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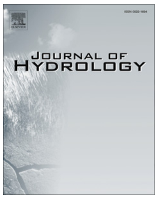

Quantifying the combined effects of climatic, crop and soil factors on surface resistance in a maize field

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SUMMARY

Land surface evapotranspiration (ET) is the central process in hydrological cycle. The accuracy in simulating ET is affected by the calculation of underlying surface resistance. However, the surface resistance is difficult to be measured and greatly affected by climatic, crop and soil factors. How to quantify the combined effects of these factors on surface resistance is still a challenge for hydrologists. Our study attempted to construct and validate a semi-empirical surface resistance model based on the analysis of the response pattern of surface resistance to climatic resistance, leaf area index (LAI) and soil moisture. The surface resistance was derived by the re-arranged Penman–Monteith (PM) equation and the measured maize ET using eddy covariance in 2007. Results indicate that the ratio of surface resistance to climatic resistance showed a logarithmic relationship with LAI, and an exponential function as soil moisture when LAI was below 2. But the ratio was nearly constant and not sensitive to variation in LAI and soil moisture when LAI exceeded 2. Based on the relationships, a surface resistance model was further constructed and compared to the widely used Katerji–Perrier and Jarvis models over the sparse maize and grape canopy. Our resistance model combined with the PM equation improved the accuracy in estimating daily maize ET by 11% in 2007 and 4% in 2008, and vineyard ET by 7% against the Katerji–Perrier model combined with PM method, while by 32% in 2007 and 104% in 2008, and vineyard ET by 5% against the Jarvis model combined with PM method. Thus our model significantly improved the performance in simulating sparse vegetation ET and can be used to estimate daily surface resistance under the partial canopy condition.

1. Introduction

Land evapotranspiration (ET) is the central process in the climate system and a nexus of the water, energy and carbon cycles. Terrestrial ET can affect precipitation, and the associated latent heat flux helps to control surface temperatures, with important implications for regional climate characteristics such as the intensity and duration of heat waves (Jung et al., 2010). How to accurately estimate land ET is a hot topic in hydrology. Penman–Monteith model is the most widely-used method to simulate ET in the world (Allen et al., 1998; Rana and Katerji, 2000). However, the model is highly sensitive to the variation in underlying surface resistance (Rana and Katerji, 1998). Accurate estimation of the parameter is critical for predicting land ET and understanding the hydrological processes in land surface.

Many empirical and semi-empirical models have been developed to estimate canopy resistance, such as the Katerji–Perrier and Jarvis models (Jarvis, 1976; Katerji and Perrier, 1983). These models take account of the effects of meteorological, physiological and soil control on stomatal resistance, and scale up the stomatal resistance to canopy resistance. The models have been used over a variety of agricultural crops, such as maize, sorghum, wheat, tomato, soybean, table grape (Jarvis, 1976; Katerji and Rana, 2006; Lhomme, 2001; Rana et al., 2011; Stewart, 1988; Whitley et al., 2009).

However, the estimated canopy resistance using theses models cannot be equal to the underlying surface resistance, which presents the mean resistance of all transmission mediums, including soil, crop and others. When the crop leaf fully covered the underlying surface, the two resistances are close, and we can use the estimated canopy resistance to replace the surface resistance in

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ET model. However, during the partial canopy condition, significant heterogeneity of water vapour transport exists in plant and soil mediums. The variations in canopy development and soil moisture greatly affect the dynamics of surface resistance. Thus how to construct the surface resistance after considering the combined effects of soil and crop remains uncertain and is of interest to hydrologists.

Our study attempted to obtain the surface resistance using the re-arranged PM equation and the measured maize ET using eddy covariance during 2007, in order to (1) analyze the response of the surface resistance to climatic resistance under different LAI and soil water conditions; (2) construct the function of surface resistance to climatic resistance after considering the modification by LAI and soil moisture; (3) validate the surface resistance model in estimating maize and vineyard ET under the partial canopy condition after parameterizing the model.

2. Models

2.1. Penman–Monteith model

The Penman–Monteith (PM) model can be written as (Monteith, 1965):

$$\lambda \mathrm{ET} = \frac{\Delta(R_n - G) + C_p \rho_a \mathrm{VPD}/r_a}{\Delta + \gamma + \gamma . r_s/r_a} \tag{1}$$

where λ is the latent heat of vaporization (J kg^{-1}), ET the crop evapotranspiration, Δ the slope of the saturation water vapour pressure versus temperature curve (kPa K^{-1}), R_n the net radiation (W m^{-2}), G the soil heat flux (W m^{-2}), C_p the specific heat of dry air at constant pressure (J kg^{-1} K^{-1}), ρ_a the air density (kg m^{-3}), VPD the water vapor pressure deficit (kPa), r_a the aerodynamic resistance (s m^{-1}), γ the psychrometric constant (kPa K^{-1}), r_s the surface resistance (s m^{-1}). The aerodynamic resistance r_a can be calculated as (Businger et al., 1971; Massman, 1992; Paulson, 1970):

$$r_a = \frac{[\ln(z/z_0) - \psi_h][\ln(z/z_0) - \psi_m]}{k^2 u} \tag{2}$$

where z is the reference height (m), z_0 the roughness length of the crop relative to momentum transfer (m), h_c mean crop height (m), k the von Karman constant (0.41), ψ_h the stability correction function for heat and water transfer, ψ_m the stability correction function for momentum transfers. These stability correction functions are taken from the models of Paulson (1970) and Businger et al. (1971), and are the ones most commonly used for estimating atmospheric stability corrections. u is the wind speed at the reference height (m s^{-1}). According to Monteith (1965), z_0 can be calculated as 0.13 h_c.

According to Katerji and Perrier (1983), the climatic resistance can be defined as:

$$r^* = \frac{\Delta + \gamma}{\Delta \gamma} \cdot \frac{C_p \rho_a \mathrm{VPD}}{(R_n - G)} \tag{3}$$

2.2. The Katerji–Perrier and Jarvis canopy resistance models

The Katerji–Perrier (KP) resistance model can be expressed as (Katerji and Perrier, 1983):

$$\frac{r_s}{r_a} = a\frac{r^*}{r_a} + b \tag{4}$$

where r_a is the aerodynamic resistance, r^* is the climatic resistance. a and b are empirical calibration coefficients requiring experimental determination. In this study, the values were 0.85 and 1.83 for maize, and 1.74 and −1.86 for the vineyard, respectively. These were obtained by the least squares fitting method using the eddy covariance ET. The model has been used to calculate ET for different species: alfalfa, sunflower, grain sorghum, grass, soybean (Katerji and Perrier, 1983; Katerji and Rana, 2006; Todorovic, 1999).

The Jarvis resistance model can be expressed as (Jarvis, 1976; Stewart, 1988):

$$r_s = r_{s_{\min}} / \{f(R_s) f(\mathrm{VPD}) f(T_a) F(\theta)\} \tag{5}$$

$$f(R_s) = \frac{R_s(1000 + k_1)}{1000(R_s + k_1)} \tag{6}$$

$$f(\mathrm{VPD}) = \exp(-k_2 \mathrm{VPD}) \tag{7}$$

$$f(T_a) = \frac{(T_a - T_L)(T_H - T_a)^t}{(k_3 - T_L)(T_H - k_3)^t} \quad t = \frac{T_H * k_3}{k_3 - T_L} \tag{8}$$

$$F(\theta) = (\theta - \theta_w)/(\theta_f - \theta_w) \tag{9}$$

where r_{smin} is the minimum stomatal resistance observed in optimal condition, i.e. none of the controlling variables are limiting. R_s is the incoming solar radiation (W m^{-2}), T_a the air temperature (°C), VPD the water vapour saturation deficit (kPa), θ_w the wilting point at 0–100 cm depth with a value of 0.11 cm^3 cm^{-3} in this study and $F(\theta)$ the normalized soil water factor. Four parameters (r^c_{smin}, k_1, k_2 and k_3) can be obtained by the least squares fitting method. The values were adopted as 20 s m^{-1}, 5 W m^{-2}, −3.25 kPa^{-1}, 10 °C for maize, and 25 s m^{-1}, 10 W m^{-2}, 0.5 kPa^{-1}, 30 °C for vineyard, respectively.

The surface resistance also can be derived from the re-arranged PM equation:

$$r_s = \frac{C_p \rho_a \mathrm{VPD} + r_a \Delta (R_n - G)}{\gamma \lambda \mathrm{ET}_{EC}} - r_a\left(1 + \frac{\Delta}{\gamma}\right) \tag{10}$$

where $\lambda \mathrm{ET_{EC}}$ is the latent heat flux measured by eddy covariance system (W m^{-2}).

2.3. Evaluation of model performance

The model performance is evaluated based on a linear regression between estimated ($\lambda \mathrm{ET_i}$) and observed (O_i) λET, and a paired T statistic analysis. Also, root mean square error (RMSE) is included as follows (Poblete-Echeverr and Ortega-Farias, 2009):

$$\mathrm{RMSE} = \left\{\frac{1}{n}\sum_{i=1}^{n}(\lambda \mathrm{ET}_i - O_i)^2\right\}^{1/2} \tag{11}$$

3. Materials and methods

3.1. Experimental site and description

The experiment was conducted at Shiyanghe Experimental Station for Water-saving in Agriculture and Ecology of China Agricultural University, located in Wuwei City, Gansu Province of northwest China (N 37°52′, E 102°50′, altitude 1581 m) during April 16th to September 23rd, 2007 and May 3rd to September 24th, 2008. The experimental site is located in a typical continental temperate climate zone where mean annual temperature is 8 °C, annual accumulated temperature (>0 °C) 3550 °C, annual precipitation 164 mm, mean annual pan evaporation approximate 2000 mm, the average annual duration of sunshine 3000 h, and the average number of frost free days 150 d. The groundwater table is 40–50 m below the ground surface. The soil is irrigated desert soil (Siltigic-Orthic Anthrosols) and soil texture is sandy loam, with

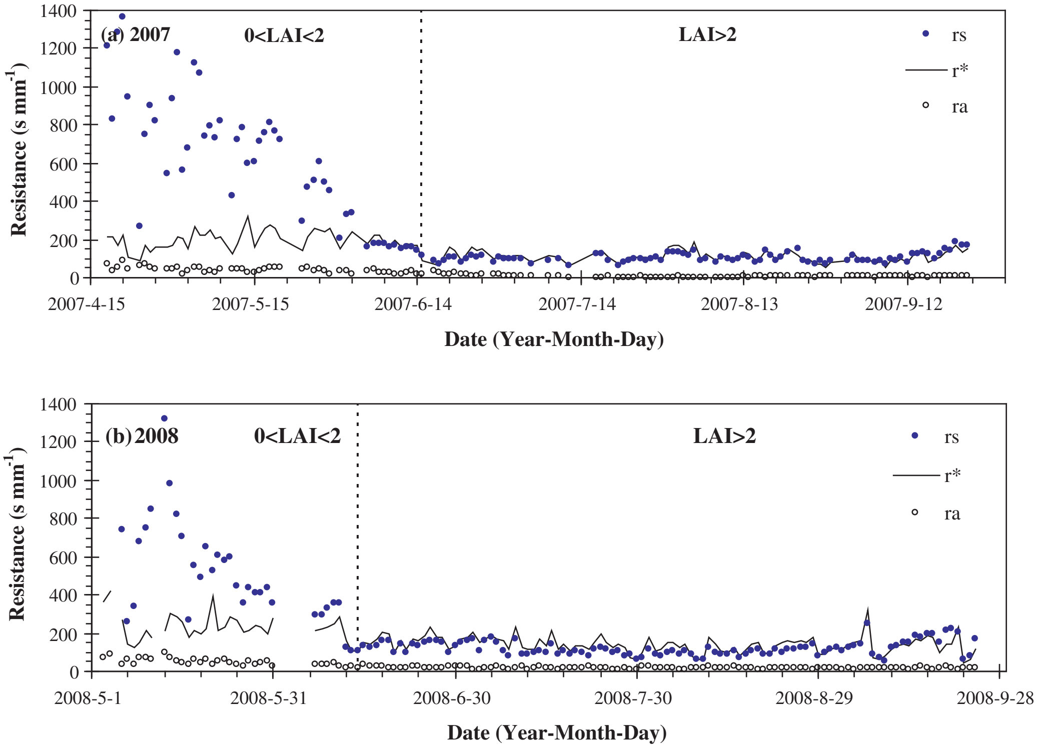

Fig. 1. Seasonal variation of resistance parameters during different leaf area index stages. r_s is the surface resistance, r^* is the climatic resistance and r^* is the aerodynamic resistance. r_s was obtained by the re-arranged Penman–Monteith model (Eq. (5)).

a mean dry bulk density of 1.43 g cm^{-3} and volumetric soil water content at a field capacity of 0.29 cm^3 cm^{-3}. These issues have been described in detail in Li et al. (2008).

Measurements in the maize field: Spring maize was planted with row spacing of 40 cm and plant spacing of 30 cm. The plant density was about 66,000 plants per hectare and total area was

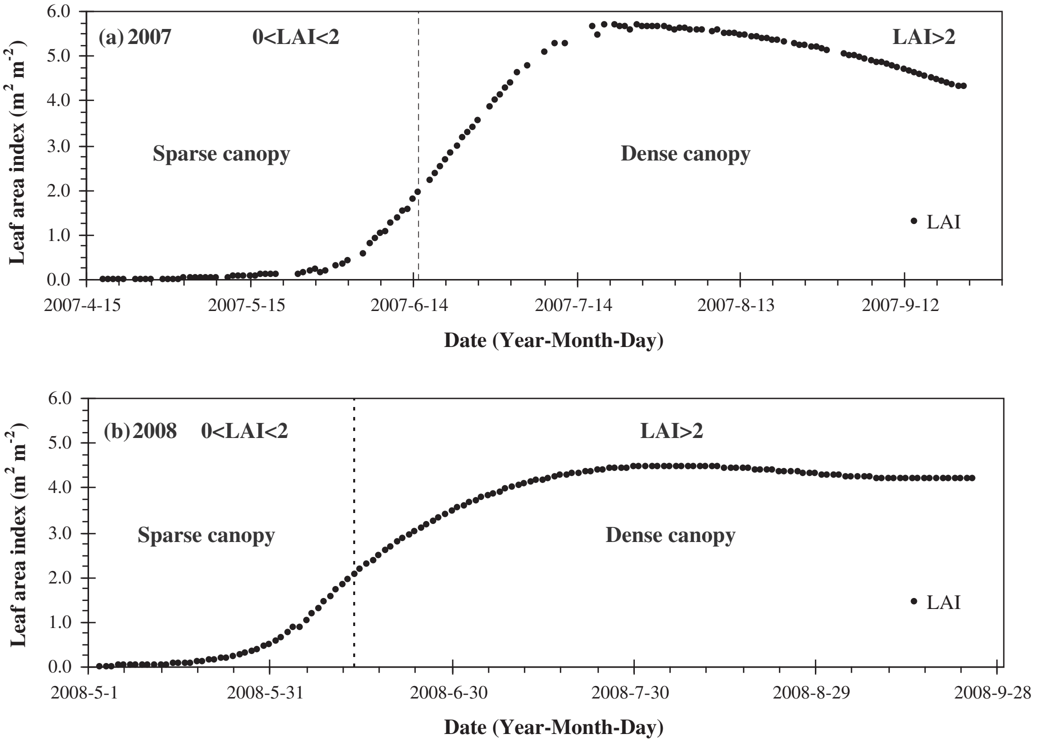

Fig. 2. Seasonal variation of maize leaf area index (LAI) during 2007 and 2008.

about 39 h m^2. Crops were also extensively cultivated in surrounding fields. The experimental field was irrigated four times on June 3rd, July 13th, August 3rd and August 22nd with total irrigation water of 320 mm in 2007, and on June 14th, July 11th, July 28th and August 28th with total 420 mm in 2008. The border irrigation was adopted to deliver water in the field. The precipitation was 153 mm and 71 mm during the whole growing stage in the 2 years. The main root located at depth of 0–60 cm.

An open-path eddy covariance (EC) system was installed in the northwest of the maize field. The sensor height was adjusted weekly to keep the relative height of 1.0 m between sensors and maize canopy constant. Maize is the principal crop cultivated in the surrounding region, and its planting area is large enough to provide adequate fetch length for EC measurement. The minimum fetch length is 100 m. The EC system consisted of a 3-D sonic anemometer/thermometer (model CSAT3), a Krypton hygrometer (model KH20) and a temperature and humidity sensor (model HMP45C). Model CSAT3 and KH20 measured vertical fluctuations of wind, temperature and water vapour density at 0.1 s intervals, and temperature and humidity at 10 min intervals. Net radiation (R_n) was measured by a net radiometer (model NR-LITE, Kipp & Zonen, Delft, Netherlands) at a height of 1.5 m above the canopy. Two soil heat flux plates (model HFP01, Hukseflux, Netherlands) were used to measure soil heat flux. All the sensors were connected to a data logger (model CR5000, Campbell Scientific Inc., USA), and the 10-min statistics were computed. Measurements were made from April 16th to September 23rd, 2007 and March 3rd to September 24th, 2008 (Li et al., 2008).

Sixteen PVC access tubes with the depth of 1.2 m were evenly installed in the experimental site to determine soil volumetric water content using a monitoring system using the RF capacitance method (Diviner 2000, Sentek Pty Ltd., Australia). Measurements were made at 0.1 m intervals with maximal soil depth of 1.0 m at 3–7 days intervals. Data were collected from a network of access tubes installed at selected sites. Measurements were taken more frequently before and after irrigation and rainfall. The measurements were calibrated by oven drying method.

Ten maize plants were randomly selected to measure leaf length and width weekly during the growing season, and then leaf area was calculated by summing lamina length × maximum width of each leaf and multiplied by a factor of 0.74 (Li et al., 2008).

Measurements in the vineyard: Measurements in the vineyard were made in a field with a length of 1650 m and a width of 1400 m in 2008. The area was planted with grapevines (Vitis vinifera L. cv Merlot Noir) in 1999 with row spacing of 270 cm and plant spacing of 100 cm. The trellis for grapevine was 1.5 m height. The vine soil texture is sandy loam, with a mean dry bulk density of 1.47 g cm^{-3}, porosity of 52%, field capacity of 0.35 cm^3 cm^{-3} and a permanent wilting point of 0.12 cm^3 cm^{-3} for the 0–100 cm layers. The vineyard was furrow irrigated four times over the whole growing season.

Another eddy covariance system (Campbell Scientific Inc., USA) was installed at 4.2 m above the ground at the northwest of vineyard. Measurements were made continuously from May 1 to October 11 in 2008. Net radiation (R_n) was measured by a net radiometer (model NR-LITE, Kipp & Zonen, Delft, Netherlands) at a height of 4.5 m above the ground. Four soil heat flux plates (model HFP01, Hukseflux, Netherlands) were used to measure soil heat flux. Soil moisture content was measured using portable device (Diviner 2000, Sentek Pty Ltd., Australia). Fifteen PVC access tubes were evenly inserted in the soil in the ditch, shaded and non-shaded parts of the ridge, respectively. Furthermore, soil sample for 0–50 mm and 50–100 mm layers near each PVC access tube was taken using auger to measure soil water content. Leaf area index was measured every 10 days using AM300 portable leaf area meter (ADC BioScientific Ltd., UK), respectively.

3.2. Eddy covariance data corrections

The procedures conducted for correcting the eddy covariance measurements included: (1) 10-min interval for eddy flux

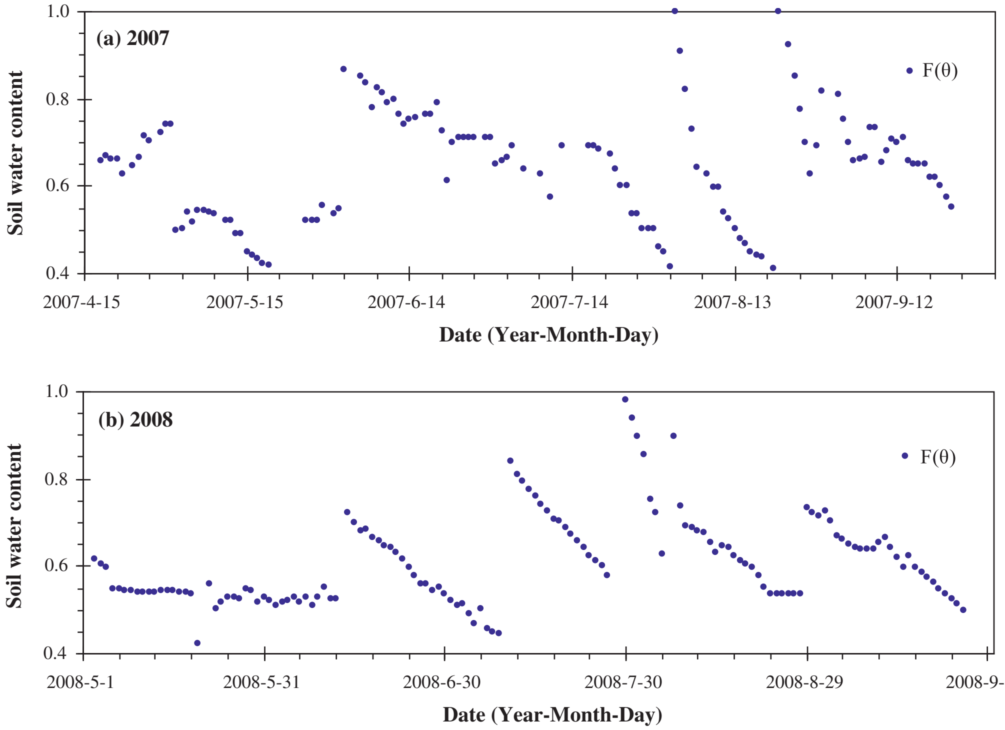

Fig. 3. Seasonal variation of the normalized soil water content during 2007 and 2008. The normalized soil water content is calculated as: $F(\theta) = (\theta - \theta_w)/(\theta_f - \theta_w)$, where θ is the measured soil water content, θ_f is the field capacity, θ_w is the wilting coefficient.

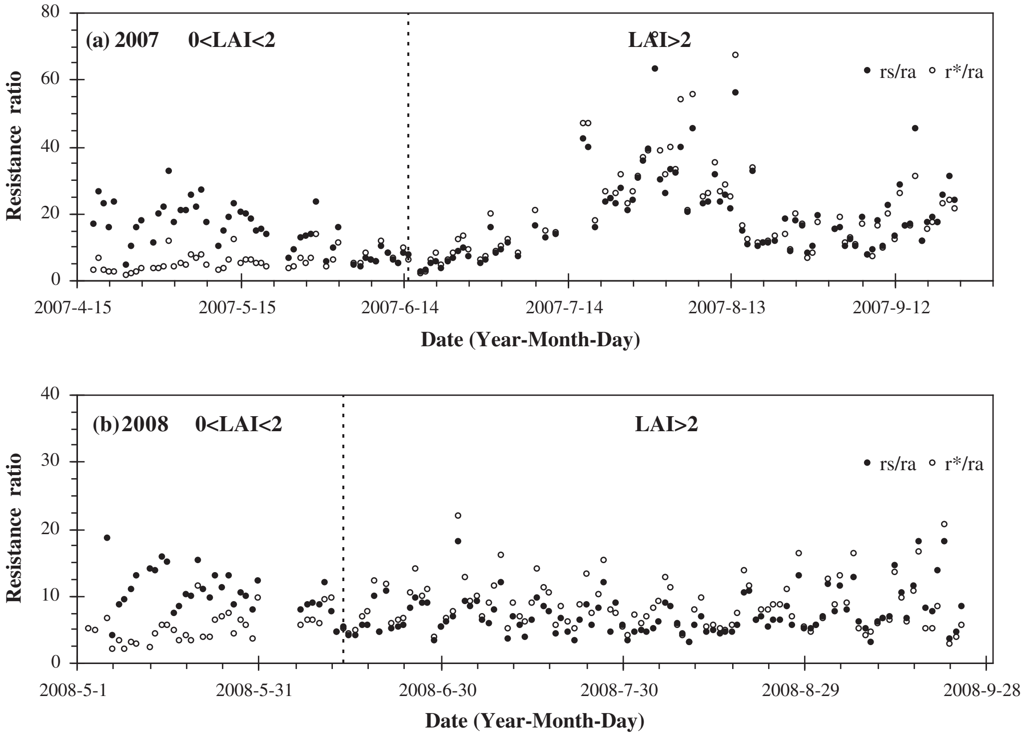

Fig. 4. Seasonal variation of the ratio of surface resistance to aerodynamic resistance (r_s/r_a), the ratio of climatic resistance to aerodynamic resistance (r^*/r_a) during different LAI stages. r_s was obtained by the re-arranged Penman–Monteith model (Eq. (5)).

computation (Twine et al., 2000); (2) The signal asynchrony correction (Wolf et al., 2008); (3) The oxygen-correction proposed by Tanner and Greene (1989); (4) Planar fit method for coordinate rotation (Finnigan et al., 2003; Paw et al., 2000); (5) Density correction according to the method of Webb et al. (1980); (6) Filling data gaps using the mean diurnal variation (MDV) method (Falge et al., 2001).

In this study, sum of maize and vineyard (λET + H) accounted for about 93% and 95% of available energy over whole experimental period, respectively. For the daytime EC-based data, the measured energy budget components were forced to close using "Bowen-ratio closure" method proposed by Twine et al. (2000), assuming that Bowen-ratio is correctly measured by the EC system. But for the nighttime EC-based data, especially when the available energy was below zero, another method- the "residual–λET closure" method also proposed by Twine et al. (2000) was adopted to close the energy balance in our study. This method assumed that the EC-based H was accurately measured, and solved for λET as the residual to the energy-balance equation. After forcing the energy balance to be closed, the λET data by the EC system (λET_{EC}) were adopted in the following analysis.

4. Results

4.1. Variation of leaf area index, soil moisture and resistance parameters in the maize field

In order to reveal the relationship between surface resistance and environmental factors, the variation patterns of resistance parameters, leaf area index (LAI) and soil moisture were investigated primarily.

Fig. 1 shows the seasonal variation of the maize surface resistance (r_s), climatic resistance (r^*) and aerodynamic resistance (r_a) during the whole experimental period. The maize surface resistance r_s was obtained by the re-arranged PM equation, as showed

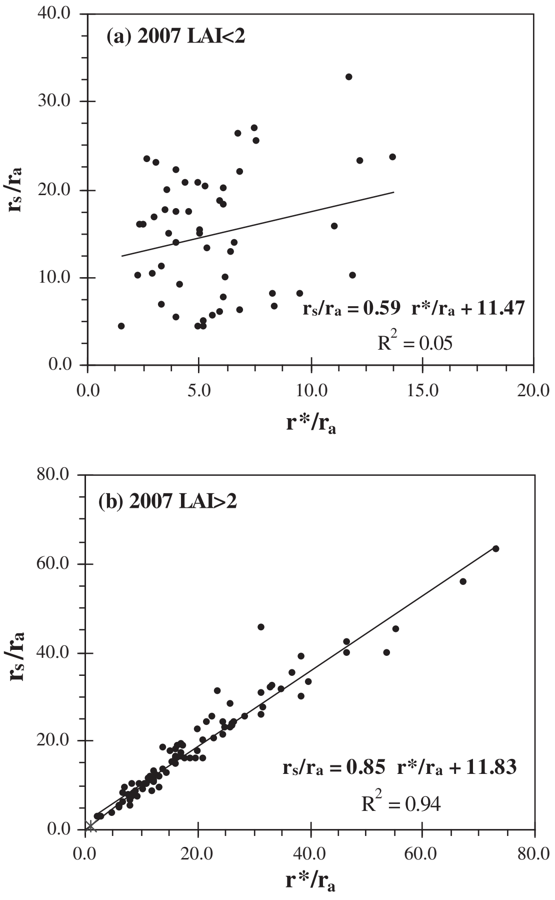

Fig. 5. Relationship between the ratio r_s/r_a and the ratio r^*/r_a during different LAI stages in 2007. r_s was obtained by the re-arranged Penman–Monteith model (Eq. (5)).

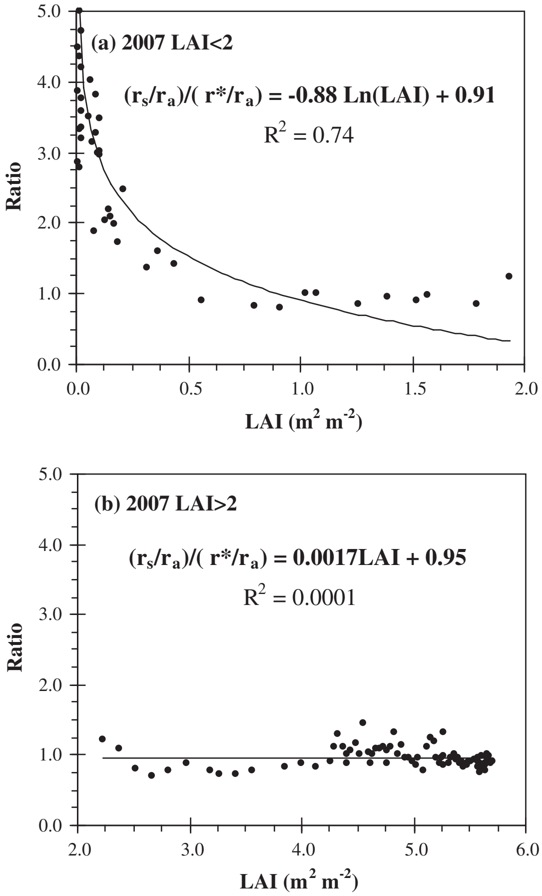

Fig. 6. Response of the ratio r_s/r^* to LAI during different LAI stages in 2007. r_s was obtained by the re-arranged Penman–Monteith model (Eq. (5)).

in Eq. (10). Maize r_s declined remarkably with the growth of crop during the early stage. After LAI exceeded 2, the maize canopy fully covered the soil substrate, maize r_s varied from 60 to 180 s mm^{-1} with an average value of 104 s mm^{-1} in 2007, and from 50 to 250 s mm^{-1} with a mean value of 120 s mm^{-1} in 2008, respectively.

Compared to maize r_s, maize r^* showed a slight variation in both years. It changed from 50 to 320 s mm^{-1} with an average of 143 s mm^{-1} in 2007, and from 50 to 400 s mm^{-1} with an average of 160 s mm^{-1} in 2008, respectively. Under the low LAI stage, maize r^* was significantly lower than the value of r_s. When LAI was above 2, the values of the both resistance parameters were close.

Compared to maize r_s and r^*, maize r_a was obviously lower than the both parameters. The lowest maize r_a value was 2.15 s mm^{-1} on July 30th while the peak value was 85 s mm^{-1} on April 21st in 2007. In 2008, maize r_a varied from 8 to 95 s mm^{-1} with a mean of 25 s mm^{-1}.

The seasonal variation pattern of maize LAI in 2007 and 2008 is showed in Fig. 2. Maize LAI presented a regular parabolic curve. In the study, we adopted "LAI = 2" as the threshold of the sparse canopy and dense canopy according to our experimental observation. When LAI was lower than 2, the vegetation is considered as a typical sparse canopy and the soil water was mainly consumed by soil evaporation rather than crop transpiration. On the contrary, when LAI exceeded 2, the maize canopy fully covered the soil substrate, soil evaporation was significantly reduced and the soil water was predominantly consumed by crop transpiration.

The variation in normalized soil water content of the maize field is showed in Fig. 3. The fluctuation in soil water content was mainly controlled by the components such as irrigation, precipitation and evapotranspiration. The farmland was irrigated four times on June 3rd, July 13th, August 3rd and August 22nd in 2007, and also four times on June 14th, July 11th, July 28th and August 28th in 2008. Soil moisture showed strong variation, especially after irrigation as depicted in Fig. 3.

4.2. Response of surface resistance to climatic resistance under different LAI and soil moisture conditions

To quantify the regulation of climatic resistance, LAI and soil moisture on surface resistance, the study analyzed the response pattern of maize surface resistance to climatic resistance under different LAI and soil moisture period using the maize data of 2007.

The seasonal fluctuations in the ratio of r_s and r_a and the ratio of r^* and r_a are presented in Fig. 4. When LAI was lower than 2, the variation trends of r_s/r_a and r^*/r_a were different, but they were similar after LAI exceeded 2 in both years. Fig. 5 presents the relationship between r_s/r_a and r^*/r_a under different LAI period in 2007. When LAI was lower than 2, there was no clear relationship between r_s/r_a and r^*/r_a. The regression equation was $r_s/r_a = 0.59\,r^*/r_a + 11.47$ with a low determination coefficient R^2 of 0.05. However, r_s/r_a showed a significant relationship with r^*/r_a after LAI exceeded 2, with a regression equation of $r_s/r_a = 0.85\,r^*/r_a + 11.83$, and a high R^2 of 0.94. The linear relationship was also indicated by many previous studies, such as Katerji and Rana (2006) and Katerji et al. (2011).

In order to understand the control on surface resistance, we also investigated the relationship between the ratio r_s/r^* and LAI during

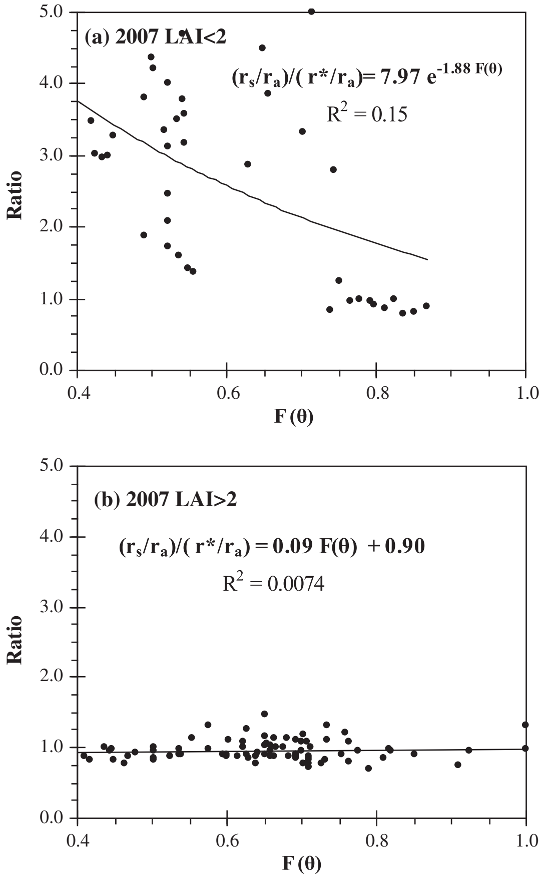

Fig. 7. Response of the ratio r_s/r^* to the normalized soil water content during different LAI stages in 2007. r_s was obtained by the re-arranged Penman–Monteith model (Eq. (5)).

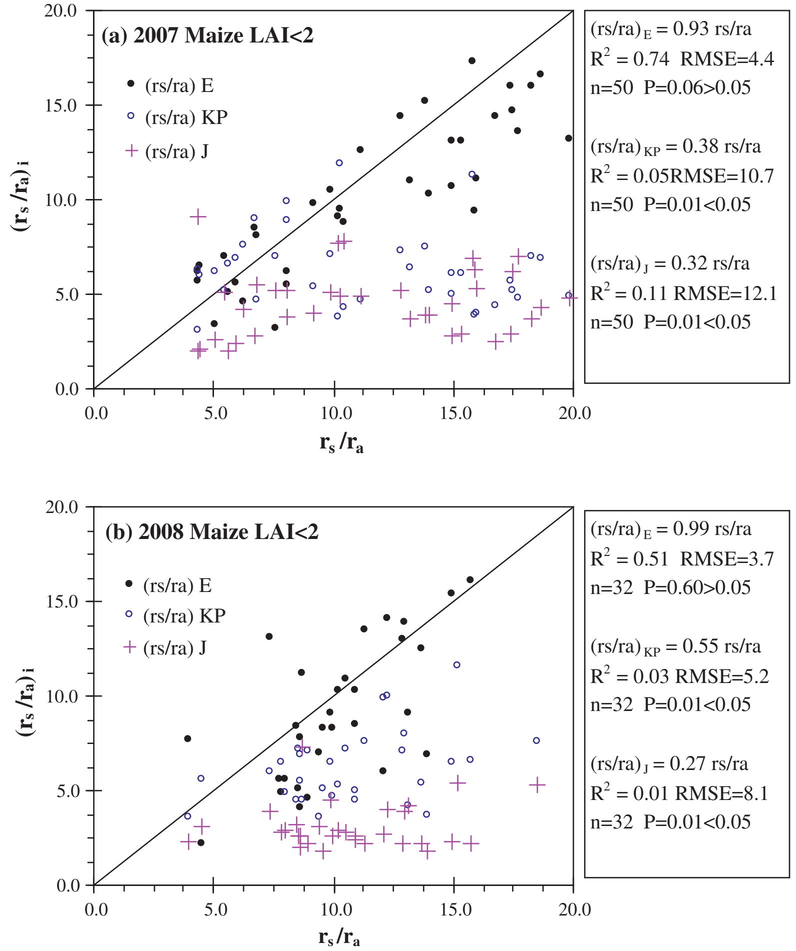

Fig. 8. Comparison of the maize r_s/r_a estimated by our surface resistance ($(r_s/r_a)_E$) and the KP ($(r_s/r_a)_{KP}$) models and that obtained by re-arranged PM equation under the stage of LAI less than 2 in 2007 and 2008.

different growing stages in 2007, as shown in Fig. 6. r_s/r^* declined logarithmically along with the increase of LAI in the early stage of crop. The regression equation was $(r_s/r_a)/(r^*/r_a)$ = - $-0.88\,\mathrm{Ln(LAI)} + 0.91$ with a R^2 of 0.74. However, the ratio r_s/r^* was close to 1, and insignificant effect of LAI on the ratio r_s/r^* was found when LAI exceeded 2.

The study further analyzed the control of soil moisture on the ratio of r_s/r^* under different growing stages in 2007 (Fig. 7). An exponential function was found between r_s/r^* and the normalized soil water content in the early stage in 2007. The equation was $(r_s/r_a)/(r^*/r_a) = 7.97\,\mathrm{e}^{-1.88F(\theta)}$ with a R^2 of 0.74. When LAI exceeded 2, the ratio r_s/r^* became a constant and did not change with soil moisture.

Using the 2007 data and results of our study, we further constructed a semi-theoretical surface resistance model after considering the coupled effects of canopy development and soil moisture:

$$\frac{r_s}{r_a} = \exp(-c_1 F(\theta) + c_2).(-c_3 \mathrm{Ln(LAI)} + c_4).\frac{r^*}{r_a} \quad 0 < \mathrm{LAI} < 2 \qquad (12)$$

where r_s is the surface resistance estimated by our model (s m^{-1}), r^* the climatic resistance (s m^{-1}), r_a the aerodynamic resistance (s m^{-1}), $F(\theta)$ the normalized soil water content, LAI leaf area index (m^2 m^{-2}). c_1, c_2, c_3, and c_4 are empirical coefficients. In the study, the values of these coefficients were 0.15, −0.10, 0.82, 1.20 for maize and 0.43, 0.10, 0.68, 1.46 for vineyard, respectively, which were obtained by the least squares fitting method.

4.3. Evaluation of models in estimating surface resistance and ET under the sparse canopy condition

In order to examine the reliability of the surface resistance model, the comparisons between our model (Eq. (12)) and the widely used KP and Jarvis models (Eqs. (4) and (5)) were conducted over the sparse maize field and vineyard, which will be analyzed as follows.

Fig. 8 shows the comparison of the maize r_s/r_a estimated by our surface resistance ($(r_s/r_a)_E$), the KP model ($(r_s/r_a)_{KP}$), and the Jarvis model ($(r_s/r_a)_J$) and that obtained by re-arranged PM equation (r_s/r_a) under the stage of LAI less than 2 in 2007 and 2008. The KP model significantly underestimated r_s/r_a in both years, with a regression of $(r_s/r_a)_{KP} = 0.38\ r_s/r_a$, a R^2 of 0.05, a RMSE of 10.7 in 2007 and a regression of $(r_s/r_a)_{KP} = 0.55\ r_s/r_a$, a R^2 of 0.03, a RMSE of 5.2 in 2008, respectively. The paired T statistic analysis indicates that the estimated r_s/r_a using the KP model was significantly different from r_s/r_a yielded by PM equation in both years, for the P values were lower than 0.05. The Jarvis model underestimated r_s/r_a by 68% in 2007 and 73% in 2008, respectively. While the surface resistance model only underestimated r_s/r_a by 7% in 2007 and by 1% in 2008 with lower RMSE and higher R^2, *P* values compared to the KP and Jarvis models.

Fig. 9 shows the seasonal variation of maize ET estimated by the surface resistance model combined with the PM equation ($\lambda \mathrm{ET_E}$), the KP model combined with PM equation ($\lambda \mathrm{ET_{KP}}$), and the Jarvis

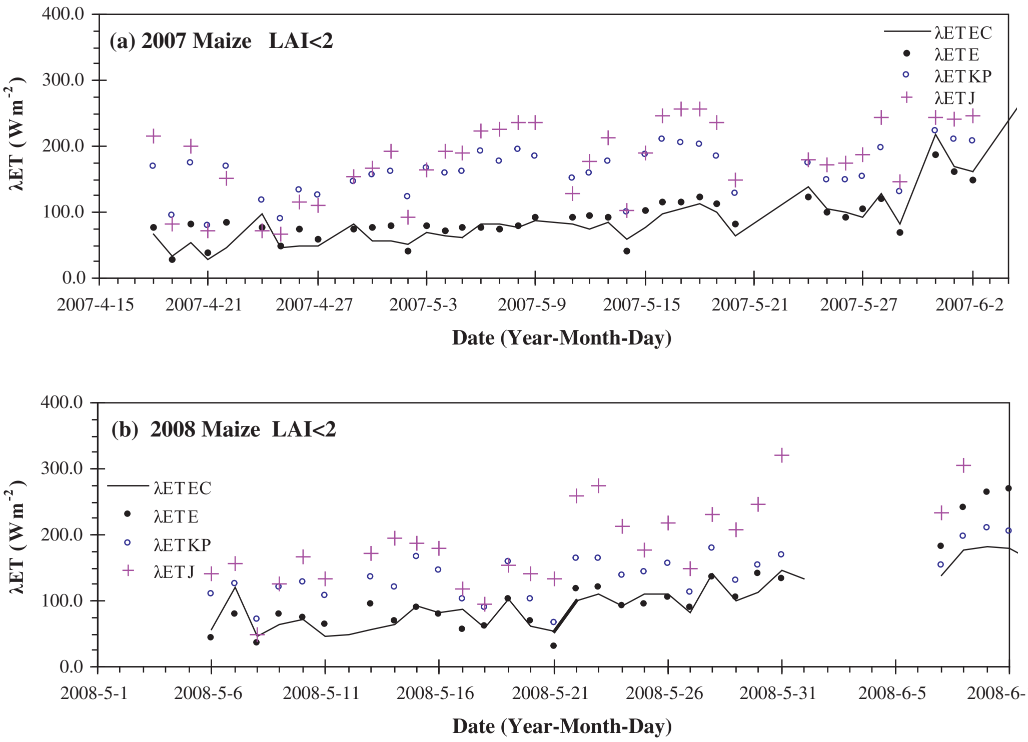

Fig. 9. Seasonal variation of maize ET estimated by the surface resistance model combined with the PM equation (λET_E), the KP model combined with the PM equation (λET_{KP}) and that measured by eddy covariance (λET_{EC}) during the stage of LAI less than 2 in 2007 and 2008.

model combined with PM equation (λET_J) and that measured by eddy covariance (λET_{EC}) during the stage of LAI less than 2 in both years. The KP model overestimated maize ET by 15% in 2007 and by 23% in 2008, with a R^2 of 0.62, a RMSE of 74 W m^{-2} in 2007 and a R^2 of 0.23, a RMSE of 43 W m^{-2} in 2008. The P values in both years were lower than 0.05, indicating that λET_{KP} was significantly higher than λET_{EC} (Fig. 10). The Jarvis model overestimated maize ET by 36% in 2007 and by 123% in 2008, with a R^2 of 0.58, a RMSE of 92 W m^{-2} in 2007 and a R^2 of 0.50, a RMSE of 166 W m^{-2} in 2008. Compared to KP and Jarvis models, the surface resistance model yielded only overestimated maize ET by 4% in 2007 and by 19% in 2008, with lower RMSE and higher R^2 in both years. The P values were higher than 0.05, which implies that λET_E was in good agreement with λET_{EC} (Fig. 10).

The comparisons of vineyard ET estimated by the surface resistance, KP and Jarvis models and that measured by eddy covariance during the stage of LAI less than 2 in 2008 are showed in Figs. 11 and 12. The KP model overestimated vineyard ET in the early crop stage, and underestimated ET in the middle to later stages. For the whole period, the KP model underestimated ET by 10% on average with a R^2 of 0.47, a RMSE of 50 W m^{-2}. The Jarvis model severely underestimated ET in the early crop stage, and underestimated ET by 8% on average with a R^2 of 0.58, a RMSE of 50 W m^{-2}. Compared to KP and Jarvis models, the surface resistance model performed better in estimating vineyard ET and only underestimated ET by 3% with higher R^2, P value and lower RMSE (Fig. 12).

5. Discussion

5.1. Response of surface resistance to climatic, crop and soil variables

Results of this study indicate that maize r_s/r^* showed a logarithmic relationship with LAI when LAI was lower than 2, and it varied slightly when LAI exceeded 2. Such results were mainly due to that (1) the surface resistance would decrease rapidly as the leaf area increases during the initial stage (Fig. 1). However, the climatic resistance mainly depends on the meteorological factors, such as radiation, temperature and VPD. It varied gently in the initial stage (Fig. 1). Thus the ratio r_s/r^* declined significantly in this stage. (2) After LAI was above 2, the canopy resistance was the main component of surface resistance, and the variation in canopy resistance was predominantly regulated by micro-meteorological factors, such as radiation, air temperature and humidity, thus the fluctuation in surface resistance was closely linked to climatic resistance, and the ratio r_s/r^* was not sensitive to variation in LAI over this period. These results were in line with Monteith (1965), Katerji and Perrier (1983), Alves and Pereira (2000), Katerji and Rana (2006), Irmak and Mutiibwa (2010), Katerji et al. (2011) and Rana et al. (2011), which indicate that the ratio r_s/r^* was approximately constant during the dense canopy stage.

The study also shows that r_s/r^* presented an exponential relationship with soil moisture when LAI was lower than 2, while it fluctuated slightly when LAI exceeded 2. During the initial stage of crop, soil evaporation accounted for most of total evapotranspiration, while soil evaporation was highly sensitive to the variation in soil moisture. The soil resistance decrease intensively along with the rise of soil moisture, which has been revealed by many studies (Stewart, 1988; Lhomme, 2001). When LAI exceeded 2, the crop transpiration became the critical component of total evapotranspiration, while crop transpiration was mainly determined by the combined effects of LAI, radiation, air temperature, water vapour deficit and soil moisture. When the normalized soil moisture exceeded 0.5, the crop can absorb water without stress. Thus r_s/r^* was nearly constant when LAI exceeded 2, as shown in Fig. 7b.

5.2. Feasibility of the surface resistance model in estimating crop ET over the low LAI condition

This study confirmed that the surface resistance model significantly improved the performance in estimating maize and

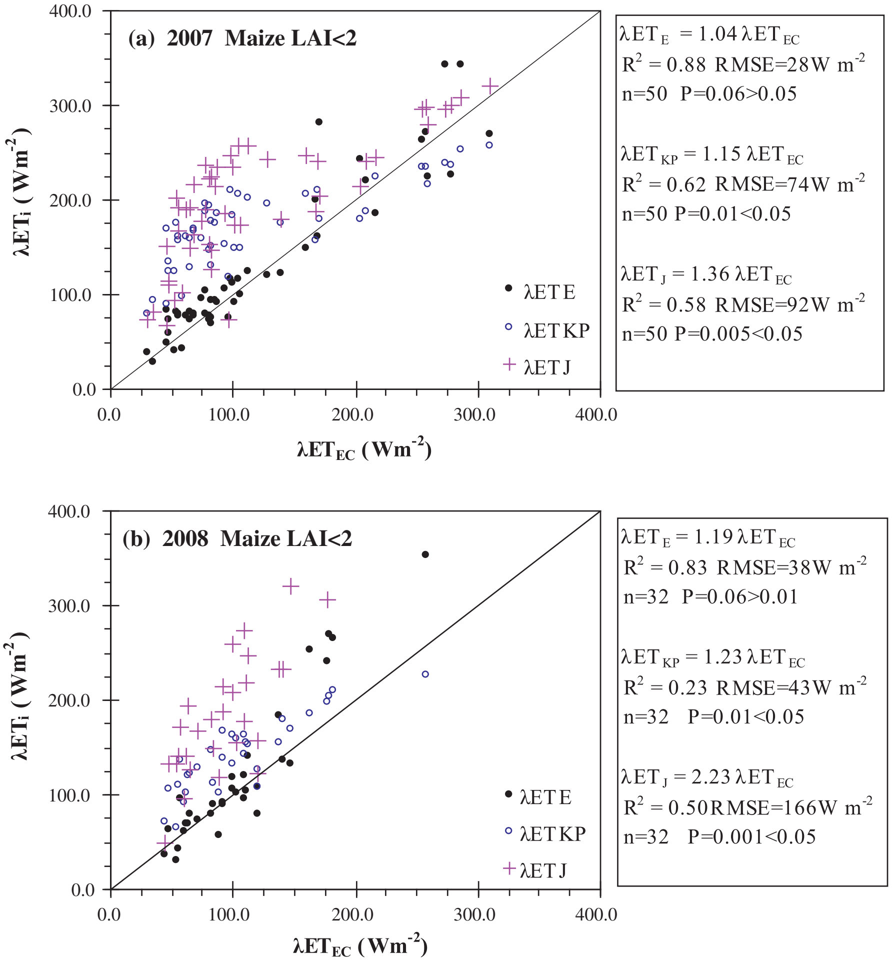

Fig. 10. Comparison of maize ET estimated by the surface resistance model combined with PM method (λET_E), the KP model combined with PM method (λET_{KP}) and that measured by using eddy covariance (λET_{EC}) and under the stage of LAI below 2 in 2007 and 2008.

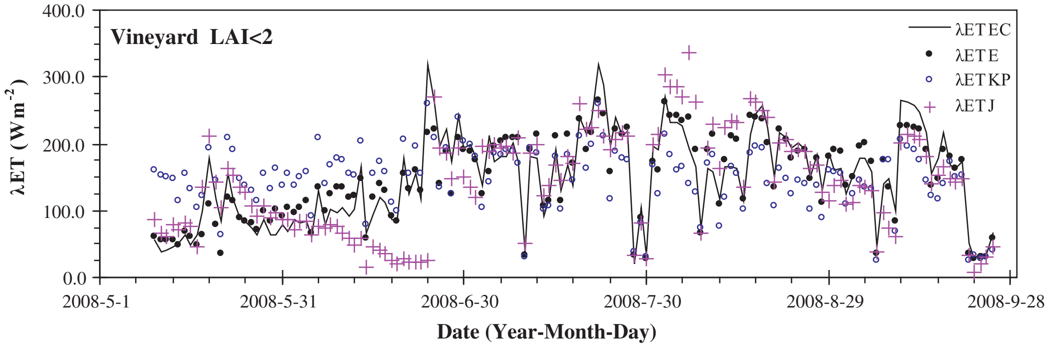

Fig. 11. Seasonal variation of vineyard ET estimated by the surface resistance model combined with the PM equation (λET_E), the KP model combined with the PM equation (λET_{KP}) and that measured by eddy covariance (λET_{EC}) during the stage of LAI less than 2 in 2008.

vineyard ET over the low LAI stage against the widely used KP and Jarvis models. Compared to these model, the resistance model considered the coupled effects of variability in climatic condition, canopy development and soil water on ET process, which can estimate the mean surface resistance of water vapour overcoming the underlying surface, thus it is especially suitable for estimating the crop ET under partial canopy conditions. The KP and Jarvis models can accurately estimate canopy resistance, but it cannot estimate the resistance of the whole underlying surface, especially during the partial canopy conditions, though the models performed well when the canopy fully covered the soil substrate in conjunction with PM model (Alves and Pereira, 2000; Chen et al.,

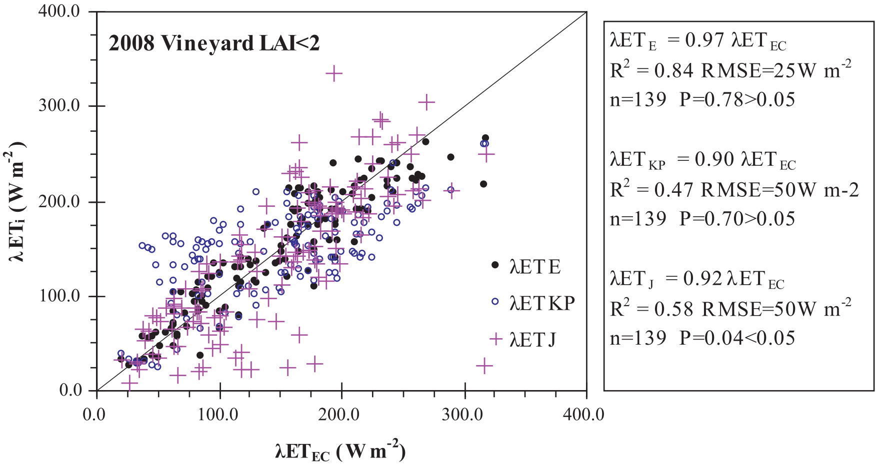

Fig. 12. Comparison of vineyard ET estimated by the surface resistance model combined with PM method (λET_E), the KP model combined with PM method (λET_{KP}) and that measured by using eddy covariance (λET_{EC}) and under the stage of LAI below 2 in 2008.

1996; Irmak and Mutiibwa, 2010; Katerji and Perrier, 1983; Katerji and Rana, 2006; Katerji et al., 2011; Rana et al., 2011; Todorovic, 1999).

Though the surface resistance model is semi-empirical method and need calibration, it provides a simple approach to calculate surface resistance for simulating daily vegetation ET over the low LAI period.

6. Conclusions

The r_s/r^* exhibits a logarithmic relationship with LAI and an exponential function with soil moisture when LAI was below 2, while the ratio r_s/r^* was nearly constant and not sensitive to variation in LAI and soil moisture when LAI exceeded 2. Based on these observations, a surface resistance model was constructed and validated over the sparse maize field and vineyard. After considering the combined effect of climatic, crop and soil factors, the surface resistance model significantly improved the performance in estimating sparse vegetation ET against the widely used KP and Jarvis models. The KP model overestimated maize λET by 15% in 2007 and 23% in 2008, and underestimated vineyard ET by 10% in 2008. The Jarvis model overestimated maize λET by 36% in 2007 and 123% in 2008, and underestimated vineyard ET by 8% in 2008. But the surface resistance model only overestimated maize λET by 4% and 19% in both years, and underestimated vineyard ET by 3% in 2008.

This study quantified the response pattern of surface resistance to climatic, crop and soil factors, and provided a practical method to estimate daily surface resistance for predicting ET under the partial canopy condition. For the limitation of the study to the general climate of the study site, ET measurement error by the EC systems for the specific site conditions, and effects of crop conditions found for the two crops studied, validation of the model over more variety of climatic and crop conditions still remains to be investigated to enhance the utility of the model.

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