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A dynamic surface conductance to predict crop water use from partial to full canopy cover

Risheng Ding[a], Shaozhong Kang[a,*], Yanqun Zhang[b], Xinmei Hao[a], Ling Tong[a], Sien Li[a]

[a] Center for Agricultural Water Research in China, China Agricultural University, Beijing 100083, China
[b] National Center of Efficient Irrigation Engineering and Technology Research-Beijing, China Institute of Water Resources and Hydropower Research, Beijing 100048, China

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ABSTRACT

The Penman–Monteith (P–M) equation has been widely used to predict crop water use or evapotranspiration (*ET*) due to its simplicity and biophysically robust framework. Surface conductance (G_s), a key variable reflecting crop physiological and soil physical responses to changing environment, often is a significant impediment to the practical application of the P–M equation. Here, we derived a dynamic biophysical model of G_s after incorporating the combined contributions of crop canopy and soil based on: (a) dynamic fraction of canopy cover; (b) response of stomata to radiation intercepted by crop canopy, vapor pressure deficit, and soil water availability in the root zone; and (c) soil evaporation coefficient affected by radiation reaching soil surface and soil moisture. The dynamic G_s model with the P–M equation can predict the variation of G_s and *ET* from partial to full canopy cover as crop growing. The model was parameterized by measurements using the eddy covariance technique over an irrigated maize field in 2009, and validated using independent data in 2010. We found good data-model agreements between *ET* predicted by the dynamic G_s model with P–M equation and measurements for both half-hourly and daily time-scales from partial to full canopy cover. The model also produced satisfactory estimation for soil evaporation. Therefore, the model is an alternative approach to predict *ET* using P–M equation for partial to full crop canopy cover.

1. Introduction

Accurate prediction of crop water use or evapotranspiration (*ET*) is required to better understand terrestrial hydrological cycles because *ET* is the largest term in the terrestrial water balance after precipitation (Leuning et al., 2008). The best and accurate prediction of *ET* is needed to develop precise irrigation scheduling and enhance water use efficiency in agricultural production because soil water depletion is mainly determined by the rate of *ET* (Ding et al., 2013; Pereira et al., 1999; Zhang et al., 2011a). The *ET* is also a major component of the energy balance, and directly determines the energy partitioning of the Earth's surface (Burba and Verma, 2005). Moreover, crop *ET* is synthetically determined by a number of interacting environmental and biological processes (Allen et al., 1998; Ortega-Farias et al., 2006). Nowadays, one key scientific challenge in the determination of *ET* is to develop mathematical approaches to predict water use through readily measurable meteorological and environmental variables.

Several models for calculating *ET* exist that range from relatively simple empirical to complex mechanistic ones (Monteith and Unsworth, 2008; Shuttleworth, 2007). The Penman–Monteith (P–M) equation is probably the most versatile and widely used mechanistic model for calculating *ET* over crop canopy (Katerji and Rana, 2006; Monteith and Unsworth, 2008; Ortega-Farias et al., 2006). This model treats the canopy as a big-leaf and calculates *ET* rate by combining the surface energy balance equation with a conductance-based mass flux equation (Katerji and Rana, 2006; Monteith, 1965). Many studies have indicated that the P–M equation is a biophysically sound and robust framework for predicting *ET* at different time-scales from hourly to monthly scales (Campbell and Norman, 1998; Monteith and Unsworth, 2008; Liu et al., 2012). The key parameter, bulk surface conductance (G_s), is needed as it is a key variable reflecting a crop's physiological and soil physical responses to changing environment (Ortega-Farias et al., 2006; Pereira et al., 1999; Rana et al., 2012). Yet, G_s cannot be easily obtained or directly measured, and therefore it is a significant impediment to the practical application of the P–M equation.

* Corresponding author. Fax: +86 10 62737611.
E-mail addresses: dingrsh@cau.edu.cn (R. Ding), kangsz@cau.edu.cn (S. Kang).

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Due to the lack of independent estimates of G_s, many researchers have assumed that G_s was equivalent to the integrated leaf stomatal conductance, g_s, weighted by leaf area and adjusted by the environmental variables (Campbell and Norman, 1998; Irmak et al., 2008). The g_s at the single leaf-level is determined through the Jarvis or Ball-Berry type model, and then scaled-up to G_s at the canopy level (Irmak et al., 2008; Zhang et al., 2011b). Generally, the scaled-up G_s is compared to G_s derived by inverting the P–M equation when *ET* and the meteorological variables measured over the crop canopy were known inputs (Ortega-Farias et al., 2006; Rana et al., 2012). In this case, G_s not only represents the variations of the physiological stomatal conductance, but also includes nonlinear physical effects of soil moisture and canopy turbulence (Paw U and Meyers, 1989; Raupach and Finnigan, 1988). Thus, a correction of G_s can be necessary, in particular for partial canopy cover or sparse canopy since soil evaporation provides another evaporating source and should be viewed as being in parallel with the crop transpiration; thereby enhancing G_s and *ET* (Baldocchi and Meyers, 1998; Kelliher et al., 1995; Shuttleworth and Wallace, 1985). Although Shuttleworth and Wallace (1985) described a well-known model with a separate treatment of soil and vegetation evaporation for sparse canopy, its practical application requires specifying five aerodynamic and surface conductances that are difficult to determine (Kool et al., 2014). In addition, some studies have developed empirical or semi-empirical models of G_s, such as the K–P model (Katerji and Rana, 2006; Rana et al., 2012), and Todorovic model (Liu et al., 2011; Todorovic, 1999). However, an analytical dynamic form for G_s combining the soil evaporation and crop transpiration has not been established yet for canopy from partial to full cover based on a dynamic fraction of canopy cover.

Our overarching goal was to develop a dynamic biophysical model of G_s after incorporating the combined contributions of crop canopy and soil. To do this we incorporate the dynamic partitioning of available energy between crop canopy and soil surface by introducing a dynamic fraction of canopy cover. Furthermore, the G_s model includes the response of stomata to intercepted radiation by crop canopy, vapor pressure deficit, soil water availability in the root zone, and soil evaporation affected by radiation reaching soil surface and soil moisture. The specific objectives of this work were: (a) to evaluate the performance of the dynamic surface conductance model with the P–M equation in predicting evapotranspiration through comparisons of modeled maize canopy *ET* with eddy covariance measurements; and (b) apply the dynamic surface conductance to provide theoretical interpretation on some problems of agricultural water management practices and efficient water use.

2. Materials and methods

2.1. The dynamic surface conductance

2.1.1. Bulk surface conductance

ET can be partitioned as two components, soil evaporation (E_s) and crop transpiration (T_c):

$$ET = T_c + E_s \quad (1)$$

ET and T_c can be calculated using the P–M equation respectively (Monteith, 1965; Monteith and Unsworth, 2008). And E_s can be calculated according to the obtained available energy using the Priestley–Taylor type approach (Priestley and Taylor, 1972).

$$\lambda ET = \frac{\Delta(R_n - G) + \rho_a C_p \mathrm{VPD} G_a}{\Delta + \gamma(1 + G_a/G_s)} \quad (2)$$

$$\lambda T_c = \frac{\Delta R_{nc} + \rho_a C_p \mathrm{VPD} G_a}{\Delta + \gamma(1 + G_a/G_c)} \quad (3)$$

$$\lambda E_s = \alpha_s \frac{\Delta}{\Delta + \gamma}(R_{ns} - G) \quad (4)$$

where λ is the heat of water vaporization (J kg^{-1}); ρ_a is air density (kg m^{-3}); C_p is specific heat of dry air at constant pressure (J kg^{-1} K^{-1}); Δ is the slope of the saturation vapor pressure curve (kPa °C^{-1}); γ is psychrometric constant (kPa °C^{-1}); R_n is net radiation (W m^{-2}); R_{ns} and R_{nc} are net radiation obtained by soil surface and intercepted by crop canopy, respectively (W m^{-2}); G is the soil heat flux (W m^{-2}); VPD is vapor pressure deficit (kPa); G_s and G_c are surface and canopy conductances, respectively (mm s^{-1}); G_a is aerodynamic conductance (mm s^{-1}); and α_s is soil evaporation coefficient.

G_a is calculated as follows (Allen et al., 1998; Monteith and Unsworth, 2008):

$$G_a = \frac{k^2 u}{\ln(z - d_o/z_{om}) \ln(z - d_o/z_{ov})} \quad (5)$$

where k is von Karman's constant (0.41); z is the height of wind speed measurement (m); d_o is zero plane displacement (m); z_{om} and z_{ov} are the roughness lengths governing transfer of momentum and water vapor (m); and u is wind speed at height z (m s^{-1}). The d_o, z_{om} and z_{ov} are calculated using $d_0 = 2h_c/3$, $z_{om} = 0.123h_c$ and $z_{ov} = 0.1z_{om}$, where h_c is canopy height (Allen et al., 1998).

The R_{ns} and R_{nc} are respectively given by the dynamic fraction of canopy cover (f_c) based on R_n.

$$R_{nc} = f_c R_n \quad (6)$$

$$R_{ns} = (1 - f_c) R_n \quad (7)$$

The f_c can be calculated by the ratio of radiation intercepted by crop canopy when LAI is known through measurement or estimation.

$$f_c = 1 - \exp(-\kappa_R \mathrm{LAI}) \quad (8)$$

$$\kappa_R = \frac{G_L}{\cos(\zeta)} \quad (9)$$

where κ_R, canopy extinction coefficient of radiation, is dependent on leaf orientation and solar zenith angle (ζ); LAI is leaf area index (m^2 m^{-2}); and G_L is 0.5 for spherical leaf angle distribution. The ζ is the angle subtended by the sun at the center of the earth and perpendicular to the surface of the earth and it is calculated as Allen et al. (1998).

In case LAI is unknown, f_c can be calculated using the observed value from directly overhead (f_{co}), which can be determined from visual inspection such as digital image analysis and using the equation.

$$f_c = \frac{f_{co}}{\cos(\zeta)} \leq 1.0 \quad (10)$$

To develop an analytical expression of G_s, G is predicted as a fraction of R_{ns} (Choudhury et al., 1987).

$$G = f_G R_{ns} \quad (11)$$

where f_G is the ratio of G to R_{ns}.

By combining Eqs. (2)–(4), (6), (7) and (11), Eq. (1) can be expressed as the following form referred to in the work of Leuning et al. (2008).

$$\frac{\Delta(1 - f_G(1 - f_c)) + \gamma G_a/G_i}{\Delta + \gamma + \gamma G_a/G_s} = \frac{\Delta f_c + \gamma G_a/G_i}{\Delta + \gamma + \gamma G_a/G_c} + \alpha_s \frac{\Delta(1 - f_c)(1 - f_G)}{\Delta + \gamma} \quad (12)$$

where G_i is the climatological conductance (mm s^{-1}) and can be calculated using the meteorological variables (Monteith and Unsworth, 2008).

$$G_i = \frac{R_n}{\rho_a C_p/\gamma \mathrm{VPD}} \quad (13)$$