to the soil surface and total available energy (W m\(^{-2} \)), respectively; these parameters are expressed as follow:

\[ A_{sw} = R_{sw}^\sigma - G \]  

\[ A_{sw} = R_{sw} - G \]  

where \( R_{sw} \) stands for the \( R \), reaching the soil surface, evaluated as follow:

\[ R_{sw}^\sigma = R_s \exp(-\kappa TLAI) \]
where $K$ represents the extinction coefficient of light attenuation.

The $r^2$ is calculated according to Jarvis (1976), as Eqs. (5–10). Above the canopy height, according to Zhang et al. (2008), eddy diffusion coefficient ($K$) is expressed as follows:

$$K = ku_*, (z - d)$$

where $u_*$ denotes the friction velocity (m s$^{-1}$). Beneath the canopy height, $K$ is expressed as follows:

$$K = K_s \exp [-n (1 - \frac{z}{h})]$$

2.4.3 The PT$_{m}$ model

The PT$_{m}$ model is expressed as follows (Ding et al., 2013):

$$λET = λE + λT = \alpha_s \frac{A}{A + γ} A_{vade} + \alpha_s \frac{A}{A + γ} (A_{vade} - A_{sw})$$

where $α_s$ and $α_m$ represent the crop transpiration and soil evaporation coefficients, respectively, expressed as follows:

$$α_s = f_{sw} α_{so}$$

$$α_m = f_{sw} (1 - f_s) \alpha$$

where $f_{sw}$ and $f_{so}$ denote soil water stress factors for crop transpiration and soil evaporation, respectively; $f_s$ signifies the fraction of leaf senescence ($=0.26$), calculated according to Ding et al. (2013), $α$ represents the reference PT coefficient ($=1.26$), and $α_{so}$ stands for the value of $α_s$ under energy-limited conditions with unlimited soil water; $α_{so}$ is calculated as follows:

$$τ = \exp (-κTLAI)$$

$$α_{so} = \begin{cases} 1.0 & \tau \leq τ_c \\ \frac{(a-1)(1-τc)}{1-τc} & \tau > τ_c \end{cases}$$

where $τ$ signifies the fraction of $R_s$ reaching the soil surface, $τ_c$ is the threshold value of $τ$ at which soil surface is entirely covered by the canopy as $α_{so}$ approaches unity ($=0.55$; Morgan et al., 2003). For $E_i$, $f_{sw}$ is expressed as follows (Deardorff, 1977):

$$f_{sw} = \begin{cases} S_c & S_c < 0.75 \\ 0.1 & S_c \geq 0.75 \end{cases}$$

$$S_c = \frac{θ_{ir} - θ_r}{θ_{ir} - θ_{sw}}$$

where $S_c$ represents the effective surface saturation in 0–10 cm soil, $θ_{ir}$ stands for the measured soil moisture in 0–10 cm soil, $θ_r$ signifies the residual soil moisture in 0–10 cm soil. For $T_i$, $f_{sw}$ is given by Ding et al. (2013) as follows:

$$f_{sw} = \min (1.0, m_1 + m_2 (1 - \exp (-m_3 W))$$

$$REW = \frac{θ_{ir} - θ_s}{θ_s - θ_{sw}}$$

where $REW$ denotes soil relative available water in 0–100 cm soil, $θ_{ir}$ stands for the measured soil moisture in 0–100 cm soil, and $m_1, m_2, m_3$ are empirical coefficients (Ding et al., 2013).

2.5 Evaluation of model performance

We performed statistical comparisons among model results using linear regression analyses, modified coefficient of efficiency (MCE), root mean square error (RMSE), mean absolute error (MAE), and mean estimated value ($\bar{E}$) (Zhao et al., 2015; Gong et al., 2019). These parameters are calculated as follows:

$$MAE = \frac{1}{N} \sum_{i=1}^{N} |E_i - O_i|$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N} (E_i - O_i)^2}{N}}$$

$$MCE = 1 - \frac{\sum_{i=1}^{N} (O_i - E_i)^2}{\sum_{i=1}^{N} (O_i - \bar{O})^2}$$

where $N$ signifies the number of observations, $\bar{O}$ denotes the mean observed value, $O_i$ and $E_i$ represent the observed and estimated values, respectively.

3. Results

3.1 Environmental parameters

During the experiment, daily mean values of PAR, $R_s$, and $G$ were 6.52–197.95 W m$^{-2}$, 2.94–200.62 W m$^{-2}$, and –32.36 to 40.35 W m$^{-2}$, respectively (Fig. 1A). Daily mean $T_i$ varied from 5.40°C to 24.21°C with an average of 17.81°C. The summer monsoon influenced the daily mean $D$, which was relatively higher before the end of June (Fig. 1B). Daily mean $u$ and $u_*$ ranged as 0.71–4.61 m s$^{-1}$ and 0.10–0.41 m s$^{-1}$, respectively (Fig. 1C). After each rainfall, the daily mean $θ_r$ increased sharply and then decreased gradually, with a minimum value of 0.18 cm$^{-3}$ cm$^{-3}$ (Fig. 1D). During the growing season, GLAI increased dramatically until mid-July, and declined significantly after mid-August; TLAI increased with GLAI, but remained at the maximum value (4.12 m$^2$ m$^{-2}$) after mid-August; the general trend of $h_s$ was similar to that of TLAI, peaking at 2.79 m (Fig. 1E).

3.2 Comparison of daily ET observed by water balance and eddy covariance methods

As shown in Fig. 2, the slope between the daily ET measured by the EC method and the daily ET measured by the WB method was 0.96. The regression line was very close to 1:1 line. During the experiment, total ET measured by EC and WB methods were 361.51 mm and 365.72 mm, respectively. These results suggest that the daily ET measured by the EC method was consistent with the WB method in this study.

The WB method is considered as a traditional and accurate method to observe cropland ET (Li et al., 2008). We used this method to evaluate the EC method’s applicability measuring rain-fed spring maize field ET in the Loess Plateau. The results, shown in Fig. 2, indicate that the EC method could accurately measure rain-fed spring maize field ET in this study, and this is agreed well with the previous studies (Li et al., 2008; Chen et al., 2016). Therefore, we used ET data measured by the EC method to evaluate the performance of the three ET models at 30 min scale. And several studies have successfully used EC data to examine the performance of different ET models in different conditions.
ecosystems (Feng et al., 2016; Li et al., 2016; Mu et al., 2017).

3.3 Comparison of model ET estimates and eddy covariance ET measurements

3.3.1 Diurnal ET estimates and observations during the experiment

The slope between ET estimates obtained from the PM model and observed ET by the EC system was 0.81 (Fig. 3A), with RMSE of 40.97 W m$^{-2}$, MAE of 23.92 W m$^{-2}$, MCE of 0.69, and $R^2$ of 60.98 W m$^{-2}$, which was significantly lower than $\bar{G}$ at 72.42 W m$^{-2}$ (Table 2). The mean diurnal pattern of PM model ET estimates was also lower than that of observed ET, particularly at midday during the growing season (Fig. 4). These results indicate that the PM model significantly underestimated ET by 15.80% in this study.

The incorporation of soil surface resistance (separate from surface canopy resistance) allows the SW and PT$_s$ models to reflect soil evaporation better. ET estimates obtained from the

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**Fig. 1.** Daily mean net radiation ($R_n$), soil heat flux ($G$), air temperature ($T_a$), vapor pressure deficit ($D$), wind speed ($u$), friction velocity ($u^*$), soil water content at a depth of 10 cm ($\theta_{10}$), precipitation ($P$), green leaf area index (GLAI), total leaf area index (TLAI), and crop height ($h_c$) from May 10 to September 30, 2011 on the Loess Plateau, China.
SW and PTm models were more coincident with observed ET than those from the PM model (Figs. 3 and 4; Table 2). For the SW model, the slope between estimated ET and observed ET was 0.95, with RMSE of 34.43 W m⁻², MAE of 21.15 W m⁻², MCE of 0.73, and E of 75.95 W m⁻², which was just slightly higher than O at 72.42 W m⁻², indicating that ET estimates obtained from the SW model were slightly higher than observed ET by 4.87% in this study. For the PTm model, the slope between the estimated and observed ET was 0.93, with RMSE of 38.41 W m⁻², MAE of 23.36 W m⁻², MCE of 0.70, and E of 66.69 W m⁻², which was slightly smaller than O at 72.42 W m⁻², indicating that ET estimates obtained from the PTm model were just slightly lower than observed ET by 7.91% in this study. Therefore, ET estimates derived from the SW and PTm models were coincident with observed ET in this study, mainly because they distinguish soil evaporation from plant transpiration.

### 3.3.2 Diurnal ET estimates and observed ET after a precipitation

As shown in Fig. 5, compared with observed ET by EC method, the PM, SW, and PTm models underestimated ET by 34.13%, 8.96%, and 15.12%, respectively, after precipitation in this study. The amplitude of ET underestimation after precipitation was higher than that at average levels of 15.80% and 7.91% for PM and PTm models, respectively.

### 3.3.3 Diurnal ET estimates and observed ET after a frost

Fig. 6 shows the diurnal variations in ET estimates, obtained from the PM, SW, and PTm models, and actual ET after a frost. Although the general trends of the ET estimates obtained from three models agreed with those of observed ET, PM, SW, and PTm models overestimated ET by 20.15%, 23.66%, and 13.14%, respectively, in the rain-fed spring maize field. And the amplitude of ET overestimation after a frost was higher than that at the average level (4.87%) for the SW model.

### 4. Discussion

Previous studies have reported that the ET estimates obtained from the PM model were lower than measured ET in many

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**Table 2.** Comparison of mean absolute error (MAE), root mean square error (RMSE), modified coefficient of efficiency (MCE), and mean estimated value (E) among three evapotranspiration models used to estimate rain-fed spring maize field evapotranspiration from May 10 to September 30, 2011 on the Loess Plateau, China.

| Model | MAE | RMSE | MCE | O | E |
|-------|-----|------|-----|---|---|
| PM    | 23.92 | 40.97 | 0.69 | 72.42 | 60.98 |
| SW    | 21.15 | 34.43 | 0.73 | 72.42 | 75.95 |
| PTm   | 23.36 | 38.41 | 0.70 | 72.42 | 66.69 |

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**Fig. 2.** Comparison of average daily evapotranspiration (ET) estimated by the eddy covariance (ETEC) and soil water balance (ETWB) methods. We calculated the daily average ET over 10 days.

**Fig. 3.** Comparison of rain-fed spring maize field ET estimates obtained using the (A) Penman–Monteith (ETPM), (B) Shuttleworth–Wallace (ETSW), and (C) modified Priestley–Taylor (ETPTm) models with eddy covariance observations (ETEC) from May 10 to September 30, 2011 on the Loess Plateau, China.
There are several possible reasons for the ET underestimation by the PM model in the present study. First, the wet surface soil during the experiment (Fig. 1D) can decrease soil surface resistance and promote soil water evaporation in the rain-fed spring maize field. Therefore, although ET estimates increased slightly as $R_n$, $T_a$, and $D$ increased, it would remain lower than observed ET. This effect occurs because the surface canopy resistance in the PM model cannot incorporate the comprehensive soil surface and canopy resistances (Zhang et al., 2008). Second, the canopy resistance was higher than surface resistance in the wet surface soil, resulting in the proportion of canopy available energy lower than that of soil surface available energy into ET (Zhang et al., 2016). However, the surface canopy resistance model not sufficiently reflect the changes of canopy and surface soil moisture conditions and energy partition, leading to higher surface canopy resistance. In consequence, all available energy entering the crop canopy in the PM model will underestimate ET. Third, the canopy cover degree of the rain-fed spring maize field was very low in May and June (Fig. 1E), not meeting the precondition of the PM model, i.e., the target vegetation has a dense canopy.

However, some studies reported by Ortega-Farias et al. (2004) and Zhang et al. (2008) have also shown that the PM model overestimates ET in different agricultural ecosystems. These differences may have resulted from differences in surface soil moisture conditions and canopy resistance. Zhang et al. (2008) investigated a furrow-irrigated vineyard in the northwest of China with low vegetation cover, resulted in lower surface soil moisture and higher soil surface resistance, which was usually higher than the canopy resistance. Stannard (1993) reported that when the soil surface resistance was greater than canopy resistance, the PM model overestimated ET. The surface canopy resistance equation in the PM model includes the soil evaporation effect, as pointed out by Shuttleworth and Wallace (1985). Thus, when the PM model is applied to certain crop types and ecosystems, the relationships between surface canopy resistance and environmental variables (canopy density, surface soil moisture, etc.) will vary (Jarvis, 1976).

Previous studies have also reported that the SW and PTm models estimate ET well in different ecosystems (Stannard, 1993; Zhang et al., 2008; Mu et al., 2017). However, some differences were observed between measured ET from EC system and ET estimates produced by the two models in the present study, possibly due to inaccurate estimates of available energy for surface soil and canopy, caused by several factors. Zhang et al. (2008) provided three factors for the erroneous estimation of the two models. First, the SW and PTm models do not take into account differences in albedo and emitted long-wave radiation of surface soil and canopy. The maximum difference in emitted long-wave radiation between surface soil and canopy is about 100 W m$^{-2}$ (Brenner and Incoll, 1997). Second, the canopy intercept model of solar radiation in these models is simple (Zhang et al., 2008), and the extinction coefficient was considered as a constant (0.7) in the present study; neither model includes diurnal and seasonal variation in the extinction coefficient (Zhang et al., 2001).
interactions significantly affect energy fluxes. For example, the canopy absorbed sensible heat originating from the soil when the soil surface was dry. This absorption accounted for more than 21% of latent heat flux from the canopy. When the soil surface is wet, the soil surface absorbed sensible heat from the canopy, which increased latent heat flux from the soil (Ham et al., 1991). The PTₙ model produced higher ET in the morning and lowered ET in the afternoon compared to the other two models (Fig. 4). The diurnal ET pattern estimated by PTₙ model was mainly controlled by solar radiation, while that estimated by the other two models was controlled primarily by solar radiation, air temperature, and water vapor deficit. The diurnal patterns of air temperature and water vapor deficit lagged behind that of solar radiation. This is the main reason that the diurnal ET patterns estimated by PM and SW models lagged behind that estimated by PTₙ model.

Following precipitation, some water attached to the crop surface was lost to the atmosphere easily (Gao et al., 2018). This situation was not included in the PM, SW, and PTₙ models, in which ET estimates obtained from the three models were lower than the observed ET by EC method. Furthermore, the amplitude of ET underestimation for PM model was significantly higher than it was for SW and PTₙ models, mainly because soil evaporation did not separate from crop transpiration in the PM model. The higher surface soil moisture after the precipitation caused soil surface resistance was smaller than canopy resistance, resulted in the PM model more significantly underestimated ET, according to Stannard (1993). Zhang et al. (2008) found that the SW model reproduced ET well after each precipitation, which is different from our study. The 2-day average values of estimated and observed ET after each precipitation event were used in the previous study, which might weaken the effect of the water attached to crop surface on the SW model precision following each precipitation.

After a frost, spring maize can suffer chilling injuries, characterized by the destruction of plant membranes and the cell framework, destroying enzymes, and inhibiting their activation, thereby increasing leaf senescence (Li et al., 2008; Zhang et al., 2008). Canopy resistance increases significantly, resulting in a significant decrease in transpiration rate of green leaves. Canopy resistance parameters in the PM and SW models did not reflect this dramatic change in canopy resistance caused by the frost; therefore, these models underestimated canopy resistance and overestimated ET. The PTₙ model had a constant leaf senescence fraction (0.26), which underestimated leaf senescence and overestimated ET for spring maize in this study.

Among the PM, SW, and PTₙ models, ET estimates produced by the SW and PTₙ models coincided closely with EC measurements, indicating their suitability for estimating ET in a rain-fed spring maize field in the Loess Plateau. Considering the simplicity of the PTₙ model, we finally recommend this model for such fields in the Loess Plateau. Feng et al. (2016) had successfully used a dual crop coefficient method to estimate ET at our study site, and the simulation accuracy of the dual crop coefficient method is similar to that of PTₙ and SW models. And the three models can distinguish soil evaporation and crop transpiration. Therefore, in a future study, we will examine the performance of the three models in ET partitioning based on measured values of soil evaporation and crop transpiration.

5. Conclusion

General diurnal variation in estimated ET from the PM, SW, and PTₙ models was similar to that of observed ET by the EC system. The PM model significantly underestimated observed ET, whereas the results of the SW and PTₙ models agreed well with observed ET. Considering the PTₙ model’s simplicity, we finally recommend it for rain-fed spring maize fields in the Loess Plateau. After precipitation, the estimated ET from the three models was significantly smaller than observed ET, especially the PM model. All three models significantly overestimated ET after a frost because they failed to capture the dramatic decrease in spring maize transpiration under these conditions.

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References

Brenner AJ, Incoll LD, 1997: The effect of clumping and stomatal response on evaporation from sparsely vegetation shrublands. Agricultural and Forest Meteorology 84, 187–205.

Chen X, Yu Y, Chen J, Zhang T, Li Z, 2016: Seasonal and interannual variation of radiation and energy fluxes over a rain-fed field in the semi-arid area of Loess Plateau, northwestern China. Atmospheric Research 176–177, 240–253.

Deardorff JW, 1977: A parameterization of ground-surface moisture content for use in atmospheric prediction models. Journal of Applied Meteorology 16, 1182–1185.

Ding R, Kang S, Li F, Zhang Y, Tong L, 2013: Evapotranspiration measurement and estimation using modified Priestley-Taylor model in an irrigated maize field with mulching. Agricultural and Forest Meteorology 168, 140–148.

Falge E, Baldocchi D, Olson R, Anthoni P, Aubinet M, Bernhofer C, Burba G, Ceulemans R, Clement R, Dolman H, Granier A, Gross P, Grünwald T, Hollinger D, Jensen N, Katul G, Keronen P, Kowalski A, Lai C, Law B, Meyers T, Moncrieff J, Moors E, Munger J, Pilegaard K, Rannik Ü, Reimbmann C, Suyker A, Tenhunen J, Tu K, Verma S, Vesala T, Wilson K, Wofsy S, 2001: Gap filling strategies for long term energy flux data sets. Agricultural and Forest Meteorology 107, 71–77.

Feng Y, Cui N, Gong D, Wang H, Hao W, Mei X, 2016: Estimating rain-fed spring maize evapotranspiration using modified dual crop coefficient approach based on leaf area index. Transactions of the Chinese Society of Agricultural Engineering 32, 90–98. (in Chinese with English abstract)

Foken T, Göockede M, Mauder M, Mahrt L, Amiro B, Munger W, 2004: Post-field data quality control, In Handbook of Micrometeorology (eds. by Lee X, Massman W, Law B), Springer, Dordrecht, pp. 269–274.

Gao X, Mei X, Gu F, Hao W, Gong D, Li H, 2018:...
Evapotranspiration partitioning and energy budget in a rain-fed spring maize field on the Loess Plateau, China. *Catena* **166**, 249–259.

Gao X, Mei X, Gu F, Hao W, Li H, Gong D, 2017: Ecosystem respiration and its components in a rain-fed spring maize field in the Loess Plateau, China. *Scientific Reports* **7**, 17614.

Gong X, Liu H, Sun J, Gao Y, Zhang H, 2019: Comparison of Shuttleworth-Wallace model and dual crop coefficient method for estimating evapotranspiration of tomato cultivated in a solar greenhouse. *Agricultural Water Management* **217**, 141–153.

Ham JM, Heilman JL, Lascano RJ, 1991: Soil and canopy energy balances of a row crop at partial cover. *Agronomy Journal* **83**, 744–753.

Jarvis PG, 1976: The interpretation of the variation in leaf water potential and stomatal conductance found in canopies in the field. *Philosophical Transactions of the Royal Society of London Series B-Biologic Sciences* **273**, 593–610.

Jung M, Reichstein M, Ciais P, Seneviratne SI, Sheffield J, Goulden ML, Bonan G, Cescatti A, Chen J, de Jeu R, Dolman AJ, Eugster W, Gerten D, Gische D, Gorbon N, Heinke J, Kimball J, Law BE, Montagnani L, Mu Q, Mueller B, Oleson K, Papale D, Richardson AD, Ropsard O, Running S, Tomelleri E, Viezy O, Weber U, Williams C, Wood E, Zaehle S, Zhang K, 2010: Recent decline in the global land evapotranspiration trend due to limited moisture supply. *Nature* **467**, 951–954.

Kato T, Kimura R, Kamichika M, 2004: Estimation of evapotranspiration, transpiration ratio and water-use efficiency from a sparse canopy using a compartment model. *Agricultural Water Management* **65**, 173–191.

Li L, Luo G, Chen X, Li Y, Xu G, Xu H, Bai J, 2011: Modelling evapotranspiration in a Central Asian desert ecosystem. *Ecological Modelling* **222**, 3680–3691.

Li S, Kang S, Li F, Zhang L, 2008: Evapotranspiration and crop coefficient of spring maize with plastic mulch using eddy covariance in northwest China. *Agricultural Water Management* **95**, 1214–1222.

Li S, Kang S, Zhang L, Zhang J, Du T, Tong L, Ding R, 2016: Evaluation of six potential evapotranspiration models for estimating crop potential and actual evapotranspiration in arid regions. *Journal of Hydrology* **543**, 450–461.

Ma Z, Yan N, Wu D, Stein A, Zhu W, Zeng H, 2019: Variation in actual evapotranspiration following changes in climate and vegetation cover during an ecological restoration period (2000–2015) in the Loess Plateau, China. *Science of the Total Environment* **689**, 534–545.

Monteith JL, 1965: Evaporation and environment. *Symposia of the Society for Experimental Biology* **19**, 205–234.

Moore CJ, 1986: Frequency response corrections for eddy correlation systems. *Boundary Layer Meteorology* **37**, 17–35.

Morgan CLS, Norman JM, Lowery B, 2003: Estimating plant-available water across a field with an inverse yield model. *Soil Science Society of America Journal* **67**, 620–629.

Mu Y, Li J, Tong X, Zhang J, Meng P, Ren B, 2017: Evapotranspiration simulated by Penman-Monteith and Shuttleworth–Wallace models over a mixed plantation in the southern foot of the Taihang Mountain, northern China. *Journal of Beijing Forestry University* **39**, 35–44. (In Chinese with English abstract)

Ortega-Farías S, Olioso A, Antonioletti R, Brisson N, 2004: Evaluation of the Penman–Monteith model for estimating soybean evapotranspiration. *Irrigation Science* **23**, 1–9.

Perrier A, 1975a: Etude physique de l’évapotranspiration dans les conditions naturelles. I. Evaporation et bilan d’énergie des surfaces naturelles. *Annales Agronomiques* **26**, 1–18.

Perrier A, 1975b: Etude physique de l’évapotranspiration dans les conditions naturelles. III. Evapotranspiration réelle et potentielle des couverts végétaux. *Annales Agronomiques* **26**, 229–243.

Priestley C, Taylor RJ, 1972: On the assessment of surface heat flux and evaporation using large-scale parameters. *Monthly Weather Review* **100**, 81–92.

Qiu R, Kang S, Du T, Tong L, Hao X, Chen R, Chen J, Li F, 2013: Effect of convection on the Penman-Monteith model estimates of transpiration of hot pepper grown in solar greenhouse. *Scientia Horticulturae* **160**, 163–171.

Rana G, Katerji N, 2000: Measurement and estimation of actual evapotranspiration in the field under Mediterranean climate: a review. *European Journal of Agronomy* **13**, 125–153.

Shuttleworth WJ, Wallace JS, 1985: Evaporation from sparse crops an energy combination theory. *Quarterly Journal of the Royal Meteorological Society* **111**, 839–855.

Stannard DI, 1993: Comparison of Penman–Monteith Shuttleworth–Wallace and modified Priestley-Taylor evapotranspiration models for wildland vegetation in semiarid rangeland. *Water Resources Research* **29**, 1379–1392.

Webb EK, Pearman GI, Leuning R, 1980: Correction of the flux measurements for density effects due to heat and water vapour transfer. *Quarterly Journal of the Royal Meteorological Society* **106**, 85–100.

Wileczak JM, Onclay SP, Stage SA, 2001: Sonic anemometer tilt correction algorithms. *Boundary Layer Meteorology* **99**, 127–150.

Xu C, Singh VP, 2005: Evaluation of three complementary relationship evapotranspiration models by water balance approach to estimate actual regional evapotranspiration in different climatic regions. *Journal of Hydrology* **308**, 0–121.

Zhang B, Kang S, Li F, Zhang L, 2008: Comparison of three evapotranspiration models to Bowen ratio-energy balance method for a vineyard in an arid desert region of northwest China. *Agricultural and Forest Meteorology* **148**, 1629–1640.

Zhang J, Meng P, Yin C, 2001: Review on methods of estimating evapotranspiration of plants. *World Forest Research* **14**, 23–28.

Zhang Y, Zhao W, He J, Zhang K, 2016: Energy exchange and evapotranspiration over irrigated seed maize agroecosystems in a desert-oasis region, northwest China. *Agricultural and Forest Meteorology* **223**, 48–59.

Zhao P, Li S, Li F, Du T, Tong L, Kang S, 2015: Comparison of dual crop coefficient method and Shuttleworth-Wallace model in evapotranspiration partitioning in a vineyard of northwest China. *Agricultural Water Management* **160**, 41–56.

Zhou H, Kang S, Tong L, Ding R, Li S, Du T, 2019: Improved application of the Penman-Monteith model using an enhanced Jarvis model that considers the effects of nitrogen fertilization on canopy resistance. *Environmental and Experimental Botany* **159**, 1–12.