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Partitioning evapotranspiration into soil evaporation and transpiration using a modified dual crop coefficient model in irrigated maize field with ground-mulching

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ABSTRACT

The accurate partitioning of crop evapotranspiration (ET_c) into two components, soil evaporation (E_s) and transpiration (T_r), is needed to better understand terrestrial hydrological cycles and develop precise irrigation scheduling. However, there is no easy way to distinguish between the two. Based on FAO-56 dual crop coefficient (K_c) approach, we developed a modified dual K_c model for better predicting T_r through basal crop coefficient (K_{cb}) and E_s through evaporation coefficient (K_e). Daily K_{cb} was dynamically calculated by introducing a canopy cover coefficient that could be simply described as a function of leaf area index or fraction of canopy cover. Also, leaf senescence factor was taken into consideration to modify K_{cb} when leaf suffers functional senescence. K_e was modified through introducing the fraction of ground-mulching (f_m) to account for the effect of mulching on E_s. The model was parameterized by measurements in 2009, and validated using independent data for grain and seed maize with and without mulching in 2010 and 2011. The results indicate that the predicted K_c values by the modified model were obviously better than those by the original model. The good agreements were found between the predicted ET_c, T_r and E_s using the modified model and the measurements for grain maize in 2010 with $f_m = 0.6$, with the slope of linear regression of 0.99 ($R^2 = 0.90$), 1.01 ($R^2 = 0.92$) and 0.96 ($R^2 = 0.78$), respectively. The modified model also well reproduced the values of ET_c and E_s for seed maize in 2011, which had lower plant height and leaf area index compared to grain maize, under mulching ($f_m = 0.7$) and non-mulching ($f_m = 0$) conditions. The slopes of linear regression between predictions and measurements were 0.98 ($R^2 = 0.91$) and 0.99 ($R^2 = 0.92$) for ET_c, and 0.98 ($R^2 = 0.79$) and 0.97 ($R^2 = 0.80$) for E_s under $f_m = 0.7$ and 0.0, respectively. These results suggest that the modified dual K_c model can accurately predict ET_c, E_s and T_r for different crop types under different mulching, thus could be a useful tool for improving irrigation water management.

1. Introduction

Crop evapotranspiration (ET_c) plays a key role in energy and water balance of agricultural systems, and is also a key process in the terrestrial hydrological cycle (Burba and Verma, 2005; Zhang et al., 2011a). More than 90% of water used in agriculture is lost by soil evaporation (E_s) and crop transpiration (T_r), referring to as ET_c (Rana and Katerji, 2000). Transpiration is strongly linked to crop productivity since it occurs simultaneously with photosynthesis through the stomatal pores of leaves (Pieruschka et al., 2010). Conversely, direct soil evaporation is not a contributing factor to crop production, and should be reduced by management practices (e.g., proper irrigation strategies and ground-mulching) (Allen, 2000; Zhao et al., 2010). Whereas the two separate processes of T_r and E_s occur simultaneously, and there is no easy way to distinguish between the two (Er-Raki et al., 2010). Therefore, accurate partitioning between soil evaporation and transpiration by models is needed to better understand terrestrial hydrological cycles, develop precise irrigation scheduling, improve crop productivity and enhance water use efficiency.

Several models have been developed to separately predict soil evaporation and transpiration since direct measurement of

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them is difficult, costly and not available in many regions (Allen et al., 1998; Monteith and Unsworth, 2008; Shuttleworth, 2007; Utset et al., 2004). The direct models include both the single-layer Penman–Monteith and two-layer Shuttleworth–Wallace (Monteith and Unsworth, 2008; Shuttleworth and Wallace, 1985). Many input parameters of these models cannot be easily obtained, thus wide application of these models is limited (Allen, 2000). In addition, weather data are routinely measured only above a grassed surface, so the application of the direct models is limited since the differences may exist between the characteristics of the weather measurements and the feedback that should be presented to reflect ET_c of the surface in question (Jarvis and McNaughton, 1986). In contrast, the indirect FAO-56 crop coefficient (K_c) approach has overcome these deficiencies since K_c has contained all differences between the reference surface and the physiologies, physics and morphologies of crop in question (Allen, 2000; Allen et al., 1998). Especially, the dual K_c model has been a preferred approach due to its simplicity for fewer input data and robustness for separately predicting E_s and T_r (Allen, 2000; Er-Raki et al., 2010). The dual K_c model has been widely used in scheduling irrigation and improving agricultural production (Allen, 2000; Liu and Luo, 2010; Paço et al., 2011; Zhao and Ji, 2010).

The basal crop coefficient, K_{cb}, is generally obtained from the guideline of FAO-56 by looking-up the tabulated value at every growth stage and then linearly interpolated to obtain daily values. The approach from the original FAO-56 dual K_c procedures cannot calculate daily actual value of K_{cb}, although daily actual value is of great importance for accurately calculating the dynamic of T_r. Furthermore, leaf senescence and the decline of physiological function at the late season stage could induce stomatal closure and sharp decrease of T_r (Ding et al., 2013; Steduto and Hsiao, 1998). The original dual K_c model has not taken into consideration the effect of leaf senescence. Thus, it is essential to modify the original dual K_c approach to accomplish daily dynamic calculation of K_{cb}. Maize, including grain and seed maize, is one of the main crops in arid regions of northwest China, and its water requirement is mainly supplied by irrigation because of low precipitation (Ding et al., 2010; Zhao et al., 2010). To reduce E_s, ground is often mulched with plastic film, which is a well-established management strategy and widely used (Ding et al., 2013; Hou et al., 2010; Zhou et al., 2009). Whereas evaporation coefficient (K_e) in FAO-56 was obtained by available energy and soil moisture regimes at the topsoil layer, the effect of ground-mulching on E_s was not accounted in K_e. As we have known, E_s would definitely decrease when ground is mulched, because the evaporation area is reduced by ground-mulching. The previous studies have indicated that E_s was reduced by ~50% with plastic film mulching over the whole growing season, especially during the early growing stages where soil surface was not fully covered by crop canopy (Hou et al., 2010; Mukherjee et al., 2010; Zhou et al., 2009). At present, an analytical formula of K_e incorporating the effect of mulching on E_s in dual K_c model has not been established yet.

In this study, to better partition evapotranspiration into soil evaporation and crop transpiration, a modified dual K_c model was developed through accomplishing daily dynamic estimation of K_{cb}, and incorporating the effects of leaf senescence and ground-mulching on T_r and E_s. Its performance was tested through comparing the predicted ET_c, T_r and E_s with measurements in irrigated grain and seed maize with and without mulching in northwest China.

2. The modified dual crop coefficient model

In FAO-56, the actual ET_c is defined as the product of crop coefficient (K_c) and reference evapotranspiration (ET_o) (Allen et al., 1998).

$$ET_c = K_c ET_o \tag{1}$$

In the dual K_c model, K_c is split into two factors that separately describe the evaporation (K_e) and transpiration (K_{cb}) components.

$$K_c = K_s K_{cb} + K_e \tag{2}$$

where K_s is water stress coefficient whose value is dependent on available soil water in the root zone. The corresponding crop transpiration (T_r) and soil evaporation (E_s) are calculated as follows:

$$T_r = K_s K_{cb} ET_o \tag{3}$$

$$E_s = K_e ET_o \tag{4}$$

2.1. The dynamic basal crop coefficient

The original basal crop coefficient, $K_{cb,o}$, is obtained by FAO-56 tabulated recommendations, incorporating the effect of climate and crop factors.

$$K_{cb,o} = K_{cb(Tab)} + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)]\left(\frac{h_c}{3}\right)^{0.3} \tag{5}$$

where $K_{cb(Tab)}$ is basal crop coefficient value taken from FAO-56 table; u_2 is wind speed at 2.0 m height (m s^{-1}); h_c is crop height (m); RH_{min} is minimum daily relative humidity (%).

In order to accurately calculate daily dynamic variation of transpiration, we introduced canopy cover coefficient (K_{cc}) to calculate daily actual K_{cb}. Also, leaf senescence factor (f_s) was taken into consideration in the dynamic K_{cb} model because leaf senescence would lead to stomatal closure and decrease of transpiration (Steduto and Hsiao, 1998).

$$K_{cb} = (1 - f_s)(K_{cb,min} + K_{cc}(K_{cb,full} - K_{cb,min})) \tag{6}$$

where $K_{c,min}$ is the minimum basal crop coefficient for bare soil (0.1 here); $K_{cb,full}$ is basal crop coefficient when crop having nearly full ground cover. $K_{cb,full}$ can be approximated as a function of crop height and adjusted for climate following Allen et al. (1998).

$$K_{cb,full} = \min(1.0 + 0.1h_c, 1.2) + (0.04(u_2 - 2) - 0.004(RH_{min} - 45))\left(\frac{h_c}{3}\right)^{0.3} \tag{7}$$

In our modified K_{cb} model, K_{cc} can be calculated in two methods. First, K_{cc} can be calculated by the ratio of radiation intercepted by crop canopy when LAI is known through measurement or estimation.

$$K_{cc} = 1 - e^{-\kappa LAI} \tag{8}$$

where κ, daily mean canopy extinction coefficient for solar radiation, is dependent on foliage orientation and solar zenith angle (Campbell and Norman, 1998). In case LAI is unknown, K_{cc} can be calculated using fraction of canopy cover, f_c, by the approaches of Allen et al. (1998) and Allen and Pereira (2009).

$$K_{cc} = \min\left(1, M_c f_{c,eff}, f_{c,eff}^{1/(1+h_c)}\right) \tag{9}$$

where $f_{c,eff}$ is the effective fraction of canopy cover (0.01–1.0) near noon; M_c is a multiplier on $f_{c,eff}$ describing the effect of canopy cover on shading and on maximum relative transpiration per fraction of