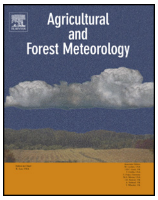
Agricultural and Forest Meteorology 208 (2015) 1–15

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet



Comparison of several surface resistance models for estimating crop evapotranspiration over the entire growing season in arid regions

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ARTICLE INFO

Article history:
Received 26 May 2014
Received in revised form 20 March 2015
Accepted 2 April 2015
Available online 21 April 2015

Keywords:
Canopy resistance
Evapotranspiration
Maize
Partial canopy
Penman–Monteith model
Vineyard

ABSTRACT

How to improve the reliability and accuracy of the single-layer Penman–Monteith (PM) model for estimating crop evapotranspiration (ET) over the entire growing season in arid regions, is still of great challenge for hydrologists. In the study, we developed a coupled surface resistance model (CO) after taking the combined restriction effect of vegetation and soil layers on ET into account. The CO model was compared with the modified Shuttleworth–Wallace model (MSW), and the traditional Jarvis, Katerji and Perrier, Irmak and Mutiibwa, Stannard, Leuning, Shuttleworth and Gurney, Massman, Garcia-Santos, Ortega-Farias, and Todorovic canopy resistance models over the partial and dense canopy stages. Maize and vineyard ET measured by the eddy covariance method during 2007–2013 were used to examine the model performance. Results indicate that the PM equation combined with the coupled surface resistance model yielded the lowest root mean square error against the other methods during all the years under either partial or dense canopy stages. Especially, the PM–CO method also performed superiorly against the dual-layer MSW model during the partial maize canopy period. After considering the meteorological, physiological and soil controls on surface resistance simultaneously, the coupled surface resistance model improved the accuracy significantly against the traditional canopy resistance models, and enhanced the reliability of the PM model for estimating partial canopy ET. Thus the coupled surface resistance equation integrated with PM model is recommended to estimate crop ET for the entire growth stages in arid regions.

1. Introduction

Precipitation resource distributes non-uniformly in the world. For the limited precipitation, the arid regions exist extensively in Africa, Asia, Oceania, America and Europe. In arid regions, agricultural crops frequently suffer from drought stress. Numerous researchers have demonstrated that the soil water stress would exert great impact on canopy resistance and evapotranspiration (ET). However, how to quantify the effect of soil water status on canopy resistance and ET accurately, is still of great challenge and interest to hydrologists (Rana and Katerji, 2000; Zhang et al., 2001; Farahani et al., 2007; Leuning et al., 2008; Jung et al., 2010; Bastiaanssen et al., 2012).

Additionally, the growth and development of agricultural crops should experience a shift of partial canopy stage to full canopy stage, such as maize, wheat, soybean and cotton. Under the full canopy condition, crop transpiration accounts for the predominant role in ET. Thus the canopy resistance can be treated as the surface resistance, and the canopy resistance models combined with Penman–Monteith equation can give accurate ET estimations, such as the classical Jarvis model, the Katerji and Perrier model and etc. (Jarvis, 1976; Stewart, 1988; Lhomme, 2001; Katerji and Rana, 2006; Whitley et al., 2009; Katerji et al., 2011; Rana et al., 2011).

However, under the partial canopy stage, the soil layer and vegetation layer exert great regulation on water vapor transfer simultaneously. If we adopted the single-layer and widely used PM model to estimate ET, the mean surface resistance rather than canopy resistance should be considered and integrated with PM equation. In a latest paper of Matheny et al. (2014), they use the North American Carbon Program data set of latent heat flux measurements from 25 sites and predictions from 9 models to evaluate models' ability to resolve subdaily dynamics of transpiration. They found that majority of models have difficulty in resolving the dynamics of intradaily hysteresis for the errors in calculating surface resistance. Thus how to parameterize the mean surface resistance accurately still remains uncertain.

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http://dx.doi.org/10.1016/j.agrformet.2015.04.002
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Thus we attempted to construct a mean surface resistance model by coupling the Jarvis canopy resistance and soil resistance equations based on the resistance law of fluid transmission. The coupled surface resistance model was compared with the ten classical canopy resistance models, such as the Jarvis (JA), Katerji and Perrier (KP), Irmak and Mutiibwa (IM), Stannard (ST), Leuning (RL), Shuttleworth and Gurney (SG), Massman (MA), Garcıía-Santos (GA), Ortega-Farias (FA) and Todorovic (TD) canopy resistance models, and the modified Shuttleworth–Wallace (MSW) model. The measured maize and vineyard ET data using eddy covariance method during 2007–2013 were adopted to evaluate the performances of the dozen methods under the partial and dense canopy stages, in order to explore the optimal method for predicting crop ET over the entire growing season in arid regions.

2. Models

2.1. Penman–Monteith model

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

$$\lambda \mathrm{ET} = \frac{\Delta(R_\mathrm{n} - G) + C_p \rho_\mathrm{a} \mathrm{VPD}/r_\mathrm{a}}{\Delta + \gamma + \gamma \times r_s/r_\mathrm{a}} \tag{1}$$

where λ is the latent heat of vaporization (J kg^{-1}), λET the crop evapotranspiration (W m^{-2}), Δ the slope of the saturation water vapor 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 (Paulson, 1970; Businger et al., 1971; Massman, 1992):

$$r_a = \frac{\left[\ln(z/z_0) - \psi_h\right]\left[\ln(z/z_0) - \psi_\mathrm{m}\right]}{k^2 u} \tag{2}$$

where z is the reference height (m), z_0 the roughness length of the crop relative to momentum transfer (m), 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 frequently used for estimating atmospheric stability corrections. u is the wind speed at the reference height (ms^{-1}). According to Monteith (1965), z_0 can be calculated as 0.13 h_c, where h_c is the mean crop height (m).

The canopy resistance and surface resistance models were described as follows:

2.1.1. The Jarvis canopy resistance model (JA)

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

$$r^s_\mathrm{JA} = r_\mathrm{smin} / \left\{ f(R_\mathrm{s}) f(\mathrm{VPD}) f(T_\mathrm{a}) F(\theta) \mathrm{LAI} \right\} \tag{3}$$

$$f(R_\mathrm{s}) = \frac{R_\mathrm{s}(1000 + a_1)}{1000(R_\mathrm{s} + a_1)} \tag{4}$$

$$f(\mathrm{VPD}) = \exp(-a_2 \mathrm{VPD}) \tag{5}$$

$$f(T_\mathrm{a}) = \frac{(T_\mathrm{a} - T_L)(T_H - T_\mathrm{a})^t}{(a_3 - T_L)(T_H - a_3)^t} \quad t = \frac{T_H \times a_3}{a_3 - T_L} \tag{6}$$

$$F(\theta) = \frac{(\theta - \theta_w)}{(\theta_f - \theta_w)} \tag{7}$$

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 vapor 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.

2.1.2. The coupled surface resistance model (CO)

Different from previous approaches, we put forward the concept of the coupled surface resistance model. In this model, the surface resistance was treated as the mean resistance overcame by water vapor when passing canopy and soil. Furthermore, the coupled surface resistance model was built according to the resistance law of fluid transmission, Jarvis canopy resistance model and soil resistance model. According to the resistance law, the couple surface resistance can be expressed as follows (Li et al., 2013a):

$$r^s_\mathrm{CO} = \frac{1}{\left\{ (b_0 \mathrm{LAI} + b_1) \frac{1}{r^s_\mathrm{JA}} + b_2 \frac{1}{r^s_s} \right\}} \tag{8}$$

where r^s_CO is the coupled surface resistance which represents the mean resistance of the underlying surface, r^s_JA is the Jarvis canopy resistance and r^s_s is the soil resistance. The soil resistance can be calculated as (Tourula and Heikinheimo, 1998):

$$r^s_s = \frac{1}{\left[b_3 + \exp\left(b_4 + b_5 F(\theta) \right) \right]} \tag{9}$$

where b_0, b_1, b_2, b_3, b_4 and b_5 are empirical coefficients, which were calibrated by the measured data of maize in 2007 and that of the vineyard in 2009, respectively.

2.1.3. The Katerji-Perrier canopy resistance model (KP)

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

$$\frac{r^s_\mathrm{KP}}{r_\mathrm{a}} = c_1 \frac{r^*}{r_\mathrm{a}} + c_2 \tag{10}$$

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

$$r^* = \frac{\Delta + \gamma}{\Delta \gamma} \times \frac{C_p \rho_\mathrm{a} \mathrm{VPD}}{(R_n - G)} \tag{11}$$

where r_a is the aerodynamic resistance, r^* is the climatic resistance. c_1 and c_2 are empirical calibration coefficients requiring experimental determination. The model has been applied to calculate ET for different species: alfalfa, sunflower, grain sorghum, grass, soybean (Katerji and Perrier, 1983; Katerji and Rana, 2006).

2.1.4. The IM canopy resistance model (IM)

Irmak and Mutiibwa (2010) related the canopy resistance to a set of quantitative and independent variables and built a linear model as follows:

$$r^s_\mathrm{IM} = \exp\left[d_0 + d_1 R_n + d_2 T_\mathrm{a} + d_3 \mathrm{RH} + d_4 u + d_5 r_\mathrm{a} + d_6 \mathrm{LAI} + d_7 F(\theta) \right] \tag{12}$$

where $r_\mathrm{IM}{}^s$ is the canopy resistance estimated from IM model (s m^{-1}), R_n the net radiation (W m^{-2}), T_a the air temperature (°C), RH the relative humidity (%), u the wind speed, r_a the aerodynamic resistance (m s^{-1}), LAI the green leaf area index, $F(\theta)$ the normalized soil water content. d_0–d_7 are empirical coefficients.