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Soybean crop-water production functions in a humid region across years and soils determined with APEX model

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ABSTRACT

Crop production as a function of water use or water applied, called the crop water production function (CWPF), is a useful tool for irrigation planning, design and management. However, these functions are not only crop and variety specific they also vary with soil types and climatic conditions (locations). Derivation of multi-year average CWPFs through field experiments for different locations and soils is time-consuming and expensive, as it requires careful long-term and multi-location field experiments to obtain them. Process based crop system models provide a useful tool for determining CWPFs using short term field experimental data for calibration and validation. The aim of this study was to determine soybean CWPFs using the Agricultural Policy/Environmental eXtender (APEX) model across three soil types (Vaiden-silty clay, Cahaba-sandy loam, and Demopolis-clay loam) and three weather conditions (14-year average from 2002 to 2015, dry, and wet) of a humid irrigated region in Mississippi, USA. The results showed that the relationship between simulated soybean grain yield (GY) and the seasonal crop evapotranspiration (ET) for each soil under 14-year average weather condition was linear. Compared with the Vaiden soil, the Cahaba and Demopolis soils had slightly higher water use efficiency (WUE) over 14-year average weather conditions. The CWPFs for GY vs supplemental irrigation were cubic polynomials for all soil types and weather conditions, with varying coefficients. The maximum values of irrigation water use efficiency (IWUE) derived from these cubic CWPFs varied from 2.58 to 9.89 $kg\,ha^{-1}\,mm^{-1}$ across soils and weather conditions. The irrigation amount during the growing season required (I_{max}) to achieve the maximum GY for soybean also had a wide range of values, from 110 to 405 mm. The IWUE and I_{max} were related to available water holding capacity of soils. The relationship between GY and total plant available water supply (TWS) was also a cubic function, with coefficients varying with soil types and climatic conditions. The yield response factor (K_y) was 1.24 (greater than 1.00) when averaged over 14 years' weather data, indicating that soybean was very sensitive to water stress even in a humid region like Mississippi. Thus, supplemental irrigation was necessary to increase GY and ensure stability in yields.

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1. Introduction

Worldwide, there has been a rapid increase of urban and industrial water demand in recent decades, which in turn makes water become a limiting factor for crop production. Most soybean in the world is grown under rainfed conditions, such as in USA, India, Africa, Brazil and China (Bhatia et al., 2008; Heinemann et al., 2016). There is a common view that achieving the maximum possible economic yield through optimizing irrigation management is crucial to meet the increasing food and nutritional demands of the growing global population (Bhatia et al., 2008; Van Ittersum and Cassman, 2013). Even in a humid region, like Mississippi, USA, due to the uneven distribution of precipitation during the growing season (Paz et al., 2007), supplemental irrigation issues of timing and amount in the dry periods have increasingly attracted the concern of governments, experts and farmers (Karam et al., 2005; Garcia y Garcia et al., 2010; Vories and Evett, 2014). Hence, agricultural water resource management that uses the available water to obtain the most economic crop production is important all over the world.

Soybean is the dominant crop in Mississippi, with harvest area of 8.17×10^5 ha, accounting for 44% of the total crop area in 2014 (NRCS, 2015). Only 25–30% of the soybean area is irrigated (Thomas and Blaine, 2014). Although smaller in soybean irrigated area, Mississippi experienced the largest percentage increase of 92% in irrigated area from 1998 to 2008 among the Mid-South states of USA (NASS, 1999, 2010), and the increasing trend will continue. Current research on defining irrigation for optimum yield can't keep pace with the increase of soybean irrigated area in these states (Vories and Evett, 2014). The soybean producers still confront the dilemma on how much and when water should be applied to obtain optimal yield with available water. Crop water production functions (CWPFs), which express the relation between crop yield and consumptive water use, plant available water, or irrigation water applied, along with the knowledge of temporal crop water demands and deficits, are an effective way to answer these questions. However, CWPFs are crop, site and time specific, and vary considerably among soils and climatic zones (Stewart and Hagan, 1973; Kipkorir et al., 2002; Igbadun et al., 2007). Moreover, the current studies on CWPFs are mainly concentrated in arid or semi-arid regions, much less in humid regions. Hence, it is meaningful to determine soybean CWPFs in a humid region like Mississippi for optimizing irrigation management.

CWPFs have been shown to be a very useful tool to optimize irrigation planning and management strategies, as well as to calculate and compare water use efficiency (Al-Jamal et al., 2000; Kipkorir et al., 2002). With the help of CWPFs, decision makers can calculate the amount of irrigation to meet the evapotranspiration demand during dry spells for targeted crop yield, accounting for rainfall and soil water, or conversely, assess likely grain yield for fixed volumes of water including effective rainfall, irrigation and soil water (Brumbelow and Georgakakos, 2007). Thus, the economic return of different irrigation levels can be estimated by CWPFs when the yield price and crop production costs are known, which supports the decision making on how much irrigation is a profitable investment in a humid region (e.g., Mississippi). The dependent variables in CWPFs are usually biomass or grain yield, while the independent variables are crop actual evapotranspiration (ET_c), irrigation amount (I), or available plant water supply, which is the sum of effective rainfall, plant available soil water and applied irrigation (Hanks, 1974; Al-Jamal et al., 2000; Kipkorir et al., 2002; Brumbelow and Georgakakos, 2007; Tolk and Howell, 2008; Saseendran et al., 2015). The current reports on CWPFs concentrated mainly on crop ET and water issues including precipitation and irrigation. The soil properties which are crucial factors to generate grain yield are much less addressed. There is a need to determine CWPFs under different soil types.

Approaches to determine CWPFs include field experiments and crop modeling. Although the experimental method is ideal, determining multiyear average CWPFs from field experiments is quite expensive and time consuming as it generally requires extensive, long-term experimental data to get reliable results (Russo and Bakker, 1987; Zhang and Oweis, 1999; Brumbelow and Georgakakos, 2007). Even when the CWPFs are derived from long-term field experiments, they are still not geographically portable (Rhenals and Bras, 1981; Clumpner and Solomon, 1987). Process-oriented crop models are an effective approach to overcome these limitations of the field experiments. However, some experimental data are still needed to ground-truth the models in simulating the daily crop growth, grain and biomass yield, and components of water balance (soil water content, runoff, percolation, ET, irrigation and precipitation) for generating the CWPFs (Brumbelow and Georgakakos, 2007; Saseendran et al., 2015). Furthermore, CWPFs developed by a crop model are not single functions, but multiple functions reflecting the variability in weather, soils and locations or multiple-year averaged functions for each soil and location (Van Ittersum et al., 2013). The Agricultural Policy/Environmental eXtender (APEX) is a process-based agricultural system model (Williams et al., 2008; Cavero et al., 2012), which was developed to simulate various agricultural management practices and land use strategies (Borah et al., 2006). Crop growth, production, irrigation, runoff, soil and N management, and water quality have been successfully simulated by APEX model (Wang et al., 2008; Powers et al., 2011; Cavero et al., 2012). APEX is very suitable for developing CWPFs, as it provides three automatic irrigation methods triggered based on soil water deficit, plant water stress and soil water tension (Williams et al., 2012), which support a fast and effective way to determine CWPFs.

Main objectives of this study were to: (1) determine the average CWPFs across 14 years for three soils in a humid region using a modeling approach; (2) examine CWPFs for a wet and a dry year for each soil, (3) develop yield response factors and determine ET, yield and irrigation amount from CWPFs of soybean grown in a humid region.

2. Materials and methods

2.1. The study site

2.1.1. Study area

This study was conducted to simulate conditions in Noxubee County, Mississippi, USA. Soybean is the dominant crop of Noxubee county, grown on 7×10^3ha, corresponding to 31% of its total cropland (NRCS, 2015). Noxubee county is located in the Blackland Prairie region of Mississippi, which is the major agricultural region in the East Gulf Coastal Plain Section of the Atlantic Plain and it's slightly elevated and hilly. Most of this area is underlain by Createaceous-age clay, marl, soft limestone, or chalk of the Selma Group. The region is characterized as a humid region, with the mean annual rainfall of about 1400 mm over 30 years (1981–2010). The mean daily temperature is about 18 °C and the mean daily solar radiation is 17 MJ m^{-2}. This research was conducted on three dominant agricultural soil types, namely the Vaiden silty clay, Cahaba sandy loam, and Demopolis clay loam, which cover about 79% of the total soybean area in Blackland Prairie, Mississippi (Fig. 1; USDA, 2003).

2.1.2. Field experiments

The field experiments were conducted on a 7.04 ha irrigated field in 2014, and on a 1.2 ha irrigated field in 2015, located in Noxubee County, Mississippi. These experimental fields were conducted on Vaiden (VA), Okolona (OK), Demopolis (DE) and Brooksville (BR) soil types. The experiments consisted of three irrigation treatments both in 2014 and 2015, which utilized a completely randomized block design with four replicates. The size of field experimental plots is 6 rows × 5 m, namely 4.23 m × 5 m. The soil hydraulic properties of Ksat, FC and PWP of the three soil types were used for model inputs in the simulations (Table 1). A soybean group IV cultivar, Asgrow 4632 was planted at 296,525 seeds per hectare for the experimental trials. Soils of VA, OK and DE were provided three irrigation levels of 25.4, 12.7 and 0 mm during the soybean growing season in 2014, while irrigation levels of 114, 57 and 0 mm were supplemented for BR soil for experimental trials in 2015. The irrigation was applied when measured root zone soil moisture is 50% of total plant available water (TAW) in experimental trials. The treatments are defined as (i) 'SM', the amount of irrigation is the water needed to recharge to field capacity; (ii), 'halfSM', only half amount of 'SM' is applied; (iii), 'RF', rainfed or not irrigated. Accordingly, the evaluated treatments were named with acronyms of VARF, OKSM, BRSM, DERF, OKhalfSM and BRhalfSM.

During the growing season, crop height, canopy cover, rooting depth, leaf area, and dry biomass of leaf, stem and root were determined weekly. For measurements of soil hydraulic properties (porosity, soil water retention curve, field capacity, permanent wilting point, and saturated hydraulic conductivity), undisturbed core samples of 5 cm diameter with 1 cm and 6 cm heights, were collected from the soil surface, and at 0–15, 15–30, 30–60 and 60–100 cm depths in both the bed and furrow. Four samples were collected for each soil layer. According to our observations, the root depth of soybean in a humid region, Mississippi is 80–100 cm, which accorded with Kirkham et al. (1998). The hydraulic properties were determined in the laboratory using the pressure plate and water flow apparatus.

Meteorological data was obtained from Macon station (33.13°N, 88.48°W), Noxubee county, Mississippi (http://ext.msstate.edu/anr/drec/stations.cgi), which was adjacent to the experimental field with a distance of 1000 m. The air temperature at heights of 2 m was measured using thermis-

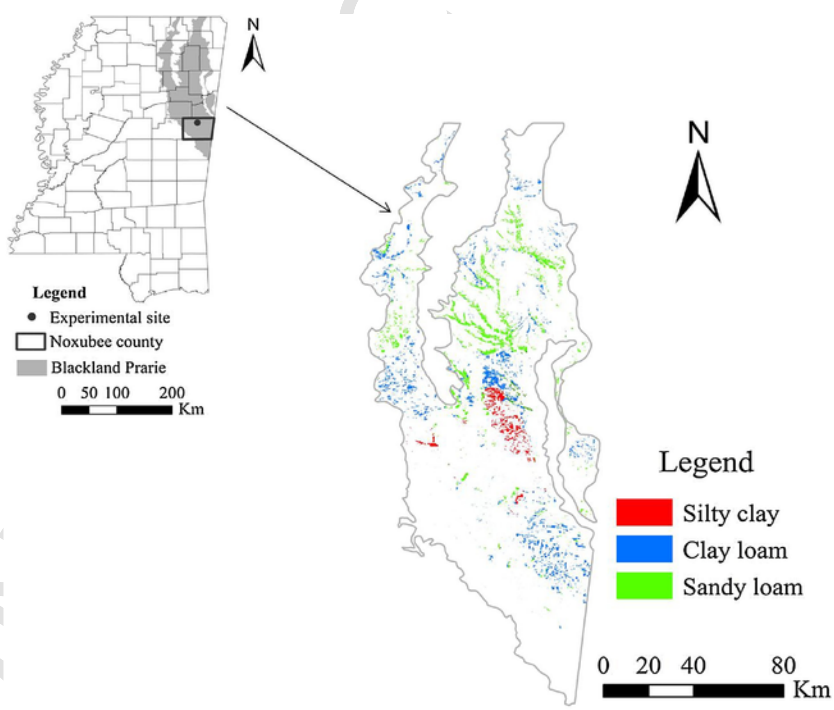

Fig. 1. Location of three dominant soils in Blackland Prarie, Mississippi.

Table 1
Soil properties in 0.3 m and 1 m depth for three major soils used in the simulating study.[a]

Soil depth (m)	Soil types	Soil texture	Bulk density	Sand content	Silt content	Clay content	Saturated hydraulic conductivity	Available water content
			(g/cm^3)	(%)	(%)	(%)	(mm/h)	(m/m)
0.3	Vaiden	Silty clay	1.25	8.40	40.10	51.50	2.15	0.19
	Cahaba	Sandy loam	1.36	62.00	19.00	19.00	7.48	0.18
	Demopolis	Clay loam	1.44	23.97	48.03	28.00	6.75	0.16
1	Vaiden	Caly	1.25	10.24	27.62	62.14	1.45	0.18
	Cahaba	Sandy loam	1.47	62.32	19.12	18.56	8.05	0.16
	Demopolis	Clay loam	1.45	30.53	42.11	27.36	6.97	0.14

[a] Soil properties were taken from USDA-NRCS (http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx).

tors (Model 107-L, Campbell Scientific Corporation). The wind speed at 2 m was measured using a propeller anemometer (Model 05103, RM Young Corporation). The sensors were monitored at a frequency of 1 Hz, with data recorded every minute using a datalogger (Model CR1000, Campbell Scientific Corporation). Combined with the weather data, the crop growth information and soil properties obtained in the two years of field experiments were used for calibration and validation of the APEX model. The detailed description on field experiments was given in the previous study by Zhang et al. (2016a,b).

2.2. The APEX model

The APEX (Williams et al., 2008) model is a flexible and dynamic tool, which was developed to evaluate a variety of land management scenarios at a farm or a small watershed scales (Borah et al., 2006). The watershed may be divided into homogeneous subareas that have similar soils, land use and topography (Steglich et al., 2014). Williams et al. (2012) provides an updated, in-depth theoretical manual for the latest APEX model (version 0806).

The APEX model is a continuous model (Wang et al., 2008; Powers et al., 2011) which operates on a daily time step (some processes use hourly or smaller time steps) and is capable of simulating up to hundreds of years if necessary. Farms may be subdivided into fields, soil types, landscape positions, or any other desirable configuration (Steglich et al., 2014). The APEX model was developed to evaluate various agriculture management strategies considering sustainability, erosion (by wind and water-sheet, and channel), economics, water supply amount and quality, soil quality, plant competition, weather, and pests. Management capabilities in the APEX model include irrigation, drainage, furrow diking, buffer strips, terraces, waterways, fertilization, manure management, lagoons, reservoirs, crop rotation and selection, pesticide application, grazing, and tillage (Steglich et al., 2014).

The major input components in APEX are weather data, soil data, crop data, equipment, management, cropping system and control file (Steglich et al., 2014). The weather data to drive the model includes daily solar radiation, precipitation, maximum air temperature, and minimum air temperature. The average daily wind speed and relative humidity were also required if the Penman or Penman-Monteith methods are used to estimate potential evaporation (Penman, 1948; Williams et al., 2008). Soil characteristics of bulk density, field capacity, permanent wilting point, saturated water conductivity, texture and soil organic carbon content are also required to run APEX model. Crop data includes root depth, crop height, biomass and leaf area index. The rate, date, times and machine types of planting, fertilizing, irrigation, pest control and harvest can be set through management inputs in APEX model. Equipment and cropping system can be set according to the purpose of study. The control file can help to set the calculating formula and choose the output items. The automatic irrigation will be triggered based on water stress level which can be set through water factor, the detail information is shown in Section 2.4.2. The APEX model supports five options of Hargreaves and Samani (1985), Penman (1948), Priestley and Taylor (1972), Penman-Monteith (Monteith, 1965), and Baier and Robertson (1965) to estimate potential evapotranspiration. The actual evapotranspiration was the sum of soil evaporation and plant transpiration, which are estimated separately by APEX model. The automatic irrigation will stop for wetted soil beyond field capacity. The WinAPEX software is a user-friendly Windows interface, designed by the Blackland Research and Extension Center (Williams et al., 2008). The program provides a watershed builder subroutine that takes the user through a series of screens in order to construct the input data for individual subareas, which will be incorporated into an APEX field, landscape, whole-farm, or watershed simulation. The APEX model provides editing tools that support assessments of the impacts of alternative scenarios. Potential increase in biomass for a day is estimated with the equation by Monteith (1977). Percolation is computed simultaneously using storage routing and pipe flow equations, and surface runoff is predicted for daily rainfall by using the USDA-SCS curve number equation (Williams et al., 2012). The APEX model can output daily, monthly or annual yield, biomass, leaf area index, irrigation amount, ETc, runoff and percolation, which depends on the users' choice. The accumulative water stress days (AWS) can be calculated according to the daily output of water stress. The outputs of APEX simulations are stored in a series of ACCESS tables, which provide post-processing or export options.

2.3. Estimation of ET in APEX model

The APEX model computes evaporation from soils and plants separately (Ritchie, 1972). Detail information to estimate ET can be found in Williams et al. (2012) and Zhang et al. (2016b). Potential plant water evaporation is computed by Eq. (1):

$$EP = \begin{cases} LAI \times EO/3 & 0<LAI<3 \\ EO & LAI>3 \end{cases} \tag{1}$$

Where, EP is the potential plant water evaporation ($mm\,d^{-1}$), EO is the potential evaporation ($mm\,d^{-1}$).

The soil water evaporation is calculated based on Eq. (2).

$$SE = \begin{cases} PSE \times e^{-2.5\times\frac{FC-ST}{FC-PWP}} & PWP<ST<FC \\ PSE & FC \le ST \end{cases} \tag{2}$$

Where, SE is the soil water evaporation (mm), PSE is the potential soil evaporation (mm), ST is soil water content in the root zone ($cm^3\,cm^{-3}$).

The crop field ET (ET_c) during the growing season is then computed as Eq. (3):

$$ET_c = EP + SE \tag{3}$$

2.4. Development of crop water production functions (CWPFs)

2.4.1. Definition of CWPFs

CWPFs were defined as the relationship between simulated grain yield (GY) and the actual evapotranspiration (ET), irrigation amount (I), or total available water supply (TWS):

$$CWPF_1 = Y\,(ET) \tag{4}$$

$$CWPF_2 = Y\,(I) \tag{5}$$

$$CWPF_3 = Y\,(TWS) \tag{6}$$

$$TWS = I_{eff} + P_{eff} + ASW\text{-}DP \tag{7}$$

$$\mathrm{ASW} = RZSW_f - RZSW_i \tag{8}$$

Where *ET* is the actual evapotranspiration, mm; *I* is irrigation amount which is equal to effective irrigation (I_{eff}) which is net irrigation in Eq. (7), as the runoff and percolation due to model irrigation were zero, mm; P_{eff} is effective rainfall, which is equal to 'rainfall – runoff', mm; *ASW* is available soil water, mm. $RZSW_i$ is the initial soil water in the root zone at planting, mm; and $RZSW_f$ is the final soil water in the root zone at maturity, mm; and *DP* is deep percolation, mm.

2.4.2. Irrigation scheduling to obtain CWPFs

The derived CWPFs are obtained by model simulations as APEX supports automatic irrigation scheduling based on the adjustment of water factor (WF), which was defined as (Steglich et al., 2014):

$$ITR = 1 - WF,\ 0 \le WF \le 1 \tag{9}$$

where *ITR* is irrigation trigger point; *WF* is the water factor, which can be set from 0 to 1 in the irrigation management interface of the APEX model. Irrigation will be triggered when the plant reaches a (1 − *WF*) stress level. The (1 − *WF*) equals the fraction of plant water stress allowed. The value of '0' for WF means rainfed conditions that automatic irrigation will never be triggered. The value of '1' for *WF* does not allow plant water stress through automatic triggering irrigation. The crop will reach yield potential without any drought stress when *WF* is set to '1'.

For the derivation of CWPFs, thirteen levels of *WF* was set to obtain the relationship between GY and ET, I and TWS: 0, 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 0.95 and 1. The APEX model simulated and outputted the yield, irrigation, ET runoff, percolation for 14 years for each of these 13 water stress factors. The TWS was calculated according to Eqs. (7) and (8).

2.5. Yield response to water stress

The yield response factor to water stress or water deficit (K_y) during soybean growing season was determined by relating the relative simulated yield decrease ($1 - Y_a/Y_m$) to the corresponding relative evapotranspiration deficit ($1 - ET_a/ET_m$), using the method given by Doorenbos and Kassam (1979) and Steduto et al. (2012) in Eq. (10).

$$(1 - Y_a/Y_m) = K_y\,(1 - ET_a/ET_m) \tag{10}$$

where Y_a is the actual harvest grain yield, $kg\,ha^{-1}$, and ET_a represents crop field ET during growing season, mm; Y_m is the maximum harvest yield under non-limiting water conditions by irrigation, $kg\,ha^{-1}$, and ET_m represents the corresponding maximum evapotranspiration under no drought stress in each soil type, mm. The Y_a, Y_m, ET_a and ET_m are obtained from simulations by APEX model.

K_y were derived using both field observations and model predictions.Values of $K_y > 1$ indicate that crop is very sensitive to water stress or water deficit with proportional larger yield reductions when water use is reduced because of drought stress; Values of $K_y < 1$ indicate that crop is more tolerant to water stress or water deficit, and recovers partially from stress, exhibiting less than proportional reductions in yield with reduced water use; Values of $K_y = 1$ indicate yield reduction is directly proportional to reduced water use (Steduto et al., 2012).

2.6. Statistical analysis

A process-based crop model generally is considered well calibrated and validated if it responds to management practices with reasonable accuracy in terms of Nash-Sutcliffe modeling efficiency (EF) and the mean absolute error (MAE) (Ahjua and Ma, 2002; Hassanli et al., 2016). To evaluate MAE more quantitatively and easily, the relative mean absolute error (RMAE), defined as the ratio of mean absolute simulation error to mean of the observed values, was used to evaluate model performance for each outcome of interest. The relative MAE (RMAE) may be calculated from MAE as:

$$MAE = \frac{\sum_{i=1}^{N} |P_i - O_i|}{N} \quad (11)$$

$$RMAE = \frac{MAE}{\bar{O}} \quad (12)$$

The Nash-Sutcliffe modeling efficiency (EF) (Nash and Sutclliffe, 1970) is defined as:

$$EF = 1.0 - \frac{\sum_{i=1}^{N} (P_i - O_i)^2}{\sum_{i=1}^{N} (O_i - \bar{O})^2} \quad (13)$$

Where P_i is the model predicted valuesand O_i is the experimental measured values; $\bar{O}$ is the mean of measured values; N is the number of values. Small RMAE means a better model performance, so RMAE = 0 indicates a perfect match between experimental and modeling results. If the RMAE value was within 10% for all measurements, it was considered a 'very good' for model evaluation, and a value within 20% was considered 'good', within 30% is considered 'satisfactory', and greater than 30% is considered 'poor' for agricultural models (Jamieson et al., 1991; Ma et al., 2011). The performance of crop model was acceptable when EF was greater than 0.5 (Moriasi et al., 2007a,b). EF = 1 indicates a perfect match between simulations and measurements.

Several statistical parameters such as sum, average, standard deviation, maximum and minimum were used in this paper. All statistical computation for this paper were implemented using SAS software, version 9.2.

3. Results

3.1. Evaluation of APEX model for simulation of soybean growth and yield

The APEX model was successfully calibrated and validated using the two-year field experimental data in the previous study by Zhang et al. (2016a), and the calibrated plant parameters were utilized for the work presented here. The detailed comparison of simulated and measured soybean growth and grain yield results were not repeated in this paper. In brief, we conducted detailed evaluation of simulated and measured soybean growth, including daily dry biomass (BIOM) and leaf area index (LAI).

Validation results for BIOM indicated a good agreement between simulated and measured values for VARF, DERF, OKSM, BRSM, OKhalfSM and BRhalfSM, with RMAE values ranging between 4.64% and 10.64% (Fig. 2), respectively. Although OKhalfSM (particularly on July 14, July 25, Aug 18 and Sep 10) had a large bias of 1.23–2.11 Mg ha^{-1} between simulated and measured BIOM, and the corresponding RMAE was also large, the simulated BIOM was reasonable and within acceptable error levels (Fig. 2). Fig. 3 shows a good validation on LAI, with R^2 = 0.91 and RMAE = 12.44%. However, the deviation from a 1:1 line indicated the different treatments had different performance for LAI validation. The relationship between predicted and observed LAI values appeared to have somewhat larger bias for VARF and OKSM than that for OKhalfSM, DERF, BRSM and BRhalfSM, in disagreement with treatment rankings for bias on simulated vs. measured BIOM values. Simulated GY and ET_c were in good accordance with those measured values in the evaluation dataset (Table 2). Additionally, the evaluation results of GY and ET_c were reasonable, with EF of 0.89 and 0.90 respectively, which fitted to the established criteria for acceptable correlation. Moreover, it was a good

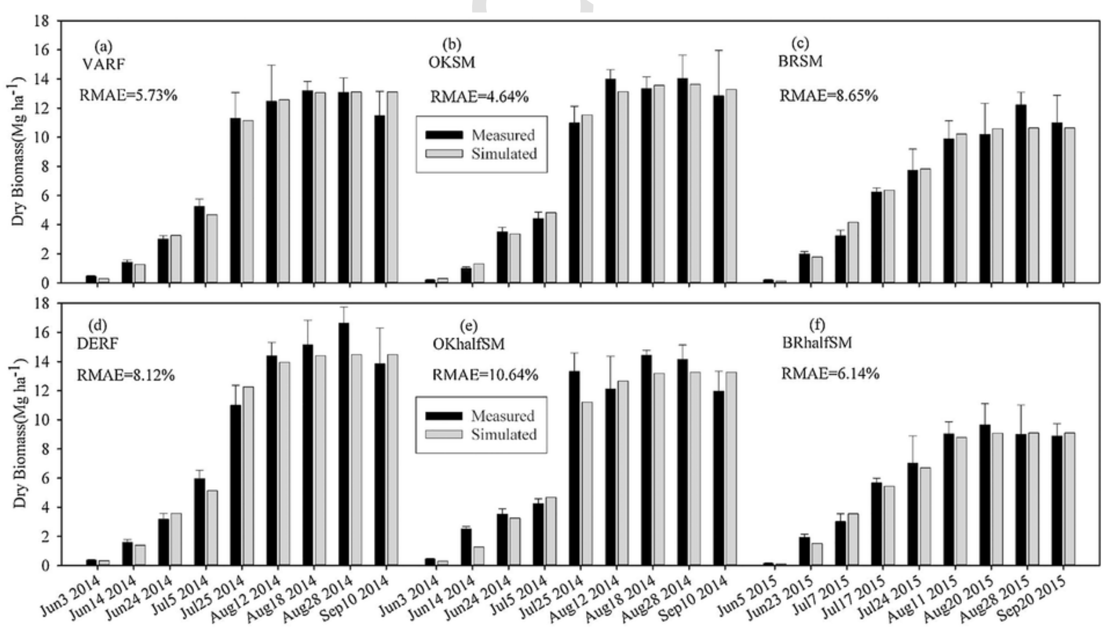

Fig. 2. Measured and simulated daily dry biomass (BIOM) along the crop season for six treatments (VARF, OKSM, BRSM, DERF, OKhalfSM and BRhalfSM). RMAE is the ratio of the mean absolute error (MAE) to the mean measured values, and the error bars are standard deviation of measured BIOM.

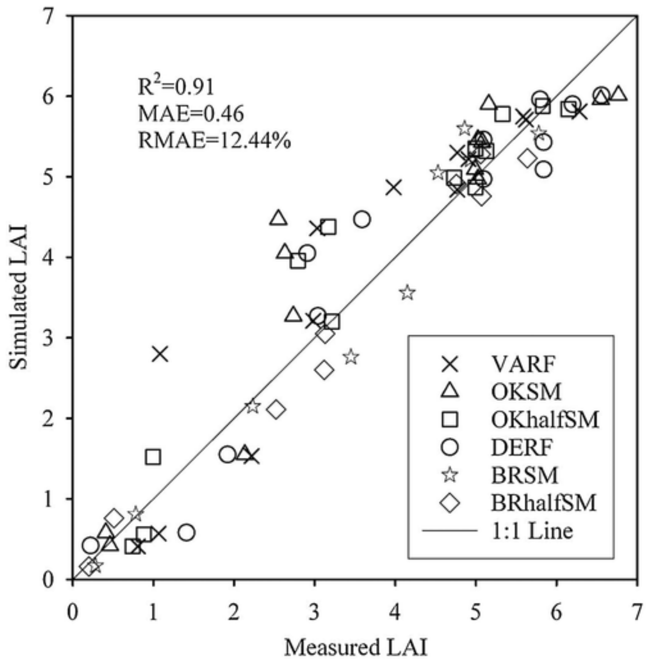

Fig. 3. Relationship between measured and simulated daily leaf area index (LAI) for six treatments (VARF, OKSM, OKhalfSM, DERF, BRSM and BRhalfSM). RMAE is the ratio of the mean absolute error (MAE) to the mean measured values.

comparison between simulated and measured GY and ET_c, with RMAE values of 9.7% and 13.34% respectively (Table 2).

3.2. Long-term average CWPFs across 14 years for three soils

The long-term (14-year) average CWPFs were defined as averaged simulated soybean grain yield (GY) in response to different levels of averaged seasonal actual evapotranspiration (ET), irrigation amount (I) and total water supply (TWS) for Vaiden, Cahaba and Demopolis soil types. Scatter plot (Fig. 4) showed a strong linear relationship between simulated soybean grain yield (GY) and the seasonal crop evapotranspiration (ET) for each soil under 14-year average weather condition, with R^2 of 0.96 for Vaiden, 0.97 for Cahaba, and 0.99 for Demopollis, respectively. WUEs indicated by the slopes in the linear regression models of CWPF for yield vs. ET were 13.41 kg ha^{-1}mm^{-1} for Vaiden, 14.91 kg ha^{-1}mm^{-1} for Cahaba, 14.76 kg ha^{-1}mm^{-1} for Demopollis. However, the 95% confidence intervals of the slopes were (11.67, 15.14) for Vaiden, (13.20, 16.61) for Cahaba, and (13.90, 15.62) for Demopollis, respectively, and this overlap pattern of confidence intervals showed no significant difference among the three estimated slopes from the linear regression models. Therefore, an overall model should be adequate to describe WUE for all the three soil types, which was y = 13.60 *ET* – 1245.60, $R^2 = 0.95$, and the 95% confidence interval of the slope was between 12.55 and 14.64. The physical meaning of the slope of the CWPF for yield vs ET has been interpreted as the water productivity (WP) or water use efficiency (WUE) (Tolk and Howell, 2008), and a higher slope expressed a higher WUE. Overall, the Y(ET) functions averaged over all 14 years across three soils was linear, with the WUE of around 13.60 kg ha^{-1}mm^{-1}.

On the other hand, the functions (CWPFs) of average simulated GY with irrigation amount (I) for all the three soil types fitted well by cubic polynomials, with R^2 values of 0.98–0.99 (Fig. 5). At zero level of irrigation (rainfed condition), the point at which the response to irrigation started, Vaiden-silty clay soil had the highest yield, followed in order by Cahaba-sandy loam and Demoplis-clay loam (Fig. 5). Considering the variance in soil properties, this order corresponded to the available water capacity of the three soils (Table 1). The data in Fig. 5 also shows that the maximum yield obtained with irrigation was the same in all three soils. In addition, the slope of CWPFs for simulated GY vs irrigation represented irrigation water productivity (IWP) or irrigation water use efficiency (IWUE), and a higher slope meant higher IWUE. As the CWPFs for GY vs irrigation was $y = f(I) = aI^3 + bI^2 + cI + d$, $I \geq 0$ and $a < 0$, the IWUE can be estimated using the method proposed by Bos (1980, 1985), IWUE = $\{f(I) - f(0)\}/I = aI^2 + bI + c$. So, the relationship for IWUE and irrigation was quadratic. Averaged across 14 years, Demopolis had the highest maximum IWUE value of 7.70 kg ha^{-1}mm^{-1}, that value of 5.83 kg ha^{-1}mm^{-1} was in the middle for Cahaba, and that value of 3.07 kg ha^{-1}mm^{-1} was the lowest for Vaiden (Table 3). Accordingly, under average weather conditions (averaged across 14 years), the irrigation amount to achieve maximum IWUE was 108, 123 and 132 mm for Vaiden, Cahaba and Demopolis, respectively (Table 3).

Similar cubic equations were found in the functions (CWPFs) of average simulated GY with TWS for all the three soil types, with R^2 values of 0.99–1.00 (Fig. 6). The CWPFs for three soils varied greatly at TWS values between 300 and 400 mm, but then gradually came closer together at larger values of TWS. This indicates that in this range of TWS, in addition to TWS, the differences among soils in hydraulic conductivity and pressure head-water relation were important factors affecting the plant water uptake and GY. These differences also affected the rainfall use efficiency (ratio of yield and effective rainfall) in the soils before irrigation was applied, as indicated by large differences in GY

Table 2
Summary statistics of evaluation results for grain yield (GY), and weekly evapotranspiration (ETc). STDEV is standard deviation. This is a comparison between simulated and measured values for evaluation of the APEX model.

	N[a]	Simulated		Measured		EF	MAE	RRMAE
		Mean	STDEV	Mean	STDEV			
GY (Mg ha^{-1})	12	5.08	1.15	5.14	1.54	0.86	0.5	9.70%
ET_c (mm)	216	23.62	12.51	24.01	12.74	0.9	3.2	13.34%

[a] N, number of observations; EF, Nash-Sutcliffe efficiency; MAE, mean absolute error; RRMAE, mean absolute error normalized to the mean of the observed values.

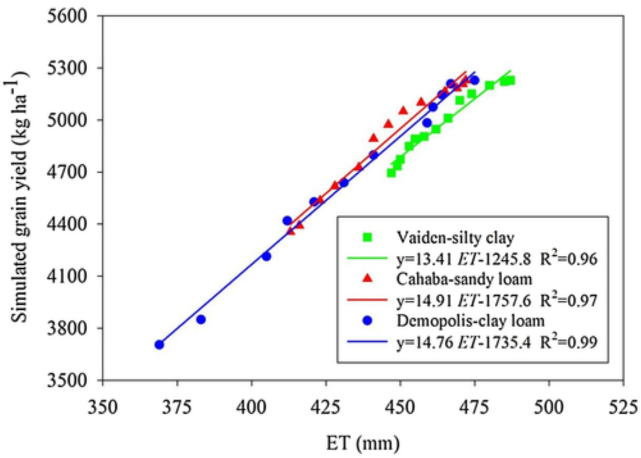

Fig. 4. Average simulated soybean grain yield *vs.* evapotranspiration across 14 years.

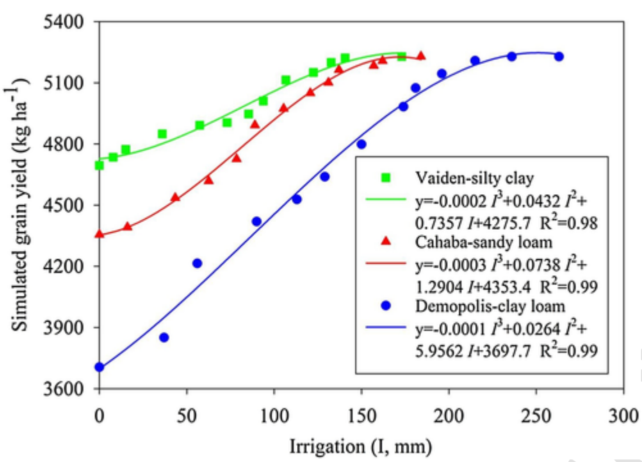

Fig. 5. Average simulated soybean grain yield *vs.* seasonal irrigation across 14 years.

values among the soils just before the irrigation was applied, corresponding to TWS values of 309, 303 and 222 mm for Vaiden, Cahaba and Demopolis, respectively (Table 3). Furthermore, the difference of the yield response to TWS in this range was mostly due to the initial soil water content, which was different for the different soils of 0.28–0.46 m/m (Zhang et al., 2016a,b). The maximum GY (Y_{max}') under average weather conditions were similar for three soils (close to yield potential under non-water limitation) and obtained at the same value of TWS (TWS_{max} values to obtain Y_{max}' were 489, 487 and 487 mm for Vaiden, Cahaba and Demopolis, respectively) (Table 3). Because of cubic nature of the GY-TWS curve, the highest GY increase was found at the TWS value of 399, 395 and 355 mm for Vaiden, Cahaba and Demopolis, respectively (Table 4).

3.3. CWPFs in wet year and dry year for Vaiden, Cahaba and Demopolis

In addition to the average CWPFs across 14 years, CWPFs were examined in one wet year (2003) with seasonal rainfall of 566 mm and one dry year (2006) of 272 mm to demonstrate the CWPFs of Y(I) and Y(TWS) under extreme wet and dry weather conditions in a humid region like Mississippi, which would support more detailed information for irrigation management. The wet and dry category year was determined by the value of rainfall during growing season based on empirical frequency analysis, the detailed steps were shown in Zhang et al. (2016a). Similar to average CWPFs on Y(I), the relationships between simulated GY and irrigation amount in the wet year ($CWPF_{WI}$) and dry year ($CWPF_{DI}$) were non-linear. Cubic polynomials fitted well to these data, with R^2 values of 0.98–0.99 for the three soil types (Fig. 7). The functions for wet year were closer together than the functions for 14-year average weather conditions, but for the dry year, they were similar to the average functions. The maximum GY obtained with irrigation was similar for all soils in the wet year, as well as the dry year; however, the maximum yield was higher in the dry year than in the wet year. The slope of CWPFs on Y(I) indicated that the IWUE from the three soils was relatively similar in the wet year though a relatively higher value was found for Demopolis soil type (Fig. 7a). However, the slope of CWPFs indicated that the values of IWUE varied greatly among the soil types in the dry year, with a higher value for Demopolis, a mediate value for Cahaba and a lower value for Vaiden (Fig. 7b). The maximum IWUE ($IWUE_{max}$) was relatively low in the wet year compared with that in the dry year. The $IWUE_{max}$ values in the dry year varied greatly among the three soils, with values of 3.14, 6.77 and 9.89 kg ha^{-1} mm^{-1} for Vaiden, Cahaba and Demopolis, respectively (Table 2). While, the $IWUE_{max}$ val-

Table 3
The maximum irrigation water use efficiency ($IWUE_m$) and the corresponding irrigation amount (I_{max}). The $IWUE_{max}$ and I_{max} variables are provided for different weather conditions and soil types, and those values are derived from simulation.

Category weather conditions	Soil types	$I_{max} = -b/2a$	$IWUE_{max}$
		mm	kg ha^{-1} mm^{-1}
Average weather conditions†	Vaiden	108	3.07
	Cahaba	123	5.83
	Demopolis	132	7.70
The wet year (2003)	Vaiden	83	2.58
	Cahaba	97	2.69
	Demopolis	94	3.27
The dry year (2006)	Vaiden	252	3.14
	Cahaba	289	6.77
	Demopolis	237	9.89

Average weather conditions means the mean weather conditions, for which simulation results obtained under each of the different weather conditions across 14 years from 2002 to 2015 were averaged.

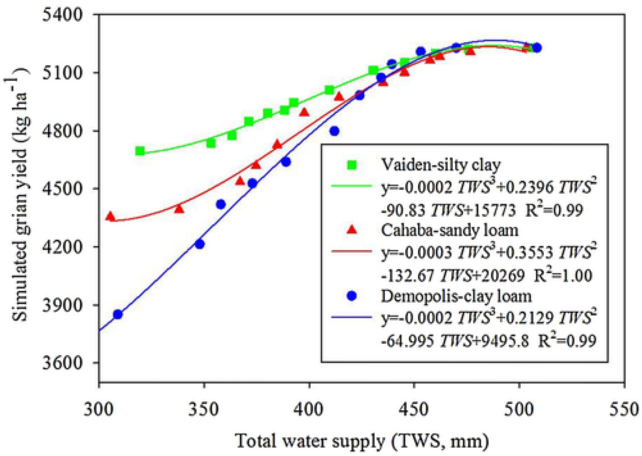

Fig. 6. Average simulated soybean grain yield vs. total water supply across 14 years. TWS is equal to "effective irrigation + effective rainfall + available soil water − deep percolation".

ues in the wet year were close to each other among the three simulated soils, with the values of 2.58, 2.69 and 3.27 $kg\,ha^{-1}mm^{-1}$ for Vaiden, Cahaba and Demopolis, respectively (Table 3). Similar to the average conditions, the highest $IWUE_{max}$ value was found in Demopolis, while the lowest $IWUE_{max}$ was found in Vaiden soil type both in the wet and dry year. The irrigation amount required to obtain $IWUE_{max}$ in the dry year ranging from 237 to 289 mm was higher than that in the wet year from 83 to 97 mm (Table 3).

The CWPFs for GY vs TWS were also cubic polynomials for the three soils in both the wet and dry year, with R^2 values from 0.99 to 1.00 (Fig. 8). Again, the functions Y(TWS) for wet year were closer together than the functions for 14-year average weather conditions, but for the dry year, were similar to the 14-year average functions. The rainfed yield values among the three soil types varied greatly from 2170 to 4696 in the dry year, while those values in the wet year were very close to each other from 4575 to 4643 $kg\,ha^{-1}$ (Table 4). For the dry year, the yield difference (Y_d') between Y_{max}' (the maximumu yield under certain TWS) and Y_{min}' (rainfed yield) was 923, 2540 and 3521 $kg\,ha^{-1}$ for Vaiden, Cahaba and Demopolis, respectively, indicating a large variance among the three soil types, whereas variance in the wet year was relativley small, with corresponding Y_d' values of 246, 252 and 320 $kg\,ha^{-1}$, respectively (Table 4). Relatively lower rainfed (Y_{min}') values in the dry year corresponded to lower TWS values caused by low rainfall in the dry year. On the contrary, higher TWS amount corresponding to Y_{max}' (TWS_{max}) values from 569 to 585 mm were observed in the dry year, which produced higer Y_{max}' values than the wet year among the simulated three soils (Figs. 8 and 9; Table 4). The TWS values obtianed the rapidest GY increase velocity (TWS_{maxv}) were close across the simulated three soils both in the wet and dry year, ranging from 363 to 412 mm (Table 4).

3.4. Yield response factor for water stress conditions

Averaged across 14 years and three soils, linear relationships were found between relative GY reduction ($1 - Y_a/Y_m$) and relative evapotranspiration loss ($1 - ET_a/ET_m$), with R^2 of 0.97 and $P < 0.01$(Fig. 9). The yield response factor (K_y) indicates the relative sensitivity of a given crop to drought stress or water deficit (Doorenbos and Kassam, 1979). The average K_y values across 14 years among three soils were 1.24 (Fig. 9), which indicated that the yield reduction was more than proportional to water deficit as $K_y > 1$. So, it was obvious that the soybean GY was easily affected by water deficit due to drought stress even in a humid region like Mississippi, with average K_y values more than 1. The yield estimation errors between measured and predicted values varied from 1.63% to 14.34% when using the derived K_y for the experimental years across soils to predict yield values. Meanwhile, the yield estimation errors of measured and predicted values were acceptable, with the EF value of 0.93.

4. Discussion

The three types of CWPFs developed here provide information on how much irrigation is needed to obtain the maximum profitable yield for a given soil type. If the required

Table 4
Grain yields and corresponding total water supply (TWS) obtained from soybean crop-water production functions.[a]

Category weather conditions	Soil types	Y_{max}'	Y_{min}'	TWS_{max}	TWS_{min}	TWS_{maxv}
		$kg\,ha^{-1}$		mm		
Average weather conditions	Vaiden	5264	4683	489	309	399
	Cahaba	5274	4344	487	303	395
	Demopolis	5236	3371	487	222	355
Wet year (2003)	Vaiden	4863	4617	459	341	400
	Cahaba	4895	4643	459	359	409
	Demopolis	4895	4575	431	329	380
Dry year (2006)	Vaiden	5619	4696	569	256	412
	Cahaba	5669	3130	585	215	400
	Demopolis	5692	2170	570	157	363

Y_{min}' and Y_{max}' are the minimum and maximum soybean grain yield under certain total water supply; and TWS_{min} and TWS_{max} are the corresponding total water supply.
TWS_{maxv} is the total water supply when yield got the highest increase velocity.
Average weather conditions means the normal weather conditions, for which simulation results obtained under each of the different weather conditions across 14 years from 2002 to 2015 were averaged.
[a] TWS is equal to "effective irrigation + effective rainfall + available soil water − deep percolation".

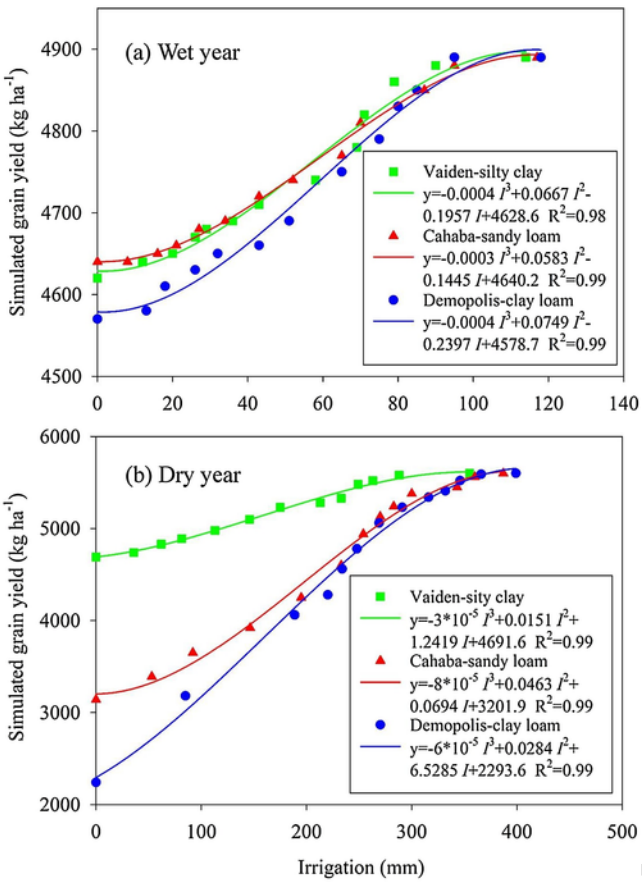

Fig. 7. Simulated soybean grain yield *vs.* irrigation in the wet and dry year.

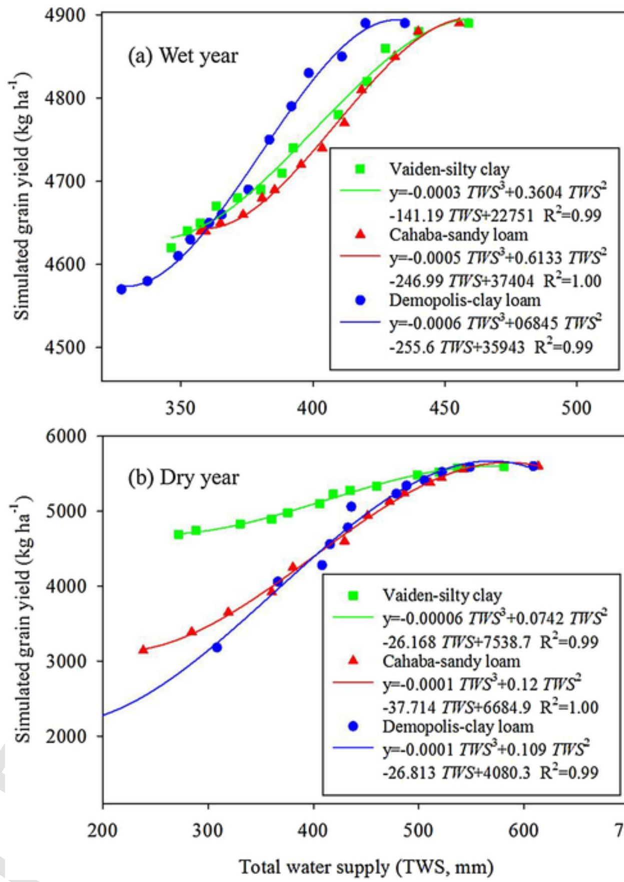

Fig. 8. Simulated soybean grain yield vs. total water supply in the wet and dry year. TWS is equal to "effective irrigation + effective rainfall + available soil wate − deep percolation".

amount of irrigation water is not available, they provide estimate of the crop yield obtainable with available water, thus helping to make the best use of available water.

4.1. Grain yield vs. evapotranspiration

Previous studies have shown a linear relationship between GY and crop evapotranspiration for many crops under irrigated conditions if water is not applied in excess, such as sorghum, corn, cotton and wheat (Tolk and Howell, 2008; Saseendran et al., 2015). The linear relationship between soybean GY and seasonal evapotranspiration in Fig. 4 is in agreement with the results of linear relationship between GY and seasonal ET_a reported by Nielsen (1990), Schneekloth et al. (1991), Stone (2003) and Pejić et al. (2011). Furthermore, the relationship for GY vs ET was mostly linear for 37 crops at various climatic conditions and locations in the world (Solomon, 1985). According to the observations, the GY and ET from experimental trials were within those simulated for the 14-years, which were also in the range of those reported in literature for soybeans. The linearity of GY and ET equation was on the basis of the assumption that the yield/biomass ratio was either constant, or decreased or increased linearly with change in plant transpiration (T) or ETc (Saseendran et al., 2015). However, Klocke et al. (1989) concluded that soybean GY was related to seasonal ET by a quadratic equation for four locations independent of stress timing. Similar quadratic polynomial for the relationship between soybean GY and ET for 2 years was observed by Candogan et al. (2013).

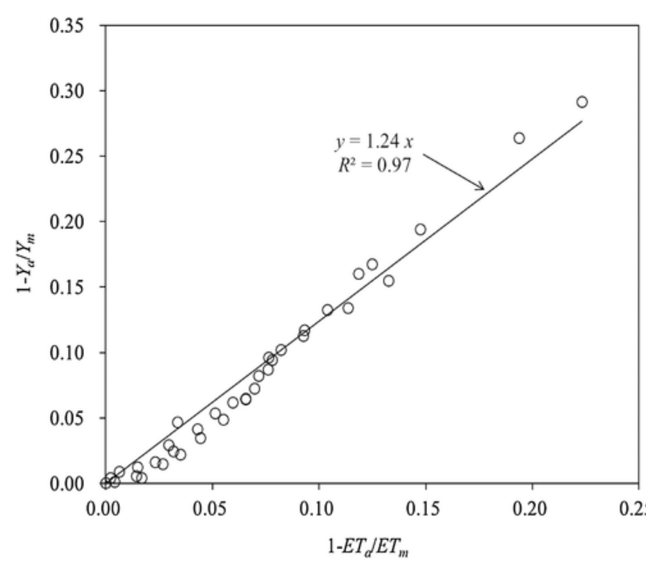

Fig. 9. Average soybean yield response factor (K_y) across 14 years and three soils. K_y is grain yield response to evapotranspiration reduction, which expresses the sensitivity of the crop to water stress. K_y is the ratial of $(1 - Y_a/Y_m)$ to $(1 - ET_a/ET_m)$.

The slope of the CWPFs for GY vs ET can be used as the WUE of soybean. In comparison of Vaiden-silty clay, the Demopolis-clay loam with a higher K_{sat} and lower AWC had a higer WUE (Fig. 4 and Table 1). Hence, The soil characteristics like K_{sat} and AWC was the main reason for the difference of CWPFs for GY vs ET among soils throng affecting soil evaporation, as the crop transpiration was relative similar. Meanwhile, it is reported that a change in slope of the function for GY vs ET was found when ET demand increased beyond an upper limit (Tolk and Howell, 2008).

4.2. Grain yield vs. irrigation

Compared with this study, similar cubic function for GY vs irrigation was reported for corn across three locations and soils (Saseendran et al., 2015). While, Gerçek et al. (2009) reported a quadratic polynomial relationship for soybean GY vs irrigation for four irrigated treatments from two year's field study in Turkey. The cubic equations fitted to the yield (irrigation) functions ($Y\ (I) = aI^3 + bI^2 + cI + d$, $I \geq 0$ and $a < 0$) can be used to estimate grain yield under rainfed conditions, as well as yield at different levels of irrigation. The maximum possible yield and the corresponding maximum irrigation amount can be obtained by setting the derivative of this equation equal to zero and taking the positive root of the resulting quadratic equation, as described in the text.

The maximum IWUE values ($IWUE_{max}$) derived from CWPFs for GY vs irrigation varied from 2.58 to 9.89 $kg\,ha^{-1}\,mm^{-1}$ across three simulated soil types and three weather conditions (Table 2). These results agreed with the IWUE for soybean ranging from 2.0 to 11.4 $kg\,ha^{-1}\,mm^{-1}$ under full seasonal irrigation found in a similar humid region of Georgia, the southeastern USA (Garcia y Garcia et al., 2010), as well as with soybean IWUE values from 3.1 to 11.5 $kg\,ha^{-1}\,mm^{-1}$ for the same region in Mississippi (Heatherly and Elmore, 1986). Some differences can result from the fact that this is a long-term simulated (14 years) study across three soil types, compared with the field experimental studies. In a different climatic region, relatively low IWUE values from 3.0 to 7.1 $kg\,ha^{-1}\,mm^{-1}$ in a 2-year soybean field study in Italy were reported by Casa and Lo Cascio (2008). Considering the soil types, Demopolis had the highest $IWUE_{max}$ ranging from 3.27 to 9.89 $kg\,ha^{-1}\,mm^{-1}$, that values for Cahaba were moderate from 2.69 to 6.77 $kg\,ha^{-1}\,mm^{-1}$ and the lowest for Vaiden from 2.58 to 3.14 $kg\,ha^{-1}\,mm^{-1}$ under three set of weather conditions. These results across three soil types probably can be explained by the great yield difference (Y_d) between maximum yield under full irrigation conditions and rainfed yield (Table 4). Whereas, the full irrigation yields (Y_{max}) were similar for all soils, the rainfed yield (Y_r) was highest for Vaiden, medium for Cahaba, and lowest for Demoplis, and these yield differences are proportional to the soils' available water holding capacities (Table 1).

The irrigation amount to achieve the maximum GY (I_{max}) for soybean was greatly different across three soil types and among three weather conditions, with a wide range of I_{max} values from 110 to 405 mm during the growing season (Table 5). Mullen et al. (2009) noted that the average irrigation demand from 1998 to 2003 was 221 mm for soybean in Mississippi. Garcia y Garcia et al. (2010) applied a relatively lower supplemental irrigation amount of 78–137 mm with sprinkler system during the growing season to obtain the maximum GY in a similar humid region of Georgia, Southeastern USA. Meanwhile, a higher irrigation amount of 617 mm was applied using drip system for soybean under a full seasonal irrigation conditions in a sub-humid region in Turkey (Sincik et al., 2008). Therefore, considering the wide range of irrigation amount in other similar humid regions, our findings of supplemental irrigation needed to obtain maximum yield were in agreement with the previous results.

Based on the characteristics of CWPFs for GY vs irrigation, it was decreasing function in the range of $I \geq I_{max}$, suggesting that GY will decrease when extra irrigation was applied after the I_{max} point. Similar result was reported by Risadi et al. (2005) that negative effect on GY may occur when irrigation was applied before a heavy rain. Because in that situation soil moisture may approach to field capacity or saturation, which reduced soil aeration for roots' respiration and brings percolation and runoff taking nutrients

Table 5
Grain yields and corresponding irrigation amount derived from soybean crop-water production functions.[a]

Category weather conditions	Soil types	Y_r	Y_{min}	Y_{max}	I_r	I_{min}	I_{max}	I_{maxv}
		$kg\,ha^{-1}$			mm			
Average weather conditions	Vaiden	4728	4728	5135	0	0	152	72
	Cahaba	4353	4353	5232	0	0	172	82
	Demopolis	3698	3698	5275	0	0	254	88
The wet year (2003)	Vaiden	4628.60	4628.46	4882	0	1.49	110	56
	Cahaba	4640.20	4640.11	4948	0	1.25	128	65
	Demopolis	4578.70	4578.51	4938	0	1.61	123	62
The dry year (2006)	Vaiden	4692	4692	5699	0	0	373	168
	Cahaba	3202	3202	5526	0	0	387	193
	Demopolis	2294	2294	5610	0	0	405	158

Y_{min} and Y_{max} are the minimum and maximum soybean grain yield, and I_{min} and I_{max} are the according irrigation amount.
I_{maxv} is the irrigation amount when yield got the rapidest increase velocity.
Average weather conditions means the normal weather conditions, for which simulation results obtained under each of the different weather conditions across 14 years from 2002 to 2015 were averaged.
[a] Y_r is the soybean grain yield under rainfed conditions and I_r is the according irrigation amount.

away. Vaiden soil had the highest Y_r values of 4728 and 4629 Mg ha^{-1} under average weather conditions and the dry year, Cahaba was in the middle with values of 4353 and 3202 Mg ha^{-1}, and Demopolis produced the lowest values of 3698 and 2294 Mg ha^{-1} (Table 5). However, similar Y_r values of 4600 Mg ha^{-1} were estimated for three soils in the wet year. Notably, the minimum GY (Y_{min}) across the three soils in the wet year was a little lower than the corresponding rainfed yield (Y_r), which probably caused by extra water by irrigation (Table 5).

The maximum yield (Y_{max}) values were similar for the three soils under the average weather conditions, the wet year or the dry year (about 5200, 4900 and 5600 kg ha^{-1} respectively, Table 6). The lower Y_{max} on the wet year was that a wet year means more rainfall and lower solar radiation which was used to calculate the plant growth by APEX model. These results agreed that under optimal conditions of water and nutrition, crop growth and yield was not affected by soil properties, but determined solely by solar radiation, temperature, atmospheric CO_2, and genetic traits (Evans, 1993, 1998; Van Ittersum et al., 2013; Grassini et al., 2015). However, the small Y_{max} difference among three soils under full irrigation may be caused by the difference speed of supplemental irrigation determined by soil properties. The K_{sat} values was 2.15, 7.48 and 6.85 mm/h for Vaiden-silty clay, Cahaba-sandy loam and Demopolis-clay loam, respectively (Table 1).

For 14 year averages, the irrigation amounts to achieve Y_{max} values (I_{max}) for Vaiden, Cahaba and Demopolis soils were 152, 172 and 254 mm, respectively (Table 5). As expected, the corresponding I_{max} values were higher in the dry year. Meanwhile, similar I_{max} values were founded in the wet year for the three soils (Table 5).

4.3. Grain yield vs. total water supply

The relationship between GY and TWS was cubic function regardless of soil types and weather conditions. Similar cubic function for GY and TWS was reported for corn by Saseendran et al. (2015). On the other hand, a quadratic equation of GY and TWS has been reported by many researchers (Stewart and Hagan, 1973; Zhang and Oweis, 1999; Sepaskhah and Akbari, 2005). The amount of TWS for soybean varied from 431 to 585 mm during the growing season (Table 4), which agreed with the reported water demand for soybean of 385–617 mm to produce maximum yield depending on climatic conditions and variety (Sincik et al., 2008; Garcia y Garcia et al., 2010); while to achieve Y_{max} under full irrigation conditions, the soybean cultivars Sahar, G3 and DPX required 550, 580 and 640 mm of TWS, respectively (Kiani and Abbasi, 2012). Furthermore, TWS varied greatly as TWS was very dependent on climatic conditions. The irrigation amount for different conditions and probably location can be calculated by Y(TWS) function with the knowledge of local rainfall. Similar to Y(I), Y(TWS) was decreasing function on the range of $TWS \geq TWS_{max}$, which mean that GY will decrease if the amount of TWS were higher than the value of TWS_{max} (Table 4).

4.4. Yield response factor

Under average weather conditions, the yield response factor (K_y) was greater than 1 (Fig. 9), which indicated that soybean was very sensitive to water stress (WS) even in a humid region like Mississippi. Similar results were reported by Karam et al. (2005) and Paz et al. (2007) that supplemental irrigation was required to alleviate WS and achieve a high soybean yield due to the uneven distribution of rainfall during the growing season in a humid region. The simulated results showed that soybeans were more sensible to water stress in R4 and R5 stages. Korte et al. (1983) observed a single irrigation during R3-R4 increased seeds per plant and irrigation during R5-R6 increased weight per seed. Pejić et al. (2011) noted that yield soybean was more sensitive to water stress at the stage of flowering and yield formation-pod development and pod filling with K_y of 0.41 and 0.46, compared with vegetative of K_y of 0.31. Thus, soybeans were more sensitive to water stress during R3 to R5. Under rainfed conditions, Demopolis-clay loam produced the lowest, Cahaba-sandy loam the moderate GY and Vaiden-silty clay the highest GY (Table 5). These results show that Demopolis was the most sensitive to WS, while Vaiden-silty clay can be more tolerant to WS. A relatively higher soil available water content (AWC) of 0.19 m/m probably were the main reason to ensure Vaiden-silty clay more tolerant to WS with a relatively low K_y (Table 1). In contrast, the lowest AWC value of 0.16 m/m probably resulted in Demopolis-clay loam the most sensitive to WS accompanying the proportional yield reduction with the highest K_y (Table 1). Thus, AWC (FC, PWP) was the main reason of the K_y difference. Related to FC (Ahuja et al., 1989), the saturated hydraulic conductivity (K_{sat}) may be another factor to affect water stress and water use through affecting water loss. This agreed with that Cahaba produced the highest percolation of 171.40 mm by the highest K_{sat} of 7.48 mm/h among three simulated soils.

The linear relationship between relative yield reduction $(1 - Y_a/Y_m)$ and relative evapotranspiration deficit $(1 - Y_a/Y_m)$ observed in the three soil types agreed with the reports by Doorenbos and Kassam (1979), Rosadi et al. (2007) and Pejić et al. (2011). The soybean K_y values of 1.24 under average weather conditions agreed with those of 0.00–1.30 in Indonesia reported by Rosadi et al. (2007). Therefore, the K_y values can serve as a reference and knowledge base for soybean growers to determine irrigation schedule under different soil conditions in this humid region like Mississippi. Under rainfed conditions in humid areas, variability in seasonal rainfall leads to year-to-year variability in the uptake of water and nutrients, and in the growth, development and yield of the crop (Scott et al., 1986), supplemental irrigation was necessary to increase GY and ensure stability in yields. Hence, the relative yield $(1 - Y_a/Y_m)$ versus the relative evapotranspiration $(1 - ET_a/ET_m)$ functions, presented in Eq. (10) and Fig. 9, bring the yield (ET) function of all different soils to coalesce together and thus have a technology transfer application. These functions allow the transfer of the knowledge of CWPF for one location to another if the maximum ET (ET_m) and Y (Y_m) of the other location are known.

5. Conclusions

(1) Linear relationships were established between simulated soybean GY and the seasonal ET for all the three soils under 14-year average weather conditions, with R^2 of 0.97.
(2) The relationship of CWPFs for GY vs irrigation was cubic polynomial among the three soils under three weather conditions. The irrigation amount to achieve the maximum GY (I_{max}) of 110–405 mm during the growing season was greatly different across three soils and weather conditions. Cubic equations were also observed for the relationship between GY and TWS regardless of soils and climatic conditions. The amount of TWS to obtain maximum GY for soybean varied from 431 to 585 mm during the growing season under three weather conditions.
(3) The yield response factor (K_y) values can serve as a reference and knowledge base for soybean growers to apply irrigation under different soil conditions. Our results indicated that K_y was greater than 1 across three soils under average weather conditions, suggesting soybean was sensitive to water stress even in a humid region like Mississippi. The sensitivity to water stress (K_y) differed with soil properties of available water content (AWC), indicating that soil properties of water holding capacity and permanent wilting point should be considered to illustrate water stress.
(4) The soil-specific soybean CWPFs presented in this study can be used to optimize the use of the available water resources for agricultural production. The long-term average functions are very useful tool for strategic planning of supplemental irrigation, system design, and management for soybean in Mississippi. The examples of wet and dry year CWPFs also help in allocation of irrigation water from year to year using the weather forecasts.

Uncited reference

Hanks (1983).

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