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Modelling transpiration, soil evaporation and yield prediction of soybean in North China Plain

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ABSTRACT

The main objectives of this study were to assess and partition soybean evapotranspiration and modelling to predict yields. The SIMDualKc water balance model, that adopts the dual crop coefficient approach, was used to evaluate the transpiration and soil evaporation components. Transpiration estimates were then used with the Stewart's water-yield model to predict soybean yields. SIMDualKc was calibrated and validated using soil water observations relative to four crop seasons and six treatments. In addition, the adopted soil evaporation approach using the Ritchie's model was validated against microlysimeter observations, also for the four years of study. The calibrated K_{cb} was 1.05 for the mid-season and 0.35 at harvesting. Model results show a good agreement between available soil water data observed and predicted by the model, with root mean square errors of estimates (RMSE) smaller than 5% of the total available soil water. Testing the soil evaporation approach also produced good fitting results, with RMSE averaging 0.50 mm d^{-1}, hence confirming the appropriateness of the Ritchie's model to estimate soil evaporation of a cropped soil. The yield prediction through combining SIMDualKc and the Stewart's model was successful for all treatments, leading to a small RMSE of 381 kg ha^{-1} representing less than 11.5% of the maximum observed yield. These results indicate that yield may be predicted with that simple empirical approach provided that transpiration is accurately estimated and the water yield factor K_y is adequately calibrated. Consumptive water productivity WP_{ET} were high, ranging 0.95–1.46 kg m^{-3}, showing that both the crop variety and the agronomic practices may be extended in North China Plain.

1. Introduction

Soybean is a major legume crop in North China and a significant source of high-quality protein and edible fat for human beings. Appropriate irrigation schedules in supplement to rainfall are crucial to ensure the normal growth and yield of soybean because they are vulnerable to water stress, mainly during flowering and seed filling (e.g., Stegman et al., 1990; Foroud et al., 1993; De Costa and Shanmugathasan, 2002; Karam et al., 2005). However, there are not studies available for North China Plain where supplemental irrigation of soybeans may be used.

The irrigation requirements of soybean are generally determined adopting the single crop coefficient (K_c) and the reference grass evapotranspiration (ET_o) (Mao, 2009; Suyker and Verma, 2009), whose product is the crop evapotranspiration (ET_c). However, as referred by Odhiambo and Irmak (2012), the dual crop coefficient approach may be more suitable for operational applications where daily estimates of ET_c are available. Crop evapotranspiration consists of crop transpiration (T_c) and soil water evaporation (E_s). The dual crop coefficient method separately estimates both T_c and E_s through partitioning K_c into two coefficients, the basal crop coefficient (K_{cb}), which is crop-specific and represents the ratio of T_c to ET_o, and the soil evaporation coefficient, K_e, that represents the daily ratio of E_s to ET_o, thus providing for estimating E_s. When using the dual crop coefficient method, the K_{cb} values are adjusted for local climate (Allen et al., 1998); under water stress conditions K_{cb} are adjusted using a water stress coefficient, K_s, i.e., $K_{cb\,adj} = K_s\,K_{cb}$. The K_e values are computed daily considering soil surface cover and wetness (Allen et al., 1998, 2005).

The computation of the soil water dynamics is often based on the direct calculation of the soil water balance with a daily time step, or on the accurate simulation of soil water fluxes. The later approach is highly demanding in terms of data acquisition and

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model parameterization, particularly relative to the soil hydraulic properties. In addition, these deterministic models are too complex to apply in the irrigation management practice but are appropriate when it is required to assess water table and salinity behaviour, or when it is aimed to recognize the dynamics of fertilizers and related biomass production. Typical examples include models such as CropSyst (Stöckle et al., 2003), CROPGRO-soybean (Wang et al., 2003), HYDRUS (Ramos et al., 2011), or SWAP (Xu et al., 2013). In contrast, soil water balance models are of more easy application to irrigation scheduling and allow appropriate understanding of the crops behaviour when submitted to diverse management strategies. Examples are the models ISAREG (Liu et al., 1998), OSIRI (Chopart et al., 2007), PILOTE (Khaledian et al., 2009) and SIMDualKc (Rosa et al., 2012a). However, these models often need coupling with water yield functions describing the relationships between ET and yield, e.g., the Stewart's models (Stewart et al., 1977) as reported by Paredes et al. (2014).

Various studies report the applicability of the dual K_c methodology to several field crops, namely for the North China Plain (Liu and Pereira, 2000; Pereira et al., 2003; Liu and Luo, 2010; Zhang et al., 2013; Zhao et al., 2013). However, applications to the soybean crop are not reported for China. The use of the dual K_c methodology is more demanding than the single K_c approach, which justifies the need for implementing an appropriate model application but few model applications are available. Therefore updated research is required to appropriately implementing the dual crop coefficient approach and calibrating/validating an irrigation scheduling model using that approach. The SIMDualKc model (Rosa et al., 2012a) was therefore selected. Moreover, since studies relative to assess soil evaporation for soybeans are not available, it was advisable to test the soil evaporation component of the model. This model implementation should contribute to better using the available water resources and coping with water scarcity, that is a major challenge in the North China regions.

The main purposes of this study consist of implementing the dual crop coefficient approach and the use of the SIMDualKc model for soybean, hence performing the partitioning of ET into crop transpiration and soil evaporation, as well as calibrating the Stewart's model for yields prediction using transpiration data. In addition, it was also aimed to validate the soil evaporation approach used in SIMDualKc using microlysimeter observations performed along four crop seasons.

2. Material and methods

2.1. Site characteristics

The field experiments with soybean (*Glycine max* (L) var. Zhonghuang No.13) were conducted at the Irrigation Experiment Station of the China Institute of Water Resources and Hydropower Research (IWHR) located at Daxing (39°37′ N, 116°26′ E, and 40.1 m altitude), south of Beijing. The soybean variety Zhonghuang No.13 is a high-protein and high-yielding semi-determinate cultivar of maturity group II (Hao et al., 2012; Wang et al., 2013). The climate in the experimental site is sub-humid of monsoon type, with cold and dry winter and hot and humid summer. An automatic meteorological station is installed inside the experimental station over clipped grass, which provides for measurements of precipitation, air temperature, relative humidity, global and net radiation, wind speed at 2 m height, and soil temperature at various depths. Meteorological data sets from the automatic weather station were used to compute the reference ET using the FAO Penman-Monteith method (Allen et al., 1998). Data sets were checked for quality as recommended by Allen et al. (1998). The climatic characterization relative to the experimental seasons of 2008–2011 is presented in Fig. 1. The total precipitation during the four experimental soybean seasons was 238, 328, 212 and 288 mm, respectively.

Table 1
Basic soil hydraulic properties of Daxing experimental station.

Layer	Depth (m)	θ_S (cm^3 cm^{-3})	θ_{FC} (cm^3 cm^{-3})	θ_{WP} (cm^3 cm^{-3})
1	0.00–0.10	0.46	0.32	0.09
2	0.10–0.20	0.46	0.34	0.13
3	0.20–0.40	0.47	0.35	0.10
4	0.40–0.60	0.45	0.33	0.11
5	0.60–1.00	0.44	0.31	0.16

θ_{FC}, θ_{WP} and θ_S represent the soil water content at field capacity, wilting point and saturation respectively.

The soil is an alluvial silt loam whose basic hydraulic properties are summarized in Table 1. The total available soil water (TAW) is 198 mm m^{-1}.The average groundwater table is at approximately 18 m depth; thus, capillary rise from the groundwater was not considered. Deep percolation was computed using the parametric equation developed by Liu et al. (2006), which is a component of the SIMDualKc model. More information on the soil and the study area were given by Cai et al. (2009) and Zhao et al. (2013).

The irrigation experiments were developed from June 2008, when the first soybean season started, to October 2011, at the harvest of the fourth soybean season. The irrigation thresholds for treatments T1 and T2 were 75% and 60% of θ_{FC}, respectively; lower thresholds were not selected because the crop develops during the monsoon season and those were not likely to be attained. Therefore, water stress was avoided. In seasons with abundant rainfall no distinction could be made among treatments when analyzing related data. The treatments were performed with three replications in plots of 30 m^2 each. The irrigation water was delivered to the field by a PVC pipe and irrigation water depths were measured with a flow meter installed at the well pump outlet. Basin irrigation was used. The applied irrigation schedules are described in Table 2. Pre-planting irrigation were applied in 2008 and 2010 to assure adequate soil water conditions for emergence; differently, in 2009 and 2011, there was abundant rainfall that made not necessary pre-planting irrigation. Furthermore, due to abundant rainfall along 2011 season no irrigation was applied.

2.2. Field observations

Soybean was sown by early June and harvested by mid-October. Conventional tillage was adopted. Fertilization varied according the chemical analysis of soil samples and no nitrogen fertilizer was applied. Weeds control was performed manually. The crop density was 15 plants m^{-2} with an inter-row spacing of 0.4 m. Dates for each crop growth stage and all experimental years are presented in Table 3; no differences in dates of crop growth stages were observed between treatments of the same year. The crop height (h) was observed every 5 days (Table 4). The root depth (Z_r) at start

Table 2
Irrigation treatments: applied water depths and dates.

Irrigation season	Plot	Date	Irrigation depth (mm)
2008-T1	1	23-6-2008[a]	45
		4-9-2008	50
2008-T2	2	23-6-2008[a]	45
2009	2	30-6-2009	30
2010-T1	2	23-6-2010[a]	30
		24-7-2010	35
		11-8-2010	45
2010-T2	1	23-6-2010[a]	30
		2-8-2010	40

[a] Pre-planting irrigation.