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Performance assessment of the FAO AquaCrop model for soil water, soil evaporation, biomass and yield of soybeans in North China Plain

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ABSTRACT

Four years of soybean experimental data observed at Daxing, North China Plain, were used to assess the ability of the AquaCrop model to predict soybean final biomass and yield. The model was parameterized and calibrated using field data on leaf area index (LAI), available soil water, soil evaporation, biomass and final yield data. The model was assessed using calibrated and default parameters. Data on LAI were used to derive the fraction of ground cover and to calibrate the green canopy cover (CC) curve. An accurate calibration of the CC curve was performed, with low root mean square errors (RMSE < 7.3%). Results relative to soil water balance simulations show a high variability of the predictions, thus a bias of the estimation, with R^2 ranging 0.22–0.86 and low Nash-Sutcliffe efficiency EF, ranging between −0.47 and 0.82. The estimation errors were relatively high, with RMSE not exceeding 22.9 mm. AquaCrop was compared with the soil water balance model SIMDualKc, that has shown better performance with $R^2 \geq 0.83$, EF generally greater than 0.75 and RMSE smaller than 12.5 mm. The soil evaporation (E_s) simulations were compared with the observations performed using microlysimeters; results for Aquacrop have shown a clear trend for under-estimation of E_s, with "goodness-of-fit" results worse than for SIMDualKc (Wei et al., 2015). In general, AquaCrop has shown serious limitations to estimate crop transpiration or soil evaporation, which is likely due to abandoning the FAO dual K_c approach. However, the model performed well relative to biomass and yield predictions, with a yield RMSE of 302 kg ha^{-1}. Overall, results show the adequacy of AquaCrop for estimating soybean biomass and yield when the model is appropriately parameterized. However, AquaCrop is not appropriate to support irrigation scheduling.

Abbreviations: ARE, Average relative error (%); ASW, Available soil water (mm); B, Above ground dry biomass (t ha^{-1}); b, Regression coefficient (non-dimensional); BWP*, Biomass (water) productivity adjusted for ET$_o$ and CO_2 (g m^{-2}); CC, Green canopy cover (%); CC*, Actual crop canopy cover adjusted for micro-advective effects (%); CC$_o$, Canopy cover at 90% of emergence (cm^2 per plant); CC$_x$, Maximum green canopy cover (%); CDC, Canopy decline coefficient (% GDD^{-1} or % day^{-1}); CGC, Canopy growth coefficient (% GDD^{-1} or % day^{-1}); CGDD, Cumulative growing degree days (°C); CN, Curve number (non-dimensional); CR, Capillary rise from shallow water table (mm); DP, Deep percolation (mm); EF, Modelling efficiency (non-dimensional); E$_s$, Soil evaporation (mm); ET, crop evapotranspiration (mm); ET$_c$, Potential (non-stressed) crop evapotranspiration (mm); ET$_{c\ act}$, Adjusted or actual crop evapotranspiration (mm); ET$_d$, Crop evapotranspiration deficit (mm); ET$_o$, Reference evapotranspiration (mm); f_c, Fraction of soil cover by vegetation (non-dimensional); f_{ew}, Fraction of soil wetted and exposed to solar radiation (non-dimensional); f_K, Decline factor (non-dimensional); GDD, Growing degree days (°C); HI$_o$, Reference harvest index (%); K_c, Crop coefficient (non-dimensional); $K_{c\,max}$, Maximum value of crop coefficient (following rain or irrigation) (non-dimensional); K_{cb}, Basal crop coefficient (non-dimensional); $K_{cb\,act}$, Actual or adjusted basal crop coefficient (non-dimensional); $K_{cb\,end}$, Basal crop coefficient at end of the late season growth stage (non-dimensional); $K_{cb\,ini}$, Basal crop coefficient during the initial growth stage (non-dimensional); $K_{cb\,mid}$, Basal crop coefficient during the mid-season growth stage (non-dimensional); $K_{c\,max}$, Maximum value of the crop coefficient (K_c) following rain or an irrigation event (non-dimensional); $K_{c,Tr}$, Crop transpiration coefficient (non-dimensional); $K_{c,Tr\,act}$, Actual crop transpiration coefficient (non-dimensional); $K_{c,Tr\,x}$, Maximum standard crop transpiration coefficient (non-dimensional); $K_{e\,x}$, Soil evaporation coefficient for fully wet and non-shaded soil surface (non-dimensional); K_d, Density coefficient (non-dimensional); K_r, Evaporation reduction coefficient (non-dimensional); K_s, Water stress coefficient (non-dimensional); K_{sat}, Saturated hydraulic conductivity (cm d^{-1}); K_y, Yield response factor (non-dimensional); LAI, Leaf area index (cm^2 cm^{-2}); R^2, Determination coefficient (non-dimensional); RAW, Readily available soil water (mm); REW, Readily evaporable soil water (mm); RMSE, Root mean square error (same units as observations); RO, Runoff (mm); RYL, Relative yield losses (%); T_a, Actual transpiration (mm); TAW, Total (plant) available soil water (mm); T_c, Crop transpiration (mm); T_d, transpiration deficit (mm); TEW, Total evaporable water (mm); W_{rel}, Relative soil water content (%); Y_a, Actual yield (t ha^{-1}); Z_e, Evaporable layer thickness (m); Z_r, Root depth (m); θ_{FC}, Volumetric water content at field capacity (m^3 m^{-3}); θ_{sat}, Volumetric water content at saturation (m^3 m^{-3}); θ_{WP}, Volumetric water content at wilting point (m^3 m^{-3}).

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1. Introduction

Soybeans are a main summer crop in North China Plain, where they are cropped during the rainy season, thus only requiring supplemental irrigation to fulfil the crop water requirement. The prediction of the soybean yield and of the yield response to water is mandatory for developing strategies for irrigation management and to support related farmers' decision-making under limited water availability conditions.

To assess the impacts of different irrigation scheduling strategies on yield, various modelling approaches may be used such as coupling a soil water balance model with water yield functions describing the relationships between crop evapotranspiration or crop transpiration with yield. A successful approach applied to soybeans is described by Wei et al. (2015) that adopted the SIMDualKc soil water balance model (Rosa et al., 2012) coupled with the Stewart's water-yield model (Stewart et al., 1977). The SIMDualKc model applies the FAO dual crop coefficient approach for computing and partitioning the daily crop evapotranspiration (ET_c, mm) into crop transpiration (T_c, mm) and soil evaporation (E_s, mm). SIMDualKc performs a daily soil water balance for the entire root zone and a daily water balance of the soil evaporation layer adopting the two stages Ritchie's evaporation approach (Ritchie, 1972; Allen et al., 1998; Allen and Pereira, 2009). Deep percolation (DP, mm) and capillary rise (CR, mm) are computed using the parametric equations proposed by Liu et al. (2006), and runoff (RO, mm) is estimated using the curve number (CN) approach (Allen et al., 2007). SIMDualKc allows computing the daily ET_c and T_c deficits (ET_d and T_d) defined respectively as the difference between the standard ET_c and the actual ET ($ET_{c\ act}$) and as the difference between T_c and actual transpiration (T_a). Those values may be used with the Stewart's water-yield model (Stewart et al., 1977), thus adopting a simple, linear crop-water production function that relates seasonal ET_d or T_d with the relative yield loss (RYL) through an appropriate water-yield factor, K_y, as reported by Paredes et al. (2014a) for maize.

A more complex modelling approach is used in the FAO crop yield model AquaCrop (Raes et al., 2012; Steduto et al., 2012), that simulates crop biomass and yield in response to water and other abiotic stresses (temperature, fertilization, salinity and CO_2). AquaCrop uses an empirical approach to estimate T_c and E_s depending upon the canopy cover curve, which is different from the FAO dual K_c approach described in FAO56 (Allen et al., 1998). It is based upon a K_c curve that does not relate with the common FAO K_c curve adopted in FAO24 and FAO 56 (Doorenbos and Pruitt, 1977; Allen et al., 1998). AquaCrop performs a daily soil water balance and estimates RO also using the CN method. Differently from SIMDualKc, it uses a semi-empiric DP estimation procedure that requires the knowledge of the saturated hydraulic conductivity, K_{sat}, throughout the soil profile (Raes et al., 2006).

The AquaCrop model was already applied to several annual field crops but only a few applications analysed the model behaviour relative to the soil water and evapotranspiration, e.g., Farahani et al. (2009) for cotton, Katerji et al. (2013) for tomato and Paredes et al. (2014b) for maize. However, assessments of ET partitioning in AquaCrop are limited (Pereira et al., 2015b) and there are no assessments for the model's ability to predict soil evaporation.

Considering the above discussions on the possible appropriateness and limitations of the AquaCrop model, as well as the previous results obtained when using the SIMDualKc and Stewart's modelling approaches described by Wei et al. (2015), the objectives of the present study are: (1) assessing the performance of AquaCrop for soybean yield estimation when using calibrated and default parameters; (2) to test the AquaCrop ability to partition crop ET in comparison with the FAO dual K_c approach; (3) to assess the ability of AquaCrop to simulate soil evaporation comparing with observations performed with microlysimeters along four soybean seasons; and (4) to compare the AquaCrop approaches used for soil water balance and soil evaporation estimation with the ones used by the soil water balance SIMDualKc. The same data used by Wei et al. (2015) are used in this study.

2. Material and methods

2.1. Experimental site characterisation and observations

Soybean (*Glycine max* L.) experiments were performed 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). The soybean variety Zhonghuang No. 13 was sown using conventional tillage with a plant density of 15 plants m^{-2} and an inter-row spacing of 0.4 m. This variety is a high-yielding semi-determinate cultivar that belongs to the maturity group II and takes an average of 96 days to reach full maturity (Wang et al., 2013). The experiments were performed from 2008 to 2011, with sowing by mid-June and harvesting by early October. Further information is provided by Wei et al. (2015).

The climate in the experimental site is sub-humid of monsoon type, with cold and dry winter and hot and humid summer, which is classified as Dwa according to the Köppen classification (Kottek et al., 2006). Climatic data used in the study were collected from an automatic meteorological station installed inside the experimental station. Daily data used included precipitation, maximum and minimum air temperature, relative humidity, global and net radiation and wind speed at 2 m height. The climatic data sets were checked for quality assessment as recommended by Allen et al. (1998). The reference ET (ET_o) was computed with the FAO Penman–Monteith method (Allen et al., 1998). Table 1 presents the climatic characterization of the four crop seasons for the period 2008 to 2011. Detailed information on weather data relative to the four years of observations is provided by Wei et al. (2015). Climatic data (Table 1) suggest that differences among years were small except relative to precipitation, which was higher in 2009 and 2011.

The soils in the experimental field are silty soils formed by deposits of the loess formations. By 2007, four undisturbed soil samples of 250 cm^3 for each soil layer to a depth of 1 m were collected in various plots to determine the soil water retention curve and the hydraulic conductivity curve in laboratory. The ku-pf apparatus (Umwelt-Geräte-Technik, Müncheberg, Germany) was used. Averaged values of basic soil hydraulic properties are presented in Table 2. The K_{sat} values are in the range of those proposed by Rawls et al. (1998) and Raes et al. (2012) for silt loam soils, however they are higher than those formerly observed in the region (Pereira et al., 2003). Capillary rise from the groundwater was not considered because the average groundwater table was deep, near 18 m, in all four years of observations.

The irrigation schedules were set using two soil water thresholds, of 75% and 60% of θ_{FC}, respectively treatment T1 and T2. Thus, irrigation was performed whenever the soil water content reached those thresholds. Treatments were performed with three replications in plots of 30 m^2 each. Since the crop develops during the monsoon rainy season, lower irrigation thresholds could not be selected. In 2009 and 2011, due to abundant rainfall, no distinction could be made between treatments thus, resulting in a total of six data sets.

Field observations included:

(a) The dates of each crop growth stage (Table 3).
(b) The leaf area index (LAI, $cm^2\ cm^{-2}$), that was measured along the crop season at several locations using a ceptometer