Computers in Agriculture

Effects of Estimating Soil Hydraulic Properties and Root Growth Factor on Soil Water Balance and Crop Production

Liwang Ma,* Gerrit Hoogenboom, S. A. Saseendran, P. N. S. Bartling, Lajpat R. Ahuja, and Timothy R. Green

ABSTRACT

Accurate simulation of plant growth depends not only on plant parameters, but also on soil parameters. Although there is uncertainty in measured soil parameters and root distributions, their effects on simulated plant growth have been much less studied. This study evaluates the simulated responses of six crops, wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), barley (*Hordeum vulgare* L.), soybean (*Glycine max* L. Merr.), peanut (*Arachis hypogaea* L.), and chickpea (*Cicer arietinum* L.), under various water and N management to different methods of estimating soil hydraulic properties and soil root growth factor (SRGF) in root zone water quality model (RZWQM2) that contains the decision support system for agrotechnology transfer (DSSAT) Version 4.0 plant growth models. The two methods of obtaining the soil water retention curve (SWRC) in RZWQM2 were based on (i) known soil water contents at both 33 and 1500 kPa suctions, or (ii) soil water content at 33 kPa only. The two methods of estimating saturated hydraulic conductivity (K_{sat}) were (i) soil texture class based average K_{sat} or (ii) K_{sat} calculated from effective porosity (difference between soil water contents at saturation and at 33 kPa). For the six crops, simulation results showed that the soil water balance was affected more by K_{sat} than by SWRC, whereas the simulated crop growth was affected by both K_{sat} and SWRC. Small variations in the SRGF did not affect soil and crop simulations, and SRGF could be estimated with a simple exponential equation.

Agricultural system models have become more important as research and decision support tools for optimizing water and N management, because they can be used to explore a wide range of soil-crop-management options and interactions in a quick and cost-effective manner (Tsuji et al., 1998; Ahuja et al., 2002). However, the use of such models has been a challenge to the agricultural community because of intensive input data requirements and lack of guidelines for obtaining these data, such as soil, plant, and climate characterization. Model users often do not have all the input data required for a system model and thus depend on the model to estimate missing data. Although sensitivity analyses of the missing input variables are useful, it is not an easy task to apply the sensitivity results in model parameterization (Ma et al., 2000; Walker et al., 2000; Boote et al., 2008). To help model users, various databases have been developed or included as guidelines along with parameter estimation schemes (Ahuja and Ma, 2002; Gijsman et al., 2007).

Soil hydraulic properties, including soil hydraulic conductivity and SWRCs, have significant impacts on the soil water balance and, as a result, on crop growth (Kribaa et al., 2001; Hupet et al., 2004a, 2004b). In a numerical analysis using the soil, water, air, plant (SWAP) model Hupet et al. (2004b) showed that simulated actual transpiration and yield were more responsive to soil hydraulic parameters (K_{sat} and SWRC) under dry climate conditions than under wet conditions. In another study, Hupet et al. (2004a) found that soil hydraulic conductivity curves obtained from soil water retention curves using a pedotransfer function (PTF) were questionable in estimating soil evapotranspiration. Gijsman et al. (2003) evaluated eight PTFs for estimating drained upper limit (DUL), lower limit of plant extractable water (LL), and saturated soil water content (SAT) and found that simulated soybean yield varied greatly among PTF estimated DUL, LL, and SAT. They also questioned the accuracy of lab-measured DUL and LL for parameterizing a crop model. Experimentally, effects of soil hydraulic properties on plant growth have been widely documented in the literature. For example, Kribaa et al. (2001) observed a significant variation in wheat yield due to altered hydraulic properties as a result of various cultivation methods in a semiarid climate.

Another important soil-plant parameter in system models is an empirical parameter to describe root growth in different soil layers. In the decision support system for agrotechnology transfer (DSSAT) crop growth models, this parameter is called the soil root growth factor (SRGF) (Calmon et al., 1999a, 1999b). The SRGF determines the ability of roots to grow and proliferate in a soil layer, which in turn affects the potential amount of

L. Ma, S.A. Saseendran, P.N.S. Bartling, L.R. Ahuja, and T.R. Green, USDA-ARS, Agricultural Systems Research, 2150 Centre Ave., Bldg. D, Fort Collins, CO 80526; G. Hoogenboom, Univ. of Georgia, 1109 Experiment St., Griffin, GA 30223. Received 24 Nov. 2008. *Corresponding author (Liwang.Ma@ars.usda.gov).

Published in Agron. J. 101:572–583 (2009).
doi:10.2134/agronj2008.0206x

Abbreviations: AET, actual evapotranspiration; CSM, crop system model; DSSAT, decision support system for agrotechnology transfer; DUL, drained upper limit; ET, evapotranspiration; K_{sat}, saturated soil hydraulic conductivity; LL, lower limit of plant extractable water; PET, potential evapotranspiration; PTF, pedotransfer function; RZWQM2, root zone water quality model; SRGF, soil root growth factor; SWRC, soil water retention curve.

soil water that can be extracted by roots from this layer. Wang et al. (2003) used the measured soil root distribution at harvest to derive SRGF for their CROPGRO applications. In other applications, the SRGF was used to calibrate soil moisture and crop production arbitrarily without considering soil characteristics (Calmon et al., 1999a; Fang et al., 2008). Optimization schemes such as the adaptive simulated annealing method were also used to derive SRGF for each soil layer to match soil water contents and soil water extraction (Calmon et al., 1999b; Dardanelli et al., 2003). Because there is no consensus on parameterizing SRGF for crop growth, further analysis of SRGF on crop production is needed to better understand soil-root interaction and to guide model users.

The RZWQM2 is an agricultural system model that has been widely used to simulate management effects on soil water quality and crop growth (Ahuja et al., 2000; Ma et al., 2007). It has a user-friendly interface and input databases to facilitate its applications. For example, the soil texture class based soil hydraulic properties from Rawls et al. (1982) are provided in the model. The model provides several ways of estimating SWRC as described by the Brooks–Corey equations (Brooks and Corey, 1964): soil texture class based parameters (Rawls et al., 1982), estimates from soil water contents at 33 kPa soil suction (Williams and Ahuja, 1992), and estimates from soil water contents at both 33 and 1500 kPa soil suctions (Ahuja et al., 2000). If users have measured SWRC, they can derive their own Brooks–Corey parameters and enter them in the model. The RZWQM2 also offers two methods of estimating saturated soil hydraulic conductivities (K_{sat}) if the users have no measured values: soil texture class mean values (Rawls et al., 1982) and estimation from effective soil porosity (Ahuja et al., 1989). For some applications, users also have calibrated K_{sat} values to match measured soil hydrology (soil water content, runoff, and drainage) (Fang et al., 2008).

Recently, the DSSAT4.0 crop modules (Jones et al., 2003) were incorporated into RZWQM2 (Ma et al., 2005, 2006, 2008). This hybrid model has an advantage over DSSAT4.0 in the areas of (i) detailed soil water balance calculations (e.g., solving Richards' Equation, macropore flow, subsurface drainage), (ii) a broad range of agricultural management practices, (iii) detailed surface energy balance, and (iv) pesticide fates (Ma et al., 2005, 2006).

In this new hybrid model, we also allow either user-defined SRGF or values calculated from Jones et al. (1991) by

$$\mathrm{SRGF}(z)=\begin{cases}=1 & z\le 15\ \mathrm{cm}\\ =\left(1-\dfrac{z}{z_{\max}}\right)^{\mathrm{WCG}} & z>15\ \mathrm{cm}\end{cases} \quad [1]$$

where SRGF*(z)* is the soil root growth factor at soil depth z (dimensionless); z_{max} is the maximum rooting depth (cm); and WCG is an exponential geotropism constant. In DSSAT4.0, computational soil layers are at 5, 15, 30, 45, and 60 cm, and then at 30 cm intervals thereafter. Calmon et al. (1999b) found that WCG of 3.0 was adequate in their simulation of soybean using the CROPGRO model.

Since both soil hydraulic properties and SRGF are important in simulating crop growth (Hupet et al., 2004a, 2004b; Calmon et al., 1999b), it is important to evaluate how different methods of estimating soil hydraulic properties and SRGF affect the soil water balance and plant growth. This result will increase the confidence of model users in using the different parameter estimation methods when no measured values are available. In this study, we selected the RZWQM2 model with built-in multiple methods of estimating soil hydraulic properties and SRGF. Six crops, namely, wheat, maize, barley, soybean, peanut, and chickpea, from six experiments as released with DSSAT4.0 package were chosen to test their responses to various methods of estimating soil hydraulic properties and SRGF. Each experiment was first simulated with RZWQM2 and then the simulation results were compared to those from the original DSSAT4.0 package to make sure DSSAT4.0 was implemented correctly in RZWQM2. These RZWQM2 scenarios then served as reference runs for evaluating the effects of soil hydraulic properties and SRGF on plant growth. Specific objectives of this study were: (i) to evaluate soil water balance and crop production using soil hydraulic properties (SWRC and K_{sat}) estimated from either soil texture, soil water contents at 33 kPa suction, or soil water contents at both 33 and 1500 kPa suctions; and (ii) to compare crop productions using two SRGF distributions with WCG = 2.0 and 3.0 in Eq. [1].

MATERIALS AND METHODS

The Root Zone Water Quality Model 2

An earlier linkage between a root zone water quality model and DSSAT3.5 was completed in 2005 (Ma et al., 2005, 2006), which was updated to DSSAT4.0 (Jones et al., 2003) and released as RZWQM2 (http://www.ars.usda.gov/Main/docs.htm?docid = 17740) (Ma et al., 2008). The RZWQM-DSSAT3.5 hybrid model contains only three crops (wheat, corn, and soybean) and was tested by Ma et al. (2005, 2006), Yu et al. (2006), Saseendran et al. (2007), and Thorp et al. (2007). The RZWQM2-DSSAT4.0 hybrid model has a total of 19 crops along with a few new features. For example, the new user interface allows users to derive the soil water retention curve parameters (Brooks–Corey parameters) from the soil water contents at 33 and 1500 kPa. Therefore, soil hydraulic properties can be estimated from the DUL (assumed to be soil water content at 33 kPa) and LL of plant extractable soil water (assumed to be soil water content at 1500 kPa).

The SWRC (relationship between volumetric water content θ, $cm^3\ cm^{-3}$ and suction head τ, cm) is described by the Brooks–Corey equation (Brooks and Corey, 1964) in RZWQM2:

$$\begin{aligned}\theta(\tau)&=\theta_s & \tau&\le\tau_b\\ \theta(\tau)&=\theta_r+B\tau^{-\lambda} & \tau&>\tau_b\end{aligned} \quad [2]$$

where $B = (\theta_s - \theta_r)\,\tau_b^{\lambda}$. θ_s and θ_r are the saturated and residual soil water contents, respectively; λ is a pore size distribution index; and τ_b is the bubbling suction head. The corresponding equations for soil hydraulic conductivity, K(τ), are

$$\begin{aligned}K(\tau)&=K_{sat} & \tau&\le\tau_b\\ K(\tau)&=K_{sat}\tau^{-N_2} & \tau&>\tau_b\end{aligned} \quad [3]$$

where K_{sat} is soil hydraulic conductivity (cm h^{-1}) and $N_2 = 2+3\lambda$ (Ahuja and Ma, 2002). When the soil water contents at 33 and 1500 kPa suctions are given, λ and τ_b can be calculated:

$$\lambda = \frac{\ln[(\theta_{1/3} - \theta_r)/(\theta_{15} - \theta_r)]}{\ln(15{,}000/333)} \quad [4]$$

and

$$\tau_b = \exp\left[\frac{\ln(\theta_{1/3} - \theta_r) - \ln(\theta_s - \theta_r) + \lambda\ln(333)}{\lambda}\right] \quad [5]$$

where θ_{15} and $\theta_{1/3}$ are soil water contents at 1500 kPa (15,000 cm) and 33 kPa (333 cm) suctions, and θ_r is residual soil water content and can be obtained from Rawls et al. (1982) for each soil texture class. We also found that $\theta_r = 0$ provided similar simulation results for the six experiments in this study without modifying other soil and plant parameters. If default θ_r from Rawls et al. (1982) were to be used, some recalibration of the soil and plant parameters might be needed to repeat the original results in DSSAT4.0. Soil water retention curve estimated by using both the 33 and 1500 kPa suction soil water contents is denoted as $SWRC_2$ (using two soil water contents on the curve).

Another way of deriving the Brooks–Corey parameters is the one-parameter (λ) model (Ahuja and Williams, 1991; Williams and Ahuja, 1992, 2003). Rearranging Eq. [2], we have:

$$\ln(\tau) = a + b\ln(\theta - \theta_r) \quad [6]$$

where $a = \ln(B)/\lambda$ and $b = -1/\lambda$. Ahuja and Williams (1991) found that:

$$a = p + qb \quad [7]$$

where $p = -0.52$ and $q = 0.67$ for all soil texture classes when τ is in kilopascals (1 kPa = 10 cm water suction) (Williams and Ahuja, 2003). Thus, from Eq. [6] and [7], b (hence λ) can be calculated from $\theta_{1/3}$ and θ_s, and then τ_b from Eq. [6] and B from a and λ (Williams and Ahuja, 2003). The SWRC estimated by using the 33 kPa suction soil water content only is denoted as $SWRC_1$ (using one soil water content on the curve).

Two methods of estimating saturated soil hydraulic conductivity (K_{sat}) are incorporated in RZWQM2. One is from soil texture class (*st*) based average K_{st} (Rawls et al., 1982) and the other is from effective porosity (ep) as (Ahuja et al., 1989):

$$K_{ep} = 764.5 \times (\theta_s - \theta_{1/3})^{3.29} \quad [8]$$

In this study, three combinations of K_{sat} and SWRC methods were evaluated. $K_{ep}SWRC_1$ denotes the case when K_{sat} is estimated from effective porosity and SWRC is from the one-parameter model. $K_{ep}SWRC_2$ is the case when K_{sat} is estimated from effective porosity and SWRC is from DUL and LL. $K_{st}SWRC_2$ is the case when K_{sat} is from soil texture mean value and SWRC is from DUL and LL. $K_{ep}SWRC_1$ and $K_{ep}SWRC_2$ were used to show SWRC effects, and $K_{st}SWRC_2$ and $K_{ep}SWRC_2$ were to show the K_{sat} effects on simulated AET, N leaching, water drainage, crop yield, and biomass.

Datasets Selected from Decision Support System for Agrotechnology Transfer 4.0

Of the 19 crops currently in RZWQM2 hybrid model, three cereal crops (maize, wheat, barley) and three legume crops (soybean, chickpea, and peanut) were selected to evaluate the CERES and CROPGRO models in RZWQM2. One observed field experiment was selected for each crop based on completeness of data and treatment effects. The DSSAT4.0 model adequately simulated crop responses to water and N applications in these experiments.

Maize

The maize dataset was collected at the University of Florida, Gainesville, FL (named UFGA8201 in DSSAT4.0), and documented in Bennett et al. (1989). The experiment was conducted on a Millhopper fine sand (loamy, siliceous, semiactive, hyperthermic Grossarenic Paleudults) with two N levels (low at 116 kg N ha^{-1} and high at 401 kg N ha^{-1}) and three irrigation levels (rainfed with only 1.3 cm irrigation at planting, vegetative stressed with 20.1 cm during the growing season, and fully irrigated with 26.4 cm during the growing season) in 1982. Precipitation during the growing season was 66.1 cm. The maize cultivar McCurdy 84 AA was planted on 26 Feb. 1982 at a density of 7.2 seeds m^{-2} and harvested on 2 July 1982.

Wheat

The wheat dataset was from Saskatchewan, Canada (SWSW7501 in DSSAT4.0) as documented in Campbell et al. (1977). The experiment was conducted on a Wood Mountain Loam in 1975. Wheat variety 'Manitou' was planted on 25 May at 250 seeds m^{-2} and harvested on 21 Aug. 1975. The two water levels were dry (rainfed) and irrigated (26.7 cm during growing season). Four N levels were 0, 41, 82, and 123 kg N ha^{-1} before planting. Precipitation during the growing season was 15.6 cm.

Barley

The barley dataset was collected by International Centre for Agricultural Research in the Dry Areas (ICARDA) in Breda, Syria (IEBR8201 in DSSAT4.0) as documented in Brown et al. (1987). The experiment was conducted on a Typic Calciorthid soil (clay loam) in 1982–1983. The barley cultivar Arabic Abiad was planted on 15 Nov. 1982 at 225 seeds m^{-2} and harvested on 19 May 1983. The two fertilizer treatments were 0 and 40 kg N ha^{-1}. Precipitation during the growing season was 23.6 cm.

Chickpea

The chickpea dataset was collected at International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in Patancheru, India (ITBP8502 in DSSAT4.0). The experiment was conducted on a fine montmorillonitic isohyperthermic typic pallustert (sandy clay loam) in 1985 and documented in Singh and Sri Rama (1989) and Singh and Virmani (1996). Chickpea cultivar Annigeri was planted on

Table 1. Cultivar parameters of the crops evaluated in the DSSAT4.0-CERES model.

Parameter	Definition	Maize	Wheat	Barley
P1	Thermal time from seedling emergence to the end of Juvenile phase during which the plants are not responsive to changes in photoperiod (degree days) (maize).	265	–	–
P1V	Relative amount that development is slowed for each day of unfulfilled vernalization, assuming that 50 d of vernalization is sufficient for all cultivars (wheat, barley).	–	30	10
P1D	Relative amount that development is slowed when plants are grown in a photoperiod 1 h shorter than the optimum (which is considered to be 20 h) (wheat, barley).	–	55	20
P2	Extent to which development is delayed for each hour increase in photoperiod above the longest photoperiod at which development is at maximum rate, which is considered to be 12.5 h (days) (maize).	0.3	–	–
P5	Thermal time from silking (or grain filling) to physiological maturity (maize, wheat, barley).	920	370	200
G1	Kernel number per unit weight of stem (less leaf blades and sheaths) plus spike at anthesis (g^{-1}) (wheat, barley).		30	12
G2	Maximum possible number of kernels per plant (maize) or kernel filling rate under optimum conditions (mg per day) (wheat, barley).	990	24	40
G3	Kernel filling rate during the linear grain filling stage and under optimum conditions (mg d^{-1}) (maize) or nonstressed dry weight of a single stem (excluding leaf blades and sheaths) and spike when elongation ceases (g) (wheat, barley).	8.5	1.7	0.7
PHINT	Phylochron interval (degree days) (maize, wheat, barley).	39	60	75

5 Nov. 1985 at 30 seeds m^{-2} and harvested on 22 Feb. 1986. The three irrigation levels are 4.5, 10.8, and 21.2 cm during the growing season. Precipitation during the growing season was 10.5 cm.

Soybean

The soybean dataset was collected at the University of Florida, Gainesville, FL (UFGA8501 in DSSAT4.0), and documented in Stanton (1986). The experiment was also conducted on a Millhopper fine sand in 1985. The two water levels were rainfed (only 1.7 cm irrigation at planting) and irrigated (16.3 cm during the growing season). Precipitation during the growing season was 67.5 cm. The soybean cultivar Cobb was planted on 20 June 1985 at 22 plants m^{-2} and harvested on 26 Oct. 1985.

Peanut

The peanut dataset was collected at the University of Florida, Gainesville, FL (UFGA8901 in DSSAT4.0) and documented in Ma (1991). The experiment was also conducted on a Millhopper fine sand in 1989. The two water levels were rainfed (only 1.1 cm shortly after planting) and irrigated (9.1 cm during the growing season). Total precipitation during the growing season was 60 cm. The peanut variety Florunner was planted on 6 Apr. 1989 at 17 plants m^{-2} and harvested on 3 Sept. 1989.

Calibrating the Root Zone Water Quality Model 2 for Reference Scenarios

All the DSSAT4.0 simulations for each experiment were the same as those released without any modification. To run the same experiments with RZWQM2, the crop parameters were used as they were released along with the DSSAT4.0 package (Hoogenboom et al., 2004) without any further modification, which are listed in Tables 1 and 2. The Brooks–Corey parameters used to define the SWRCs were estimated from soil water contents at 33 and 1500 kPa suctions by Eq. [4]. In the datasets selected, K_{sat} was given only for the fine sand cropped to soybean, peanut, and maize. We therefore estimated the K_{sat} for other soils from effective porosity by Eq. [8] (Ahuja et al., 1989). The RZWQM2 also requires rainfall intensity, which was not available. We assumed a 2-h duration for all daily rainfall events without attempting to match runoff from DSSAT4.0 (Ma et

Table 2. Cultivar parameters of the crops evaluated in the DSSAT4.0-CROPGRO model.

Parameter	Definitions	Soybean	Peanut	Chickpea
CSDL	Critical short day length below which reproductive development progresses with no day length effect (for short day plants), h	12.3	11.8	11.0
PPSEN	Slope of the relative response of development to photoperiod with time (positive for short day plants), h^{-1}	0.33	0.0	–0.14
EM-FL	Time between plant emergence and flower appearance (R1), photothermal days	21	21	30
FL-SH	Time between first flower and first pod (R3), photothermal days	9.2	9.2	8.0
FL-SD	Time between first flower and first seed (R5), photothermal days	16.0	18.8	15.0
SD-PM	Time between first seed (R5) and physiological maturity (R7), photothermal days	37.2	74.3	35.0
FL-LF	Time between first flower (R1) and end of leaf expansion, photothermal days	18.0	85.0	42.0
LFMAX	Maximum leaf photosynthesis rate at 30°C, 350 vpm CO_2, and high light, mg CO_2 per m^2–s	1.03	1.40	1.70
SLAVR	Specific leaf area of cultivar under standard growth conditions, cm^2 g^{-1}	375	260	150
SIZLF	Maximum size of full leaf (three leaflets), cm^2	190	18	10
XFRT	Maximum fraction of daily growth that is partitioned to seed + shell	1.0	0.92	1.0
WTPSD	Maximum weight per seed, g	0.158	0.680	0.181
SFDUR	Seed filling duration for pod cohort at standard growth conditions, photothermal days	23	40	29
SDPDV	Average seed per pod under standard growing conditions, no. per pod	1.90	1.65	1.20
PODUR	Time required for cultivar to reach final pod load under optimal conditions, photothermal days	10	24	18

Table 3. Soil organic C pools and total mineralization during the crop growing seasons.†

DSSAT4.0 crop model	Crop	Soil texture	Experimental ID	Fast organic matter pool	Intermediate organic matter pool	Slow organic matter pool	Total mineralization (RZWQM2)	Total mineralization (DSSAT4.0)
				%			kg ha^{-1}	
CERES	maize	fine sand	UFGA8201	35	35	30	46–58	49–60
	wheat	loam	SWSW7501	1	9	90	4–8	6–14
	barley	clay loam	IEBR8201	4	16	80	13	11
CROPGRO	soybean	fine sand	UFGA8501	25	25	50	22–27	30–36
	peanut	fine sand	UFGA8901	25	25	50	37–42	36–37
	chickpea	clay loam	ITBP8502	30	30	40	45–47	36–53

† DSSAT, decision support system for agrotechnology transfer; RZWQM2, root zone water quality model.

al., 1998). Albedo for dry soil was given in DSSAT4.0 for each soil and used in RZWQM2. Albedo values for wet soil, plant canopy, and crop residue were assumed to be 0.1, 0.2, and 0.8 based on default values provided in RZWQM2 for all the soils and crops (Farahani and DeCoursey, 2000).

To avoid the initialization procedure suggested by Ma et al. (1998), we did not simulate microbial growth in the RZWQM2 but used constant microbial populations throughout the simulation period (Ma et al., 2008). Soil C pools were manually partitioned so that total N mineralization was comparable to that simulated by DSSAT4.0 (Table 3).

RESULTS AND DISCUSSION

Reference Model Runs

Simulation results for the six crops using RZWQM2 were compared to results obtained from DSSAT4.0, and served as reference runs for evaluating the responses of RZWQM2 to soil hydraulic properties and SRGF(z). Using the soil albedo as defined in DSSAT4.0 for each experiment, RZWQM2 simulated similar potential evapotranspiration (PET) as DSSAT4.0 except for maize (Fig. 1). Simulated actual crop transpiration (AT) was also similar for both models (Fig. 1).

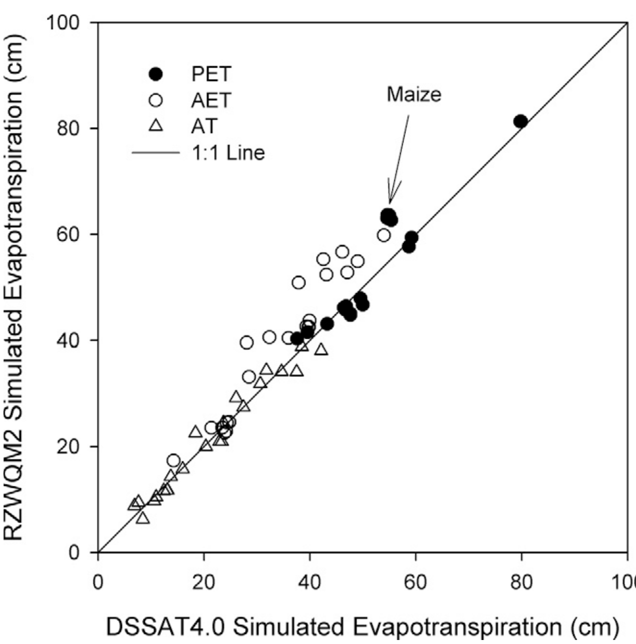

Fig. 1. Simulated potential evaportranspiration (PET), actual evapotranspiration (AET), and actual transpiration (AT) with RZWQM2 and DSSAT4.0 models.

However, simulated soil evaporation was generally higher in RZWQM2 than in DSSAT4.0 except for barley, which was possibly due to the wind effects on soil evaporation considered in the Suttleworth-Wallace PET module in RZWQM2 (Ma et al., 2005, 2006), compared to the Priestley-Taylor equation used in the DSSAT4.0 where wind effects are neglected (Ritchie, 1998). The higher actual evapotranspiration (AET) simulated in RZWQM2 was mainly due to the higher simulated soil evaporation. Utset et al. (2004) also found that the Priestley-Taylor equation simulated lower AET than the Penman–Monteith equation, but these differences did not alter the conclusion on simulated crop yield and crop water use. Almost no runoff was simulated in RZWQM2 due to the assumed 2-h rainfall events, without knowing the rainfall intensity (Ma et al., 1998). However, DSSAT4.0, using a curve number approach, simulated a few centimeters of runoff for maize, soybean, peanut, and chickpea. We could have adjusted rainfall intensity to exactly match the runoff to that of DSSAT4.0, but runoff was a very small percent of the soil water balance.

The DSSAT4.0 crop modules were adequately implemented in RZWQM2. Simulated grain yield and biomass at harvest were similar between DSSAT4.0 and RZWQM2 for all six crops (Fig. 2 and 3). Simulated overall RMSE of yield was 613 kg ha^{-1} for DSSAT4.0 and 634 kg ha^{-1} for RZWQM2. Corresponding overall RMSE of biomass for the six crops were 1194 kg ha^{-1} and 1114 kg ha^{-1}, respectively. Comparing the two models, a paired *t* test showed no significant difference across the six crops ($P = 0.45$ for yield and $P = 0.19$ for aboveground biomass). Comparing simulated yields to measured yields, values for the six crops were not significantly different ($P = 0.52$ for DSSAT4.0 and $P = 0.78$ for RZWQM2). However, comparing simulated aboveground biomass to measured aboveground biomass, values were significantly different ($P = 0.002$ for DSSAT4.0 and $P = 0.015$ for RZWQM2) based on a paired *t* test across the six crops. These tested RZWQM2 scenarios for the six crops were then used as reference model runs in subsequent sensitivity analyses for effects of soil hydraulic properties and SRGF.

Responses to Soil Hydraulic Properties

Since detailed soil hydraulic properties (K_{sat} and SWRC) are needed in RZWQM2, it is important to evaluate their effects on soil water balance and crop production. Estimated K_{sat} from effective porosity was very low compared to that from soil texture class for the Millhopper sand planted to maize, soybean, and peanut (Fig. 4), which was due to unreasonably

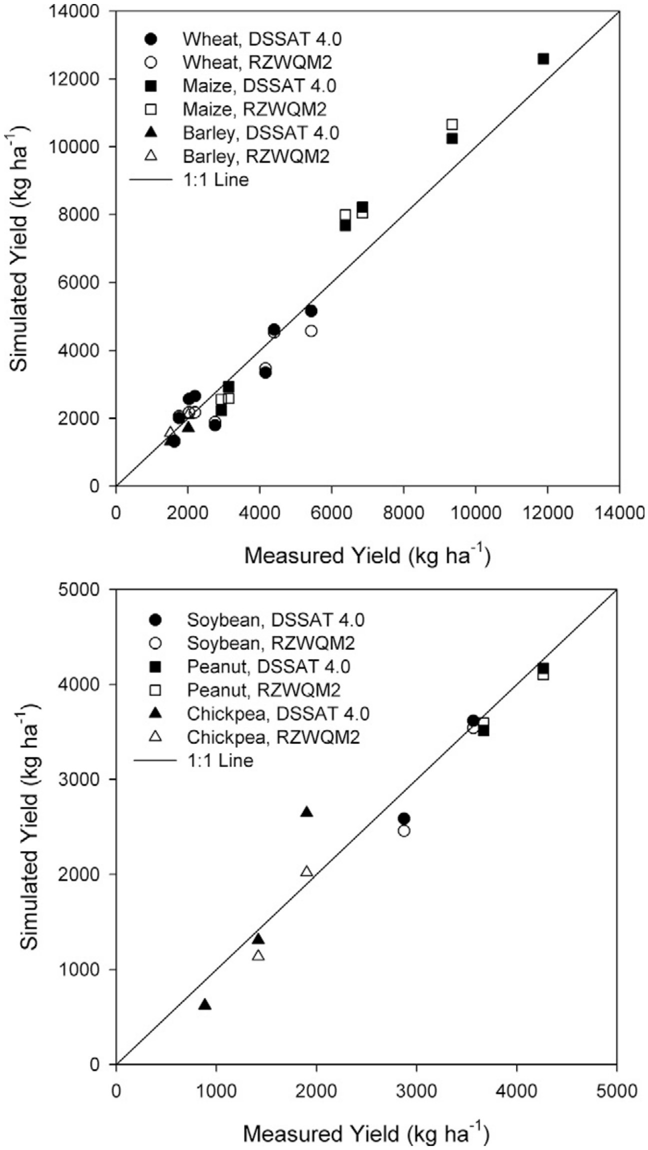

Fig. 2. For crop yield, measured vs. simulated with RZWQM2 and DSSAT4.0.

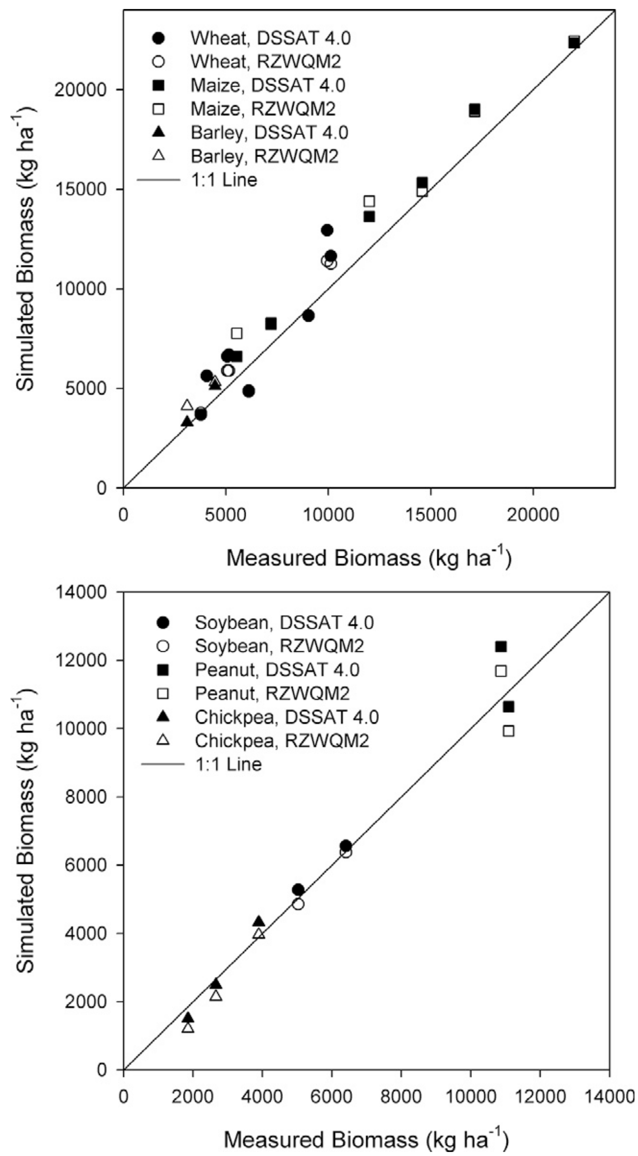

Fig. 3. For total aboveground biomass, measured vs. simulated with RZWQM2 and DSSAT4.0.

low saturated soil water content used in the DSSAT4.0 soil database for the soil (only 0.23 cm^3 cm^{-3} in the top soil layers). For the other three soils, K_{sat} from effective porosity was usually higher than those from soil texture (Fig. 4). As shown in Table 4, the two important parameters to characterize the SWRC (λ and τ_b) were quite different between the two SWRC methods, except for the Typic Calciorthid planted to barley. This result presents a challenge to model users, when only DUL (soil water content at 33 kPa) is experimentally available. The SWRC would be different depending on which method a user selects. In addition, DUL and LL might not be the same as soil water contents at 33 and 1500 kPa suctions (Ratliff et al., 1983). Although our DUL and LL values for the four soils were within the range given by Ratliff et al. (1983), there were variations among soil horizons (Table 4).

Soil water drainage at the bottom of the soil profile was affected more by K_{sat} than by the SWRC. For example, with a well-drained sand planted to maize, the average water drainage was 19 cm with $K_{ep}SWRC_2$, 21 cm with $K_{ep}SWRC_1$, and 42 cm with $K_{st}SWRC_2$, due to a much higher K_{sat} estimated from soil texture class than from effective porosity. Simulated drainage for other soils was small and was not very different among the estimated soil hydraulic properties. Surface runoff showed the opposite trend as drainage since runoff was calculated from excessive water input above K_{sat} in RZWQM2 (Ahuja et al., 2000). When K_{sat} was estimated from soil texture class, RZWQM2 generated close to zero runoff for all experiments. Higher runoff was simulated for the $K_{ep}SWRC_2$ than for the $K_{ep}SWRC_1$. Simulated effects of hydraulic properties on AET were not significantly different among the three methods ($P = 0.09$).

As expected, N leaching at the bottom of the soil profile followed the same pattern as water drainage among the three hydraulic estimation methods. In the case of maize, N leaching averaged about 20 kg N ha^{-1} for $K_{ep}SWRC_2$, 27 kg N ha^{-1} for $K_{ep}SWRC_1$, and 112 kg N ha^{-1} for $K_{st}SWRC_2$. On the average, simulated N leaching in the maize growing seasons increased 4.1 times for $K_{ep}SWRC_2$ and $K_{ep}SWRC_1$, and 5.4 times for $K_{st}SWRC_2$, as N application rate increased from 116 to 401 kg N ha^{-1}. Simulated maize yield was the best in terms of RMSE with $K_{st}SWRC_2$ (988 kg ha^{-1}). The RMSEs

Table 4. Brooks–Corey parameters for the soil water retention curves (SWRC) estimated from soil water contents at 33 and 1500 kPa.

Soil (crops)	Depth	SWRC from 33 and 1500 kPa soil water contents					SWRC from 33 kPa soil water content only				
		θ_s	$\theta_{1/3}$	θ_{15}	τ_b	λ	θ_s	$\theta_{1/3}$	θ_{15}	τ_b	λ
	cm										
Millhopper sand	5	0.230	0.096	0.026	26.08	0.3431	0.230	0.096	0.020	40.70	0.4157
(soybean, maize, peanut)	60	0.230	0.086	0.025	16.06	0.3240	0.230	0.086	0.016	36.15	0.4430
	120	0.230	0.090	0.028	15.61	0.3070	0.230	0.090	0.017	37.89	0.4317
	150	0.230	0.130	0.029	78.26	0.3940	0.230	0.130	0.036	62.30	0.3404
	180	0.360	0.258	0.070	125.93	0.3430	0.360	0.258	0.135	46.98	0.1701
Typic Calciorthid soil	5	0.460	0.290	0.170	12.42	0.1400	0.460	0.290	0.169	12.65	0.1411
(barley)	30	0.460	0.310	0.190	15.46	0.1290	0.460	0.310	0.193	13.98	0.1245
	105	0.460	0.330	0.220	14.71	0.1060	0.460	0.330	0.218	15.80	0.1090
Typic Pallustert	5	0.395	0.360	0.265	105.11	0.0805	0.395	0.360	0.258	115.12	0.0874
(chickpea)	20	0.395	0.337	0.200	104.51	0.1370	0.395	0.337	0.227	72.06	0.1038
	30	0.407	0.309	0.159	68.68	0.1750	0.407	0.309	0.192	36.95	0.1253
	40	0.407	0.310	0.154	75.68	0.1840	0.407	0.310	0.193	37.39	0.1245
	50	0.416	0.307	0.161	55.46	0.1700	0.416	0.307	0.189	30.39	0.1269
	60	0.416	0.300	0.155	50.56	0.1730	0.416	0.300	0.181	28.32	0.1326
	75	0.424	0.292	0.165	27.66	0.1500	0.424	0.292	0.172	22.91	0.1394
	90	0.424	0.262	0.165	6.32	0.1210	0.424	0.262	0.139	18.41	0.1663
	110	0.451	0.225	0.167	0.04	0.0780	0.451	0.225	0.103	11.01	0.2041
	179	0.451	0.225	0.160	0.08	0.0860	0.451	0.225	0.101	10.93	0.2074
Wood Mountain loam	5	0.440	0.230	0.096	19.71	0.2295	0.440	0.230	0.108	12.71	0.1987
(wheat)	30	0.440	0.250	0.112	22.81	0.2110	0.440	0.250	0.127	13.89	0.1779
	60	0.440	0.220	0.094	14.94	0.2230	0.440	0.220	0.099	12.21	0.2097
	90	0.440	0.235	0.103	19.05	0.2190	0.440	0.235	0.113	12.98	0.1933
	150	0.440	0.250	0.102	30.18	0.2350	0.440	0.250	0.127	13.89	0.1779

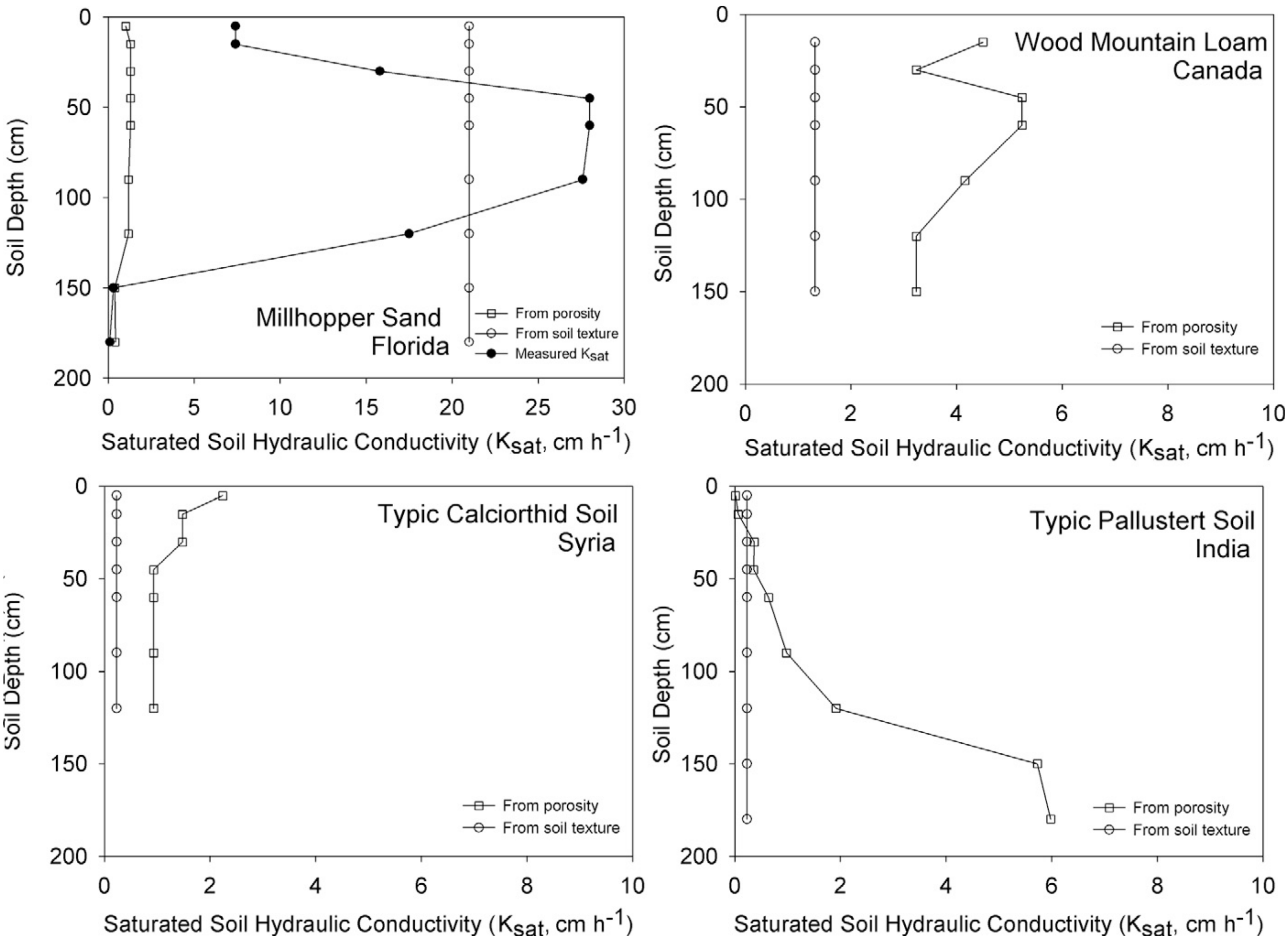

Fig. 4. Saturated soil hydraulic conductivity (K_{sat}) estimated from effective porosity (K_{ep}) and soil texture (K_{st}) for the four soils.

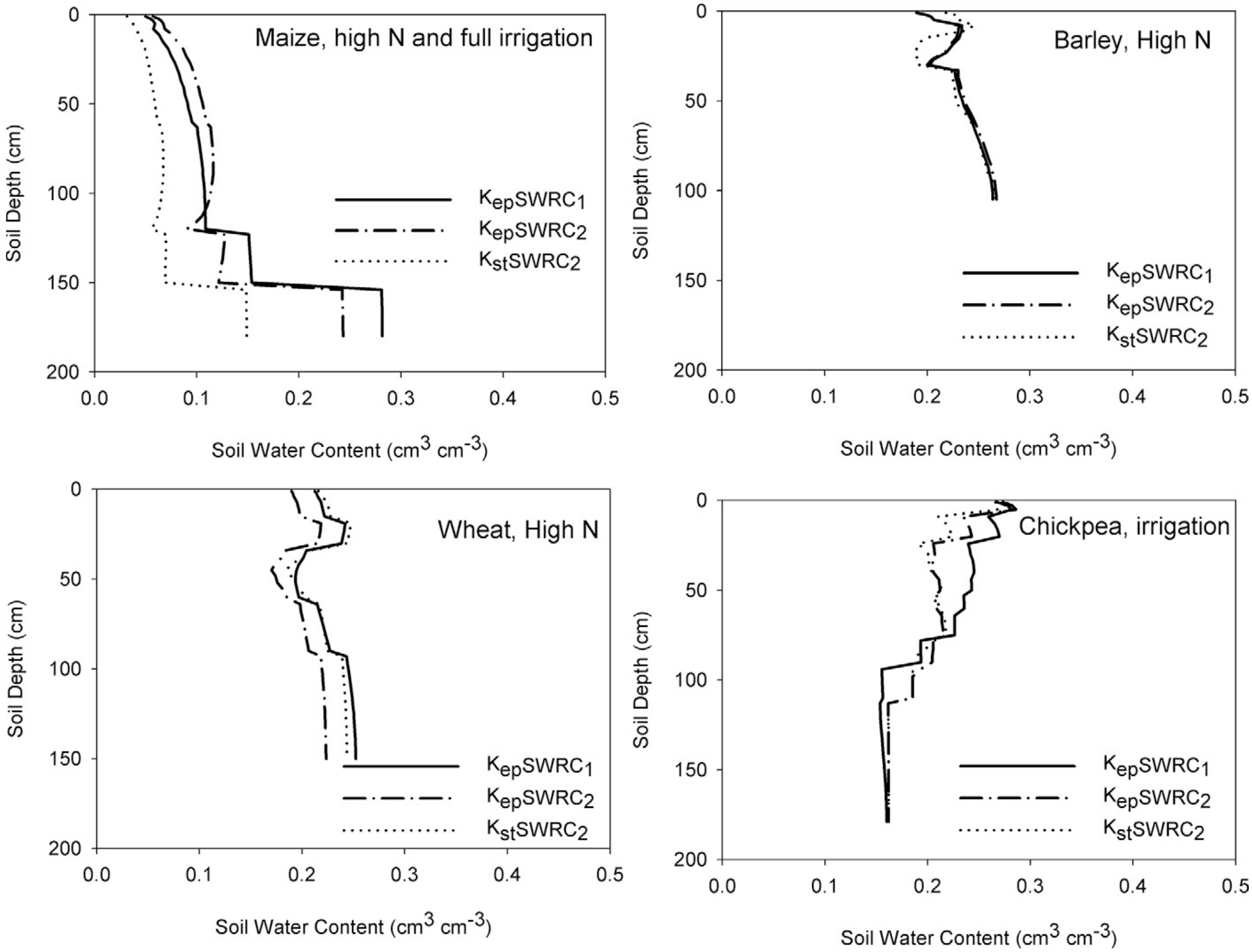

Fig. 5. RZWQM2 simulated soil water contents at harvest for the three methods of estimating soil hydraulic properties. One treatment was shown for each soil.

for simulated maize yield were 2886 and 1916 kg ha^{-1} with $K_{ep}SWRC_2$ and $K_{ep}SWRC_1$, respectively. The $K_{ep}SWRC_2$ provided the best yield prediction for all other crops with an overall RMSE of 389 kg ha^{-1} as compared to 721 and 431 kg ha^{-1} using the $K_{st}SWRC_2$ and $K_{ep}SWRC_1$ methods, respectively. Overall, the RMSE of simulated yield across the six crops were 799, 1215, and 1047 kg ha^{-1} for the $K_{st}SWRC_2$, $K_{ep}SWRC_2$, and $K_{ep}SWRC_1$ methods, respectively. Paired *t* test showed that the simulated yield across all six crops was not significantly different from measured yields for $K_{st}SWRC_2$ ($P = 0.15$) and for $K_{ep}SWRC_2$ ($P = 0.22$). However, a significant difference was found between the measured and simulated yield for $K_{ep}SWRC_1$ ($P = 0.04$), even though its RMSE was slightly smaller than $K_{ep}SWRC_2$ due to a consistent over prediction of yield for all six crops.

Similarly, simulated final aboveground biomass was the best using $K_{st}SWRC_2$, with an overall RMSE of 1520 kg ha^{-1}, followed by $K_{ep}SWRC_2$ (RMSE of 2021 kg ha^{-1}) and $K_{ep}SWRC_1$ (RMSE of 1999 kg ha^{-1}). Paired *t* test showed that simulated biomass across all six crops was not significantly different from measured values for $K_{st}SWRC_2$ ($P = 0.87$), but differences were significant for $K_{ep}SWRC_2$ ($P < 0.01$) and $K_{ep}SWRC_1$ ($P < 0.01$).

Based on these results, there is uncertainty in applying RZWQM2 when no measured soil hydraulic properties (K_{sat} and SWRC) are available. With respect to yield prediction, K_{sat} estimated from effective porosity worked well for wheat, barley, soybean, peanut, and chickpea irrespective of SWRC, but K_{sat} estimated from soil texture class did better overall for maize, even though it underpredicted the rainfed treatments. Twice as much drainage was predicted with K_{sat} estimated from soil texture class compared to K_{sat} from effective porosity for the maize experiments. In this case, the measured K_{sat} provided a better maize yield simulation (RMSE of 1057 kg ha^{-1}) than K_{sat} estimated from effective porosity (RMSE of 2286 kg ha^{-1}), but slightly worse than K_{sat} estimated from soil texture (RMSE of 988 kg ha^{-1}).

The effect of soil hydraulic properties on soil water distributions was best examined at harvest date, at the end of the growing season. Simulated soil water contents at harvest were different among the three hydraulic properties. However, the differences were not consistent from soil to soil (Fig. 5). For the sand planted to maize and the Typic Calciorthid soil planted to barley, soil water content at harvest was more determined by K_{sat}, but SWRC was the dominant factor for the Typic Pallustert soil planted to chickpea. It is interesting to see very similar soil water distributions between $K_{ep}SWRC_1$ and $K_{st}SWRC_2$,

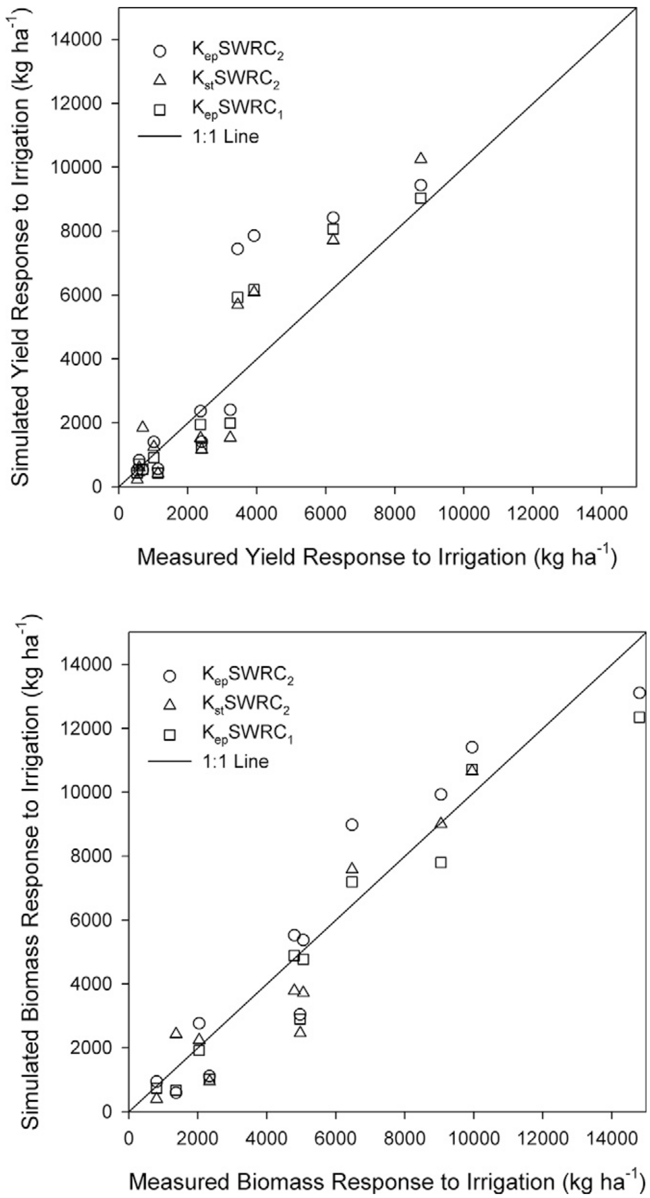

Fig. 6. RZWQM2 simulated RZWQM2 and measured differences between the irrigated and rainfed treatments (e.g., response to irrigation) for the three methods of estimating soil hydraulic properties.

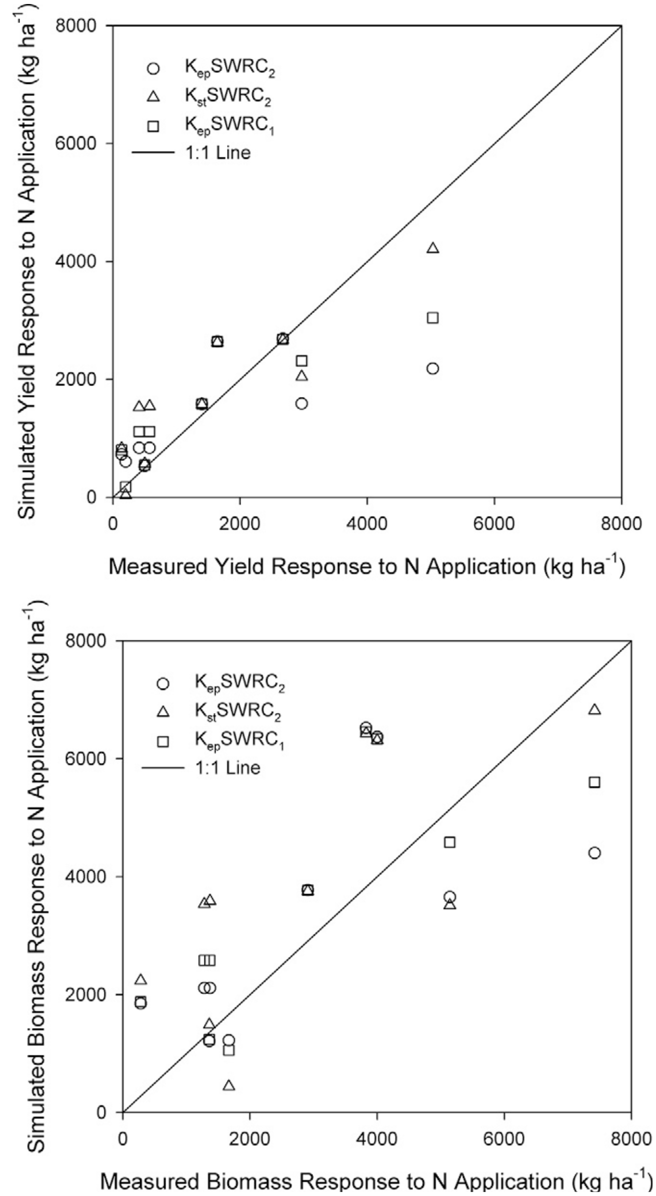

Fig. 7. RZWQM2 simulated and measured differences between the high and low N treatments (e.g., response to N) for the three methods of estimating soil hydraulic properties.

which shows the interaction between K_{sat} and SWRC on determining soil water content.

These results demonstrate the importance of evaluating soil water drainage and N leaching in addition to crop yield and biomass production. For example, simulated maize yield was the best with $K_{st}SWRC_2$. At the same time, it simulated much higher drainage and N leaching. Without the measured drainage and N leaching data to evaluate these high values, simulation of crop yield from $K_{st}SWRC_2$ should be treated cautiously. This study also demonstrated the effects of soil hydraulic properties on simulated crop responses to water and N treatments (Fig. 6 and 7). For example, when K_{sat} was estimated from effective porosity, soybean yield responded correctly to water stress, but it overresponded to water shortage when $K_{st}SWRC_2$ was used. Similarly, wheat was more responsive to N application when K_{sat} was estimated from soil texture class than K_{sat} estimated from effective porosity under dry conditions. Therefore, model users need to independently determine soil hydraulic properties (e.g., K_{sat} and SWRC) from bare soils (i.e., without crops) to make sure that the simulated management effects are not an artifact of calibrated soil properties. Otherwise, the calibrated soil properties under a cropped land may be influenced by plant growth processes (e.g., root water uptake) and may be site-specific for that particular cropping system.

Responses to the Soil Root Growth Factor

The response of the model to SRGF was conducted by comparing simulation results using the original SRGF in the reference runs with that estimated from Eq. [1], where maximum root depth (z_{max}) was assumed to be 200 cm for all the crops and soils. Two exponents (WCG = 2.0 for SRGF1 and 3.0 for SRGF2) were used to calculate SRGF in Eq. [1]. Higher WCG values produced less root distribution deeper in the soil profile (Fig. 8). As expected, SRGF1 simulated higher crop production (yield, aboveground and belowground biomass) than SRGF2 due to relatively more roots being distributed to the deeper profile, which was confirmed by a two-tail paired *t* test ($P < 0.01$). The RZWQM2 with fewer roots at the deeper soil depths (i.e., SRGF2) was slightly more sensitive to irrigation treatments (Fig. 9), but was similar in response to N treatments (Fig. 10). However, simulated yield, aboveground and belowground biomass with the original SRGF used in DSSAT4.0 (Fig. 8) were not significantly different from results with either SRGF1 ($P = 0.06$–0.32) or SRFG2 ($P = 0.26$–0.66) based on the paired *t* test. Simulated actual ET was similar to the original SRGF factors tested ($P = 0.33$ for SRGF1 and $P = 0.18$ for SRGF2). Compared to the simulations with the experimental results for yield and aboveground biomass, all three root growth factors showed no significant difference in simulated yield based on the paired *t* test, with $P = 0.78$ for original SRGF, $P = 0.43$ for SRGF1, and $P = 0.96$ for SRGF2. However, simulated aboveground biomass was not significantly different from measured biomass only for SRGF2 based on paired *t* test ($P = 0.14$). Therefore, using a maximum rooting depth of 200 cm and a WCG value of 3.0 showed the best results for the crops tested, given that other soil and crop parameters were

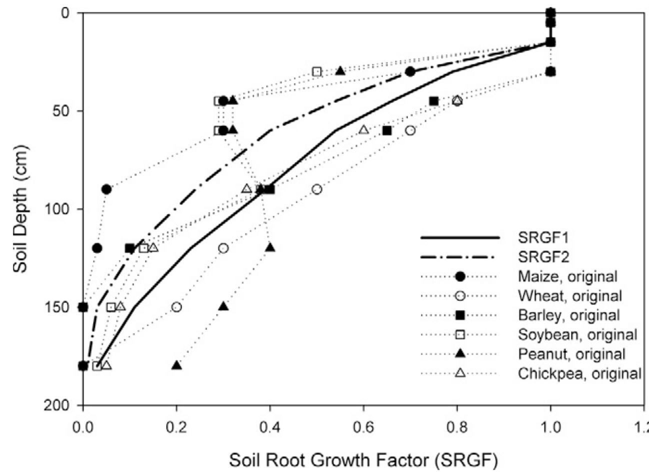

Fig. 8. Soil root growth factor (SRGF) used for sensitivity analyses. Lines are calculated from Eq. [1] and symbols are SRGF values used in DSSAT4.0 for each experiment.

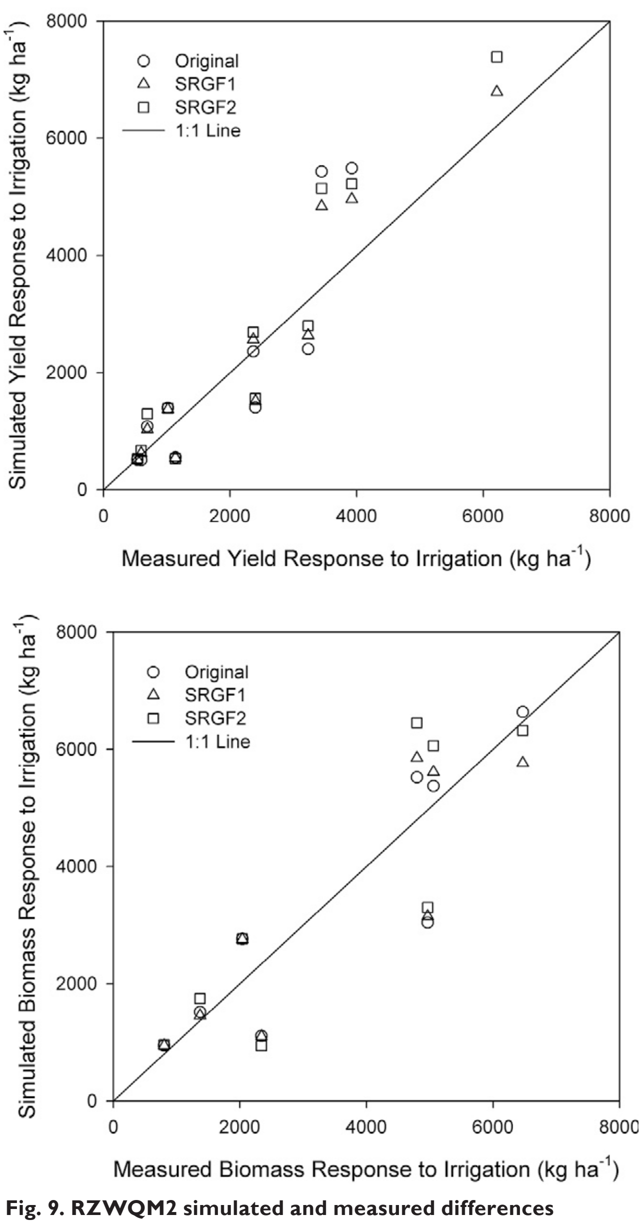

Fig. 9. RZWQM2 simulated and measured differences between the irrigated and rainfed treatments (e.g., response to irrigation) for the three soil root growth factors (SRGF).

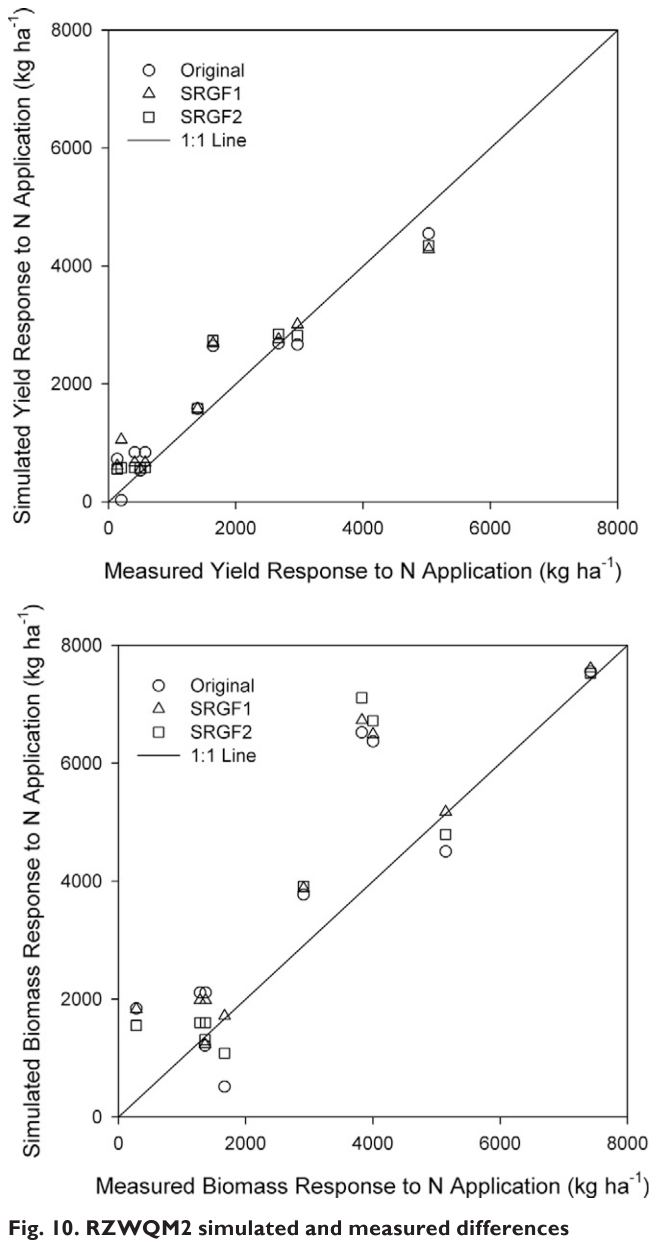

Fig. 10. RZWQM2 simulated and measured differences between the high and low N treatments (e.g., response to N) for the three soil root growth factors (SRGF).

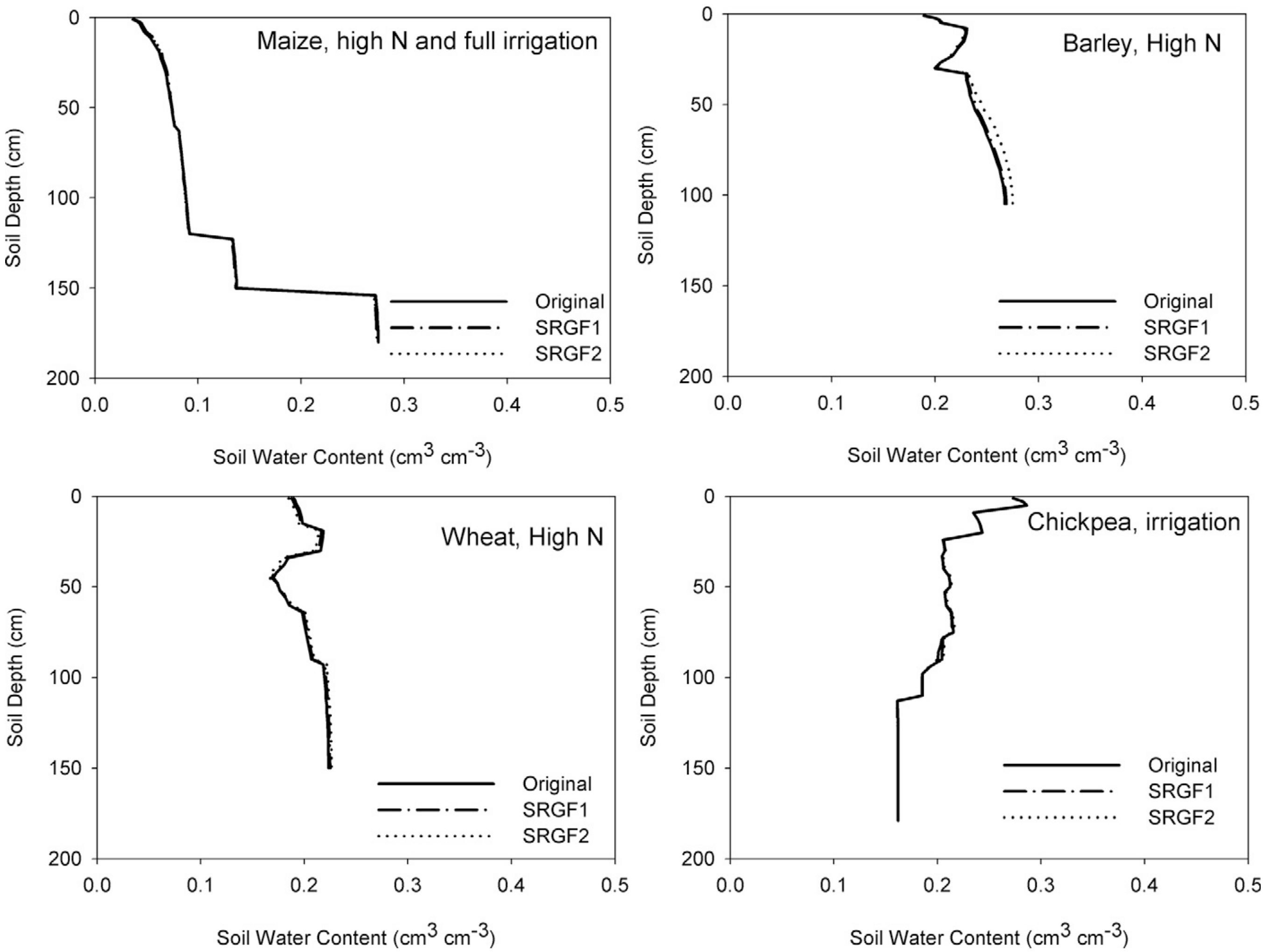

Fig. 11. RZWQM2 simulated soil water contents at harvest for the three soil root growth factors (SRGF). One treatment was shown for each soil.

unchanged. The WCG value of 3.0 was also shown to be adequate in a study by Calmon et al. (1999b). However, the value of z_{max} changes with crop and soil type. In this study, we used 200 cm for z_{max} to match the SRGF at the lowest soil depth (see Fig. 8).

Simulated soil water distributions at harvest were used to demonstrate the effect of SRGF on soil water contents, and showed no difference among the three SRGF factors (Fig. 11). This result may cause one to question the effectiveness of calibrating SRGF for each soil layer to match measured soil water content. In RZWQM2, soil water redistribution was simulated by solving the Richards' Equation and the small difference in SRGF (hence small differences in rooting depth and root distribution) does not play a major role in the soil water distribution at harvest and plant growth. As shown by Teuling et al. (2006), plants are somewhat flexible in extracting soil water from soil layers to minimize water stress.

SUMMARY AND CONCLUSIONS

Simulation results showed that DSSAT4.0 was correctly implemented in RZWQM2 based on the six crops tested. The new model should be an improved tool for both RZWQM2 and DSSAT4.0 users, and this study should facilitate the parameterization of soil properties. Evaluating the various methods of estimating soil hydraulic properties in RZWQM2 showed that simulated water drainage and runoff were much more strongly affected by saturated soil hydraulic conductivity (K_{sat}) than by the SWRC. Plant response to water and N management was affected by both K_{sat} and SWRC. Therefore, it is important to provide the model with the most accurate soil hydraulic properties to correctly simulate plant growth and its response to different crop management practices. Also, based on simulated crop yield and aboveground biomass, the SRGF calculated from Jones et al. (1991) with a maximum rooting depth of 200 cm and an exponent of 3.0 was acceptable for the six crops tested. Thus, model users can use these two parameters for SRGF(z) over the entire soil profile, rather than calibrating SRGF parameters for individual soil layers.

Care should be taken in extrapolating the simulation results, because water balance (evapotranspiration, soil moisture, drainage, and runoff) and N balance (plant N uptake, soil N, N leaching, N mineralization, etc.) were not measured and evaluated. Further studies are needed to evaluate these results with more balanced data collection on soil water, soil N, and plant growth. Without measured water and N balance, the recommended methods for SRGF, K_{sat}, and SWRC based on crop production alone could be at the expense of poor soil water and N simulations. Also, the sensitivity analyses were based on reference scenarios where RZWQM2 was calibrated to reproduce DSSAT4.0 results by using the same soil and plant parameters. Further evaluation of residual soil water content (θ_r) and rainfall intensity on crop growth in RZWQM2 is needed.

REFERENCES

Ahuja, L.R., D.K. Cassel, R.R. Bruce, and B.B. Barnes. 1989. Evaluation of spatial distribution of hydraulic conductivity using effective porosity data. Soil Sci. 148:404–411.

Ahuja, L.R., L. Ma, and T.A. Howell. 2002. Agricultural system models in field research and technology transfer. CRC Press, Boca Raton, FL.

Ahuja, L.R., and L. Ma. 2002. Parameterization of agricultural system models: Current approaches and future needs. p. 273–316. *In* L.R. Ahuja et al. (ed.) Agricultural system models in field research and technology transfer. CRC Press, Boca Raton, FL.

Ahuja, L.R., K.W. Rojas, J.D. Hanson, M.J. Shaffer, and L. Ma (ed.). 2000. The root zone water quality model. Water Resources Publ., Highlands Ranch, CO.

Ahuja, L.R., and R.D. Williams. 1991. Scaling water characteristic and hydraulic conductivity based on Gregson-Hector-McGowan approach. Soil Sci. Soc. Am. J. 55:308–319.

Bennett, J.M., L.S.M. Mutti, P.S.C. Rao, and J.W. Jones. 1989. Interaction effects of nitrogen and water stresses on biomass accumulation, nitrogen uptake, and seed yield of maize. Field Crops Res. 19:297–311.

Boote, K.J., G. Hoogenboom, J.W. Jones, and K.T. Ingram. 2008. Modeling nitrogen fixation and its relationship to nitrogen uptake in the CROPGRO model. p. 13–46. *In* L. Ma et al. (ed.) Quantifying and understanding plant nitrogen uptake for systems modeling. CRC Press, Boca Raton, FL.

Brooks, R.H., and A.T. Corey. 1964. Hydraulic properties of porous media. p. 1–15. Hydrology paper 3. Colorado State Univ., Fort Collins.

Brown, S.C., J.D.H. Keatinge, P.J. Gregory, and P.J.M. Cooper. 1987. Effects of fertilizer, variety, and location on barley production under rainfed conditions in northern Syria. 1. Root and shoot growth. Field Crops Res. 16:53–66.

Calmon, M.A., W.D. Batchelor, J.W. Jones, J.T. Ritchie, K.J. Boote, and L.C. Hammond. 1999a. Simulating soybean root growth and soil water extraction using a functional crop model. Trans. ASAE 42:1867–1877.

Calmon, M.A., J.W. Jones, D. Shinde, and J.E. Specht. 1999b. Estimating parameters for soil water balance models using adaptive simulated annealing. Appl. Eng. Agric. 16:703–713.

Campbell, C.A., H.R. Davidson, and F.G. Warder. 1977. Effects of fertilizer N and soil moisture on yield, yield components, protein content and N accumulation in the aboveground parts of spring wheat. Can. J. Soil Sci. 57:311–327.

Dardanelli, J.L., M.A. Calmon, J.W. Jones, J.M. Andriani, M.P. Diaz, and D.J. Collino. 2003. Use of crop model to evaluate soil impedance and root clumping effects on soil water extraction in three Argentine soils. Trans. ASAE 46:1265–1275.

Fang, Q., L. Ma, Q. Yu, R.W. Malone, S.A. Saseendran, and L.R. Ahuja. 2008. Modeling nitrogen and water management effects in a wheat-maize double-cropping system. J. Environ. Qual. 37:2232–2242.

Farahani, H.J., and D.G. DeCoursey. 2000. Potential evaporation and transpiration processes in the soil-residue-canopy system. *In* L.R. Ahuja et al (ed.) Root zone water quality model: Modeling management effects on water quality and crop production. Water Resource Publ., Highlands Ranch, CO.

Gijsman, A.J., S.S. Jagtap, and J.W. Jones. 2003. Wading through a swamp of complete confusion: How to choose a method for estimating soil water retention parameters for crop models. Eur. J. Agron. 18:77–106.

Gijsman, A.J., P.K. Thornton, and G. Hoogenboom. 2007. Using the WISE database to parameterize soil inputs for crop simulation models. Comput. Electron. Agric. 56:85–100.

Hoogenboom, G., J.W. Jones, P.W. Wilkens, C.H. Porter, W.D. Batchelor, L.A. Hunt, K.J. Boote, U. Singh, O. Uryasev, W.T. Bowen, A.J. Gijsman, A. du Toit, J.W. White, and G.Y. Tsuji. 2004. Decision support system for agrotechnology transfer version 4.0 (CD-ROM). Univ. of Hawaii, Honolulu.

Hupet, F., P. Bogaert, and M. Vanclooster. 2004a. Quantifying the local uncertainty of estimated actual evapotranspiration. Hydrol. Processes 18:3415–3434.

Hupet, F., J.C. van Dam, and M. Vanclooster. 2004b. Impact of within-field variability in soil hydraulic properties on transpiration fluxes and crop yields: A numerical study. Vadose Zone J. 3:1367–1379.

Jones, C.A., W.L. Bland, J.T. Ritchie, and J.R. Williams. 1991. Simulation of root growth. p. 91–123. *In* R.J. Hanks and J.T. Ritchie (ed.) Modeling plant and soil Systems. Agron. Monogr. 31. ASA, CSSA, and SSSA, Madison, WI.

Jones, J.W., G. Hoogenboom, C.H. Porter, K.J. Boote, W.D. Batchelor, L.A. Hunt, P.W. Wilkens, U. Singh, A.J. Gijsman, and J.T. Ritchie. 2003. The DSSAT cropping system model. Eur. J. Agron. 18:235–265.

Kribaa, M., V. Hallaire, P. Curmi, and R. Lahmar. 2001. Effect of various cultivation methods on the structure and hydraulic properties of a soil in a semi-arid climate. Soil Tillage Res. 60:43–53.

Ma, L. 1991. Physiological traits contributing to yield potential in peanut genotypes. M.S. thesis. Univ. of Florida, Gainesville.

Ma, L., L.R. Ahuja, and R.W. Malone. 2007. System modeling for soil and water research and management: Current status and needs for the 21st century. Trans. ASABE 50:1705–1713.

Ma, L., J.C. Ascough, II, M.J. Shaffer, L.R. Ahuja, J.D. Hanson, and K.W. Rojas. 2000. Root zone water quality model sensitivity analysis using the Monte Carlo simulations. Trans. ASAE 43:883–895.

Ma, L., G. Hoogenboom, L.R. Ahuja, J.C. Ascough, II, and S.A. Saseendran. 2006. Evaluation of the RZWQM-CERES-Maize hybrid model for maize production. Agric. Syst. 87:274–295.

Ma, L., G. Hoogenboom, L.R. Ahuja, D.C. Nielsen, and J.C. Ascough, II. 2005. Evaluation of the RZWQM-CROPGRO hybrid model for soybean production. Agron. J. 97:1172–1182.

Ma, L., R.W. Malone, D.B. Jaynes, K. Thorp, and L.R. Ahuja. 2008. Simulated effects of nitrogen management and soil microbes on soil N balance and crop production. Soil Sci. Soc. Am. J. 72:1594–1603.

Ma, L., M.J. Shaffer, J.K. Boyd, R. Waskom, L.R. Ahuja, K.W. Rojas, and C. Xu. 1998. Manure management in an irrigated silage corn field: Experiment and modeling. Soil Sci. Soc. Am. J. 62:1006–1017.

Ratliff, L.F., J.T. Ritchie, and D.K. Cassel. 1983. Field-measured limits of soil water availability as related to laboratory-measured properties. Soil Sci. Soc. Am. J. 47:770–775.

Rawls, W.J., D.L. Brakensiek, and K.E. Saxton. 1982. Estimation of soil water properties. Trans. ASAE 25:1316–1320, 1328.

Ritchie, J.T. 1998. Soil water balance and plant water stress. p. 41–54. *In* G.Y. Tsuji et al. (ed.) Understanding options for agricultural production. Kluwer Academic Publ., London.

Saseendran, S.A., L. Ma, R.W. Malone, P. Heilman, D.L. Karlen, L.R. Ahuja, R.S. Kanwar, and G. Hoogenboom. 2007. Simulating management effects on crop production, tile drainage, and water quality using RZWQM-DSSAT. Geoderma 140:297–309.

Singh, P., and Y.V. Sri Rama. 1989. Influence of water deficit on transpiration and radiation use efficiency of chickpea (C*icer arietinum L*.). Agric. For. Meteorol. 48:317–330.

Singh, P., and S.M. Virmani. 1996. Modeling growth and yield of chickpea (*Cicer arietinum L*.). Field Crops Res. 46:41–59.

Stanton, M.A. 1986. Effects of root-knot nematodes (*Meloidogyne* spp.) on growth and yield of 'Cobb' soybean (*Glycine max* (L.) Merrill). M.S. thesis. Univ. of Florida, Gainesville.

Teuling, A.J., R. Uijlenhoet, F. Hupet, and P.A. Troch. 2006. Impact of plant water uptake strategy on soil moisture and evapotranspiration dynamics during drydown. Geophys. Res. Lett. 33:L03401 10.1029/2005GL025019.

Thorp, K.R., R.W. Malone, and D.B. Jaynes. 2007. Simulating long-term effects of nitrogen fertilizer application rates on corn yield and nitrogen dynamics. Trans. ASABE 50:1287–1303.

Tsuji, G.Y., G. Hoogenboom, and P.K. Thornton. 1998. Understanding options for agricultural production. Kluwer Academic Publ., London.

Utset, A., I. Farré, A. Martinez-Cob, and J. Cavero. 2004. Comparing Penman-monteith and Priestley-Taylor approaches as reference-evapotranspiration inputs for modeling maize water-use under Mediterranean conditions. Agric. Water Manage. 66:205–219.

Walker, S.E., J.K. Mitchell, M.C. Hirschi, and K.E. Johnsen. 2000. Sensitivity analysis of the root zone water quality model. Trans. ASAE 43:841–846.

Wang, F., C.W. Fraisse, N.R. Kitchen, and K.A. Sudduth. 2003. Site-specific evaluation of the CROPGRO soybean model on Missouri claypan soils. Agric. Syst. 76:985–1005.

Williams, R.D., and L.R. Ahuja. 1992. Evaluation of similar-media and a one-parameter model for estimating the soil water characteristic. J. Soil Sci. 43:237–248.

Williams, R.D., and L.R. Ahuja. 2003. Scaling and estimating the soil water characteristic using a one-parameter model. p. 35–48. *In* Y. Pachepsky et al. (ed.) Scaling methods in soil physics. CRC Press, Boca Raton, FL.

Yu, Q., S.A. Saseendran, L. Ma, G.N. Flerchinger, T.R. Green, and L.R. Ahuja. 2006. Modeling a wheat-maize double cropping system in China using two plant growth modules with RZWQM. Agric. Syst. 89:457–477.