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Calibrating RZWQM2 model for maize responses to deficit irrigation

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ABSTRACT

Parameterizing a system model for field research is a challenge and requires collaboration between modelers and experimentalists. In this study, the Root Zone Water Quality Model-DSSAT (RZWQM2) was used for simulating plant responses to water stresses in eastern Colorado. Experiments were conducted in 2008, 2009, and 2010 in which maize (*Zea Mays* L.) was irrigated to meet a certain percentage (100%, 85%, 70%, 55%, and 40%) of the estimated crop evapotranspiration (ETc) demand during a growing season. The model was calibrated with both laboratory-measured and field-estimated soil water retention curves (SWRC) and evaluated for yield, biomass, leaf area index (LAI), and soil water content under five irrigation treatments in all three years. Simulated results showed that field-estimated SWRC provided better model responses to irrigation than laboratory-measured SWRC. The results also showed that there were multiple sets of plant parameters that achieved acceptable simulations when only one irrigation treatment was used for calibration. Model parameterization can be improved when multiple treatments and multiple years of data are included. The parameterized RZWQM2 model was capable of simulating various irrigation treatments in all years and could be used to schedule irrigation based on ETc requirement.

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1. Introduction

It is a challenge to parameterize a system model that can be applied to other soil and weather conditions without re-calibration. An agricultural system model is seldom calibrated to a high accuracy for all of its components due to inadequacy of the model, methods of calibration, lack of measured data for all system components, and variability in field measurements. Another common difficulty is the lack of evaluation for a variety of conditions after a model is calibrated. Most often, a system model is at best partially calibrated due to lack of data collected for all system components. If experimental data were available for all the system components, calibration of a model for such a comprehensive dataset may help improve the science used in the model, especially the interactions among system components. In addition, the majority of model calibration schemes involve a degree of trial and error without a rigorous optimization algorithm that accounts for uncertainties and correlation among parameters. As such, the calibrated model parameters may not be unique, and many combinations of model parameters may produce similar results (Fang et al., 2010).

Although a few studies used an optimization algorithm to obtain model parameters (Fang et al., 2010; Malone et al., 2010), it took considerable time to set up the optimization scheme for a study and to come up with the right objective function (Nolan et al., 2011). Therefore, a system model is usually calibrated manually and the goodness-of-calibration depends on the experience of model users. For example, the same model may be calibrated differently on the same dataset by two different users based on their personal experience (Ma et al., 2009; Thorp et al., 2007). A model user may be more competent to calibrate soil parameters than plant parameters. He or she may achieve a calibration of soil parameters which leaves the plant parameters at their default values. On the other hand, a user may choose to calibrate the dataset by adjusting the plant parameters and leave the soil parameters at their default settings. Without extensive evaluation and using measured soil and plant parameters, it is difficult to judge which calibration is more reasonable than the others. In addition, the manual calibration procedure usually is not reported in modeling studies.

Parameterization of a system model includes both calibration and evaluation. Usually one dataset is used for calibration and another independent dataset for evaluation or validation. A model user may use one year's data for calibration and the rest for model evaluation (Ma et al., 2003; Saseendran et al., 2004) or use one treatment for model calibration and the rest for model evaluation (Hu

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et al., 2006; Saseendran et al., 2010). When a calibrated model fails the evaluation test, re-calibration is warranted. Given that the calibrated parameters are often not unique, model users most likely can derive another set of parameters that provide reasonable simulation for all available datasets. Such an iterative parameterization procedure is documented in Ma et al. (2011).

Another commonly encountered dilemma is how to use measured data when there is uncertainty in the data. For example, laboratory-measured soil properties may not reflect in situ conditions and the spatial and temporal variability in the field. Using the Root Zone Water Quality Model (RZWQM), Starks et al. (2003) found that laboratory-measured soil water retention curves (SWRC) provided worse soil water prediction in the field than field-estimated ones. Gribb et al. (2009) also found that laboratory-measured SWRCs simulated soil water dynamics poorly compared to those estimated from field data using the HYDRUS-1D model. Using the HYDRUS-2D model, McCoy and McCoy (2009) found that laboratory-measured soil water release did not accurately predict soil water movement in field soils. Gijsman et al. (2003) concluded that laboratory-measured drained upper limit (DUL) was not suitable for crop modeling and the lower limit of plant available water (LL) was underestimated in the laboratory. Inadequacy of laboratory measured soil water retention curves on simulating field soil water dynamics was also documented by others (Zhao et al., 2010; El-Kadi, 1993). However, there is no documented study on how simulated plant water responses were affected by field- versus laboratory-measured SWRCs.

Therefore, the objectives of this study were to (1) evaluate the responses of simulated maize growth to irrigation using the newly released RZWQM model (RZWQM2) with both field and laboratory estimated soil water retention curves; (2) demonstrate a step-by-step model calibration procedure and the necessity of using multiple treatments and multiple years of data in model parameterization; and (3) evaluate the capability of RZWQM2 for irrigation scheduling based on crop evapotranspiration (ETc) requirement.

2. Materials and methods

The field experiment was initiated in 2008 near Greeley, Colorado (40.45°N, 104.64°W). The site contains three soil types, Nunn (Fine, smectitic, mesic Aridic Argiustolls), Olney (Fine-loamy, mixed, superactive, mesic Ustic Haplargids), and Otero (Coarse-loamy, mixed, superactive, calcareous, mesic Aridic Ustorthents). The soil is a sandy loam and is fairly uniform throughout the 200 cm soil profile. Weather data were recorded on site with a standard Colorado Agricultural Meteorological Network (http://ccc.atmos.colostate.edu/~coagmet/) weather station (GLY04). Missing data at the beginning of the study were estimated with data from a nearby station 800 m to the east (GLY03). Average daily temperature during the growing season was 18.2 °C in 2008, 17.9 °C in 2009, and 17.3 °C in 2010. Corresponding growing season precipitation was 24.5 cm, 23.7 cm, and 21.1 cm, respectively. Both temperature and precipitation were slightly higher than the 18-year average for the location (1992–2010) from May to October (16.5 °C and 19.1 cm). Although total rainfall amounts were similar in the three years, in 2008, the monthly total was highest in August (14.1 cm) followed by September (3.9 cm) and June (3.1 cm), whereas the rain was concentrated in June (8.7 cm) followed by August (5.2 cm) and July (4.8 cm) in 2009 and in June (8.0 cm) followed by May (5.0 cm) and July (4.1 cm) and August (4.0 cm) in 2010. The field was divided into 9 m by 44 m small plots.

Maize ('Dekalb 52-59') was planted at an average rate of 81,000 seeds per hectare with 0.76 m row spacing on May 12 in 2008 and May 11 in 2009 and 2010, and harvested on November 6 in 2008, November 12 in 2009, and October 19 in 2010. Four replicates were arranged by randomized complete block design. Five irrigation treatments (micro-irrigation with surface drip tubing adjacent to each row) with four replicates each were designed to meet a certain percentage of potential crop ET (ETc) requirements (Allen et al., 1998, 2005, 2007) during the growing seasons: 100% (treatment #1), 85% (treatment #2), 70% (treatment #3), 55% (treatment #4), and 40% (treatment #5) of ETc. However, 20% of the projected irrigation amount during the vegetative stage was saved for use during the reproductive stage. Fertilizer as urea-ammonium-nitrate (UAN) was applied at planting and then with irrigation water during the growing seasons as needed based on estimated plant growth and expected N uptake. Total N applied was 134 kg N ha^{-1} in 2008, 160 kg N ha^{-1} in 2009, and 146 kg N ha^{-1} in 2010 for all treatments. Total irrigation amounts were 46.9, 36.9, 30.3, 21.1, and 16.7 cm in 2008; 41.7, 34.6, 24.9, 16.7, and 10.9 cm in 2009; and 36.5, 30.3, 21.9, 15.3, and 10.0 cm in 2010 for treatments #1–5, respectively.

All the plots were sprinkle-irrigated with 2 cm water following planting in 2008 and 2009 to assure good germination, but no initial irrigation was needed in 2010 due to a wet April. The amount of crop water used (actual ET) for each treatment was estimated on a daily basis based on reference ET demand, a crop coefficient, rainfall, and soil water deficit (FAO 56, Allen et al., 1998). Irrigation was applied every 3–7 days. Total plant available water (field capacity [FC] minus wilting point soil water) was calculated by assuming that FC equals soil water content after a large rainfall event and that soil water at wilting point is assumed to be 50% of FC based on Allen et al. (1998) and Rawls et al. (1982).

Canopy ground cover (C_c) was measured with a nadir view digital camera and used to calculate LAI using the following equation for maize (Farahani and DeCoursey, 2000):

$$\mathrm{LAI} = \frac{\ln(1 - C_c)}{-0.594} \tag{1}$$

Soil water content was measured twice a week during the growing season with a portable time domain reflectometry (TDR) moisture meter for the 0–15 cm soil layer and with a neutron attenuation moisture meter between 15 cm and 200 cm below the soil surface at 30 cm intervals. The neutron moisture meter was calibrated for the site soils and calibration verified annually. Three intact soil profile cores were taken in the experimental area to 182 cm depth. Each core was divided into eight depths of 0–25, 25–36, 36–58, 58–92, 92–102, 102–120, 120–155, and 155–182 cm. Soil water retention curves (SWRC) were measured for each depth in the laboratory using pressure plates at 10, 33, 50, 100, and 1500 kPa suction. As shown in Fig. 1, in the first soil profile core, all depths coalesced into two distinct layers; the second soil core into three layers; and the third into two layers. The Brooks–Corey equation was fitted to these groups of soil layers to obtain the SWRC (Brooks and Corey, 1964):

$$\begin{aligned} &\theta = \theta_s && \text{when} \quad |h| < |h_b| \\ &\theta - \theta_r = B|h|^{-\lambda} && \text{when} \quad |h| \geq |h_b| \end{aligned} \tag{2}$$

where θ_s and θ_r are saturated and residual soil water contents (cm^3 cm^{-3}), h_b is the air entry water suction for the soil water content (θ)-soil water suction (h) curve (cm), and λ is the slope of the $\log(\theta) - \log(h)$ curve (dimensionless). By imposing continuity at h_b, $B = (\theta_s - \theta_r)h_b^{\lambda}$. The unsaturated hydraulic conductivity versus suction head [$K(h)$] is related as:

$$\begin{aligned} &K(h) = K_{sat} && \text{when} \quad |h| < |h_{bk}| \\ &K(h) = C_2|h|^{-N_2} && \text{when} \quad |h| \geq |h_{bk}| \end{aligned} \tag{3}$$

where K_{sat} is the saturated hydraulic conductivity ($h = 0$) (cm h^{-1}), and h_{bk} is the air entry water suction for the soil hydraulic

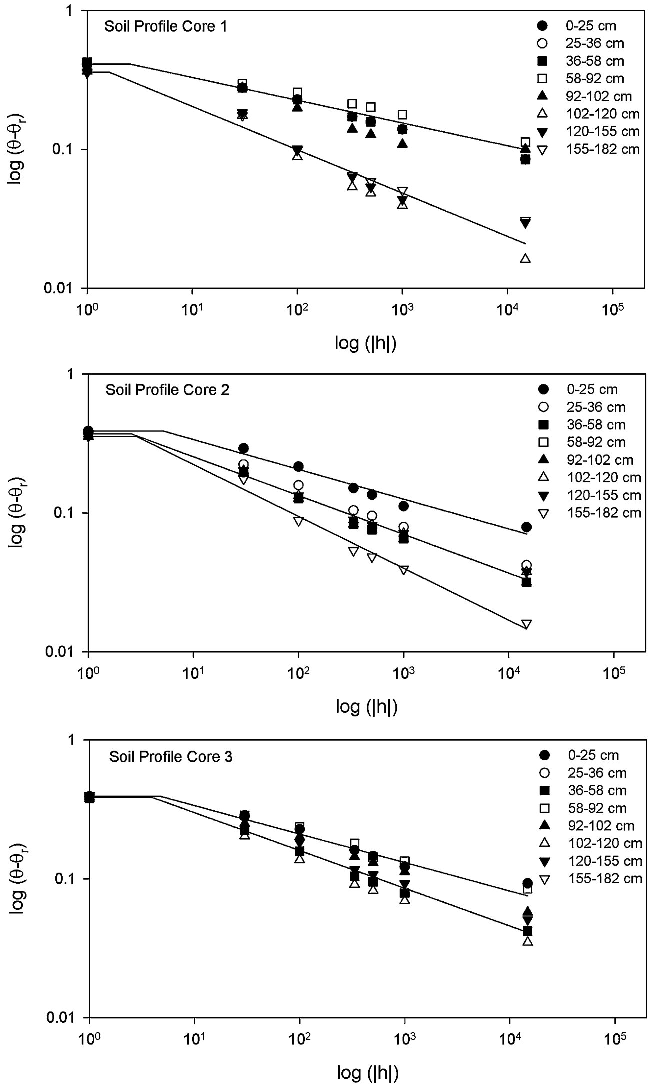

Fig. 1. Laboratory-measured soil water retention curves (SWRC) and fitted Brooks–Corey curves for the three soil profile cores.

conductivity (K)-suction head (h) curve (cm), and N_2 is the slope of the $\log(K) - \log(h)$. C_2 is obtained by imposing continuity at h_{bk}:

$$C_2 = K_{sat} h_{bk}^{N_2} \tag{4}$$

N_2 in RZWQM2 is calculated as:

$$N_2 = 2 + 3\lambda \tag{5}$$

The parameters h_b and h_{bk} were assumed to be equal and θ_r was assumed to be 0.039 cm^3 cm^{-3} for the soil texture based on Rawls et al. (1982). Table 1 shows the physical properties and fitted Brooks–Corey parameters for each soil core. Fitted porosity was then used to calculate an average bulk density using $\rho_b = (1 - \theta_s)\rho_p$, where θ_s is saturated soil water content (or porosity) and ρ_b and ρ_p (=2.65 g cm^{-3}) are bulk density and particle density, respectively.

To compare with laboratory derived SWRCs, SWRCs were also obtained from field estimated field capacity (water content approximately 24 h after a large water application, assumed to be equal to 33 kPa soil water content) and by assuming that 50% of field capacity is wilting point (1500 kPa soil water content), which is close to the average ratio between 1500 kPa water content and 33 kPa water content measured in the laboratory cores and as reported by Rawls et al. (1982) and Ma et al. (2009).

$$\lambda = \frac{\ln[(\theta_{1/3} - \theta_r)/(\theta_{15} - \theta_r)]}{\ln(15,000/333)} \tag{6}$$

$$h_b = \exp\left[\frac{\ln(\theta_{1/3} - \theta_r) - \ln(\theta_s - \theta_r) + \lambda\ \ln(333)}{\lambda}\right] \tag{7}$$

where θ_{15} and $\theta_{1/3}$ are soil water contents at 1500 kPa and 33 kPa suctions, respectively. The latter is assumed to be at field capacity (FC).

Root mean squared deviation (RMSD) or relative RMSD (RRMSD) was used to quantify the goodness of fit of the predicted results to the field measured results for a given calibration.

$$\text{RMSD} = \sqrt{\frac{\sum_{i=1}^{N}(P_i - O_i)^2}{N}} \tag{8}$$

$$\text{RRMSD} = \frac{\text{RMSD}}{O_{avg}} \tag{9}$$

where N is the number of observations. P_i and O_i are the model predicted and experimental measured points, respectively, and O_{avg} is the averaged observed value.

3. Model description and parameterization

The Root Zone Water Quality Model (RZWQM2, version 2.0) with the DSSAT 4.0 crop modules was used in this study (Ma et al., 2006). The model requires SWRC and saturated hydraulic conductivity (K_{sat}). The model provides options to calculate hourly and daily potential evapotranspiration (PET) based on the Shuttleworth–Wallace method (Shuttleworth and Wallace, 1985). In this study, the K_{sat} values were obtained from table values based on soil texture (Rawls et al., 1982) and the hourly PET calculation was used. As done previously in the literature, RZWQM2 was calibrated manually at first. The manual calibration procedure included matching simulation results with measured soil water, anthesis and maturity dates, maximum LAI, and final biomass and yield. The soil root growth factor (SRGF) was assumed to obey the following equation (Ma et al., 2009) with $wcg = 3$ and $z_{max} = 200$ cm.

$$\text{SRGF} = \begin{cases} 1 & z \leq 15\,\text{cm} \\ \left(1 - \dfrac{z}{z_{\max}}\right)^{wcg} & z > 15\,\text{cm} \end{cases} \tag{10}$$

Three model calibration studies were conducted (Fig. 2). *First*, fitted SWRCs in Fig. 1 were used. Instead of taking an average of the SWRCs at respective soil depths from the three soil cores (Fig. 1), we built soil profiles by randomly selecting a SWRC at each soil horizon from one of the three soil cores. The soil profile that provided the best simulation of soil water content was then used. Then, the plant parameters were manually calibrated for the 100% ET treatment (#1) in 2008.

Second, field-estimated water holding capacity for each soil horizon was used as 33 kPa soil water content (assumed to be DUL). The SWRC was derived from the 33 kPa soil water contents and 1500 kPa (assumed to be LL) soil water contents based on Eqs. (6) and (7). Initial calibration was for the 100% ET treatment (#1) in 2008 and the calibrated plant parameters were then evaluated for the other treatments in 2008 and all treatments in 2009 and 2010. If the calibrated model did not simulate well for other treatments, the plant parameters were recalibrated until the model responded to water stresses with simulation error within 10% of measured yield and biomass.

The *third* calibration was an ordered search of plant parameters in a given range for each parameter in Table 2, using field estimated SWRC as in the second calibration study. Each plant parameter was

Table 1
Laboratory-measured soil water contents and fitted Brooks–Corey parameters for the three soil profile cores. Bulk density was calculated from fitted porosity.

Soil depth (cm)	Bulk density ρ_b (g cm^{-3})	θ_s (cm^3 cm^{-3})	$\theta_{1/3}$ (cm^3 cm^{-3})	θ_{15} (cm^3 cm^{-3})	h_b (cm)	λ
Soil core 1						
0–100	1.436	0.458	0.233	0.147	2.589	0.163
100–180	1.617	0.390	0.098	0.051	1.609	0.312
Soil core 2						
0–38	1.511	0.430	0.200	0.111	5.140	0.214
38–150	1.568	0.408	0.134	0.072	2.597	0.279
150–180	1.617	0.390	0.095	0.050	2.884	0.374
Soil core 3						
0–46, 66–104	1.404	0.470	0.288	0.153	4.795	0.205
46–66, 104–182	1.518	0.427	0.156	0.082	3.906	0.272
Parameters determined from above soil profile cores						
0–25	1.511	0.430	0.200	0.1113	5.140	0.214
25–36	1.568	0.408	0.134	0.0719	2.597	0.279
36–58	1.568	0.408	0.134	0.0719	2.597	0.279
58–92	1.568	0.408	0.134	0.0719	2.597	0.279
92–102	1.568	0.408	0.134	0.0719	2.597	0.279
102–120	1.617	0.390	0.098	0.0508	1.609	0.312
120–155	1.617	0.390	0.098	0.0508	1.609	0.312
155–182	1.617	0.390	0.095	0.0495	2.884	0.312

varied independently within its given range by an increment shown in Table 2. The procedure was automated using a small computer program outside the RZWQM2 user interface by setting six nested loops for the six parameters with a total of 14,068 model runs. This automated calibration was intended to determine whether the manually calibrated plant parameters can be improved. The model was run for the 100% irrigation treatment (#1) in 2008 and then for the other treatments in 2008. The plant parameters that gave reasonable simulations for 2008 were then tested for the 2009 and 2010 data.

4. Results and discussion

4.1. Manual calibration with laboratory measured SWRC

The model was first calibrated with a set of plant parameters from Saseendran et al. (2005) (Table 2) and one set of laboratory-derived soil parameters (soil core 1) in Table 1. This set of plant parameters simulated plant biomass, yield, and LAI reasonably well for the 2008 treatment #1. However, the soil water content was not simulated well with RRMSD greater than 20% for total profile soil water and greater than 30% for soil water content. To improve soil water simulation, we constructed a "representative" profile for the soil by randomly selecting SWRC at each soil horizon from the three soil cores. Each soil horizon could take soil SWRC from one of the three soil cores at that depth. There were 729 combinations. The combination that gave the lowest error in simulating soil profile water content was selected as the 'optimized' soil hydraulic properties for the soil profile, which had an RMSD of 0.037 cm^3 cm^{-3} for soil water content and 3.73 cm for profile soil water.

Then we recalibrated the plant parameters manually (Table 2, second calibration) to improve the biomass and yield simulation. Simulated yield for the 100% treatment was 11,059 kg ha^{-1} versus 11,071 kg ha^{-1} measured and simulated harvest biomass was 21,487 kg ha^{-1} versus 22,112 kg ha^{-1} measured (Table 3). Simulated anthesis day was 85 days after planting (DAP) and simulated physiological maturity date was 142 DAP, which were the same as observed dates in the field. Simulated maximum LAI was 4.80 versus measured 4.61. There was no water stress simulated, as expected, but the model began to predict N stress in early

Table 2
Plant parameters calibrated for maize in the study using soil water retention curve from laboratory soil profile cores and from field estimated field capacity.

Acronyms used and definitions of traits	Laboratory measured soil water retention curves		Field estimated 33 kPa soil water content		Ranges used in optimization and increment	Final optimized value
	First rough calibration	Second calibration	First rough calibration	Second calibration		
P1 – degree days (base temperature of 8 °C) from seedling emergence to end of juvenile phase (thermal degree days)	280	280	280	250	250–290, 10	260
P2 – day length sensitivity coefficient [the extent (days) that development is delayed for each hour increase in photoperiod above the longest photoperiod (12.5 h) at which development proceeds at maximum rate]	0.4	0.4	0.4	0.2	0.2–0.6, 0.2	0.2
P5 – degree days (base temperature of 8 °C) from silking to physiological maturity (thermal degree days)	590	540	540	600	550–620, 10	570
G2 – potential kernel number	700	800	800	950	900–1000, 20	920
G3 – potential kernel growth rate (mg/(kernel d))	10	10	10	6	5–10, 1	7
PHINT – degree days required for a leaf tip to emerge (phyllochron interval) (thermal degree days)	50	50	50	38.9	35–50, 5	50

Table 3
Soil parameters estimated from field measured soil water contents.

Soil depth (cm)	Bulk density ρ_b (g cm^{-3})	θ_s (cm^3 cm^{-3})	$\theta_{1/3}$ (cm^3 cm^{-3})	θ_{15} (cm^3 cm^{-3})	h_b (cm)	λ
0–15	1.492	0.437	0.262	0.131	20.04	0.182
15–30	1.492	0.437	0.249	0.124	15.15	0.182
30–60	1.492	0.437	0.220	0.110	7.75	0.182
60–90	1.568	0.408	0.187	0.093	4.64	0.182
90–120	1.568	0.408	0.173	0.086	2.95	0.182
120–150	1.617	0.390	0.162	0.081	2.71	0.182
150–200	1.617	0.390	0.198	0.099	8.04	0.182

September. Simulated RMSD was 0.778 for LAI, 0.039 cm^3 cm^{-3} for soil water content, and 3.20 cm for soil profile water. Since simulated soil water did not deviate further from measurements after adjusting the plant parameters, the calibration was accepted even though the LAI was not predicted well towards the end of growing season.

After the calibration, the model was used to simulate other irrigation treatments in 2008. To our disappointment, simulated yield and biomass did not respond to irrigation treatments (Fig. 3). The LAI also did not change with irrigation treatment. To find out why the calibrated model did not respond to irrigation, we compared measured and simulated average plant available water (PAW)

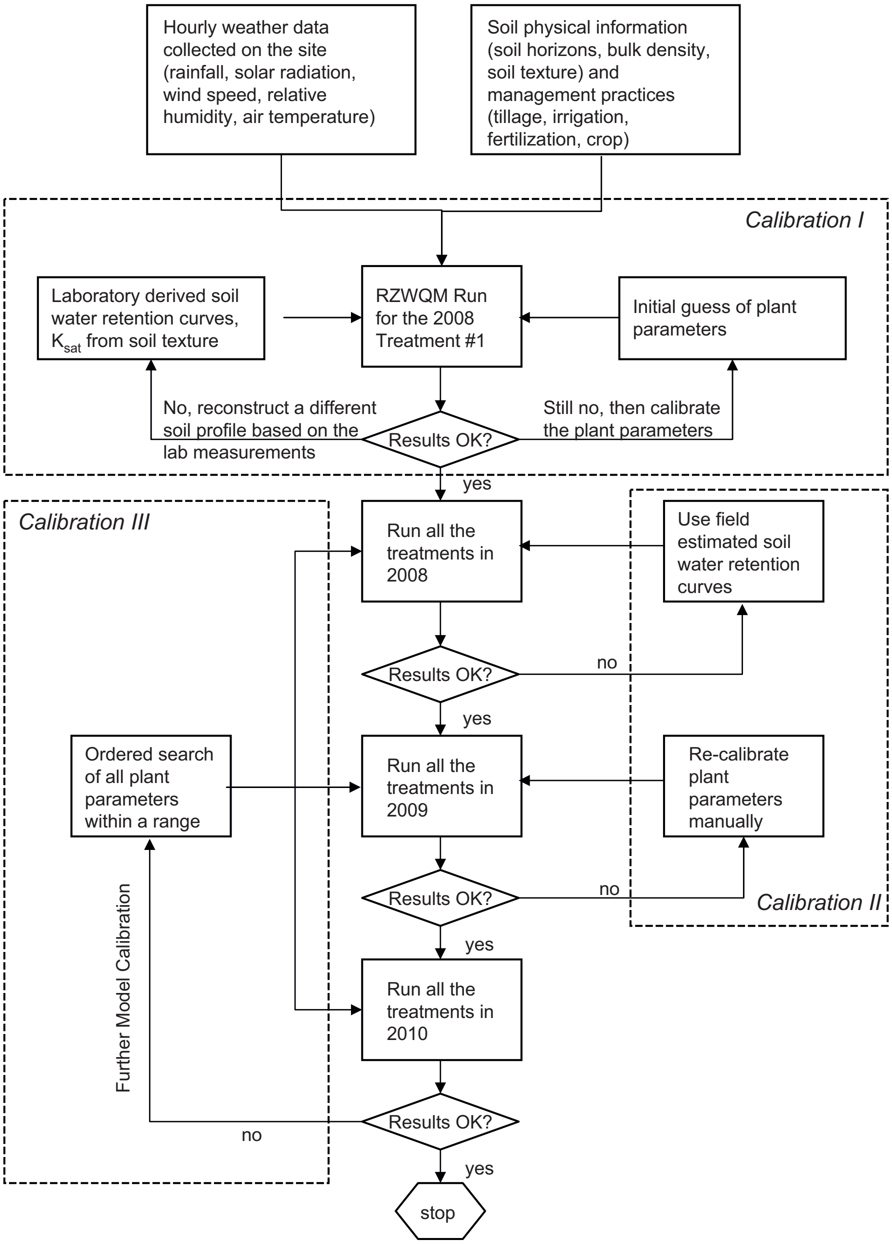

Fig. 2. A flow chart of calibration procedure used in the study.

($\theta - \theta_{15}$) with the total plant available water (TPAW) ($\theta_{1/3} - \theta_{15}$). PAW for all treatments during the 2008 growing season remained above TPAW at the three soil profile depths shown (0–90, 0–120, and 0–180 cm) (Fig. 4). Since water stress was only simulated when PAW was less than TPAW, no water stress was predicted among treatments. Similarly, the calibrated model did not respond to irrigation amount in 2009 (Fig. 5) due to high PAW in relation to TPAW (Fig. 6). The measured higher PAW for treatment #5 than those for treatments #3 and #4 in 2008 could be due to experimental error or spatial variability because this discrepancy did not occur in 2009 (Fig. 6). Similarly, the model did not adequately respond to water treatments in 2010 (Fig. 7).

4.2. Manual calibration with field estimated SWRC

As a result of failure to successfully simulate PAW with laboratory-derived SWRCs, we estimated field capacity (FC) as soil water content measured in the field 24–48 h after a large rain event that caused soil water content to increase at deeper depths. These values were higher than the laboratory measured soil water contents at 33 kPa (Table 3). Using the same plant parameters as calibrated above, we simulated both yield and biomass for 2008 treatment #1 within 10% of measured values (10,073 kg ha^{-1} versus 11,071 kg ha^{-1}; 20,014 kg ha^{-1} versus 22,112 kg ha^{-1}) and matched both anthesis and physiological maturity dates well (85 versus 85 DAP for anthesis dates and 144 versus 142 DAP for maturity). However, the model still did not respond to irrigation and failed to correctly simulate yield and biomass in 2009. The simulated anthesis date was 99 DAP compared to the observed 85 DAP in 2009.

Therefore, we recalibrated the plant parameters (second calibration) mainly to make sure the anthesis dates were reasonable for both 2008 and 2009 and increased yield and biomass responses to irrigation in 2008 by increasing kernel number and decreasing grain filling rate (Table 2). We also found that reducing the day

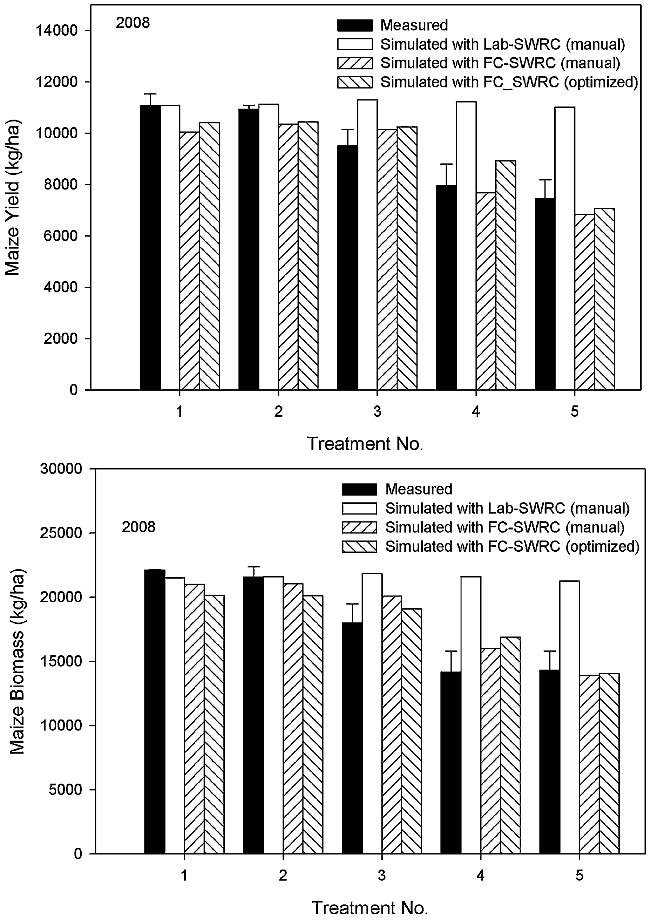

Fig. 3. Measured and simulated maize yield and biomass with field and laboratory measured soil water retention curves (SWRC) and plant parameters calibrated manually and automatically in 2008.

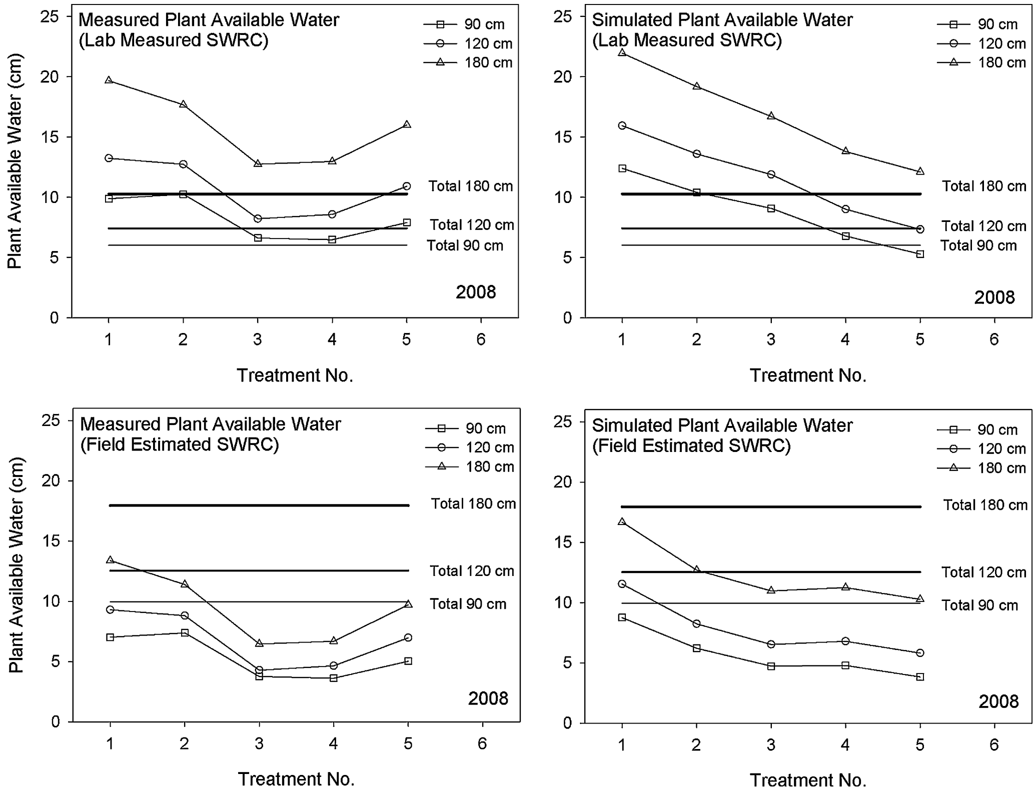

Fig. 4. Measured and simulated average plant available water (PAW) during the growing season from laboratory and field estimated SWRC in 2008. The horizontal lines are total plant available water (TPAW) in the 90, 120, and 180 cm soil profiles.

length sensitivity coefficient improved biomass simulation. In addition, we used the default 38.9 °C-days phylochron interval (PHINT). These parameters improved yield and biomass responses to irrigation amounts (Figs. 3, 5 and 7). The RMSD across all the five treatments were 0.037 $cm^3\ cm^{-3}$ for soil water content and 3.7 cm for profile soil water for 2008, which were comparable to those using laboratory-measured SWRC (0.043 $cm^3\ cm^{-3}$ for soil water content and 3.8 cm for profile soil water). Although maximum LAI simulated for the treatment #1 was close to measured (4.5 compared to 4.6), the peak LAI was 10 days early compared to maximum canopy cover. Both simulated anthesis and maturity dates were also early by a week compared to observed dates.

For 2009, the simulated anthesis date was 85 compared to 84 DAP observed and maturity date was 143 compared to 147 DAP observed. The simulated RMSD was 387 $kg\ ha^{-1}$ for yield and 1400 $kg\ ha^{-1}$ for biomass. Simulated relative difference between treatment #1 and #5 was 4353 $kg\ ha^{-1}$ compared to 5206 $kg\ ha^{-1}$ for yield and 8136 $kg\ ha^{-1}$ compared to measured difference of 8091 $kg\ ha^{-1}$ for biomass (Fig. 5). Simulated soil water content and profile soil water were slightly better than those for 2008 with RMSD of 0.030 $cm^3\ cm^{-3}$ and 2.4 cm, respectively. The worse simulation of soil water in 2008 could be due to the measurement error in treatment #5 (Fig. 4). The better response of crop growth to irrigation using field estimated 33 kPa soil water was due to the correct relationship between PAW and TPAW (i.e., TPAW > PAW; Figs. 4 and 6). When laboratory-measured SWRCs were used, PAW was always higher than TPAW. Therefore, no water stress was simulated. However, when field-estimated SWRC was used, TPAW was higher than average seasonal PAW although the simulated PAW was close to TPAW for the 100% treatments in both 2008 and 2009, for the three soil profile depths shown (90, 120, and 180 cm).

These calibrated parameters simulated maize yield well in 2010 for treatments #3, #4, and #5, but under-predicted yield for treatments #1 and #2 with an overall RMSD of 1722 $kg\ ha^{-1}$. On the contrary, the model predicted biomass well in 2010 for #1 and #2,

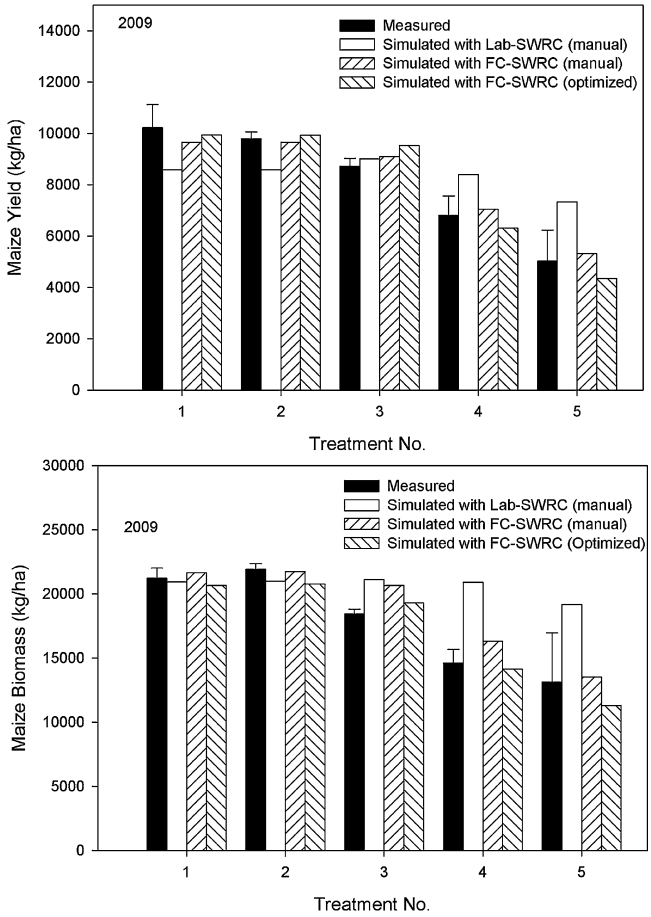

Fig. 5. Measured and simulated maize yield and biomass with field and laboratory measured soil water retention curves (SWRC) and plant parameters calibrated manually and automatically in 2009.

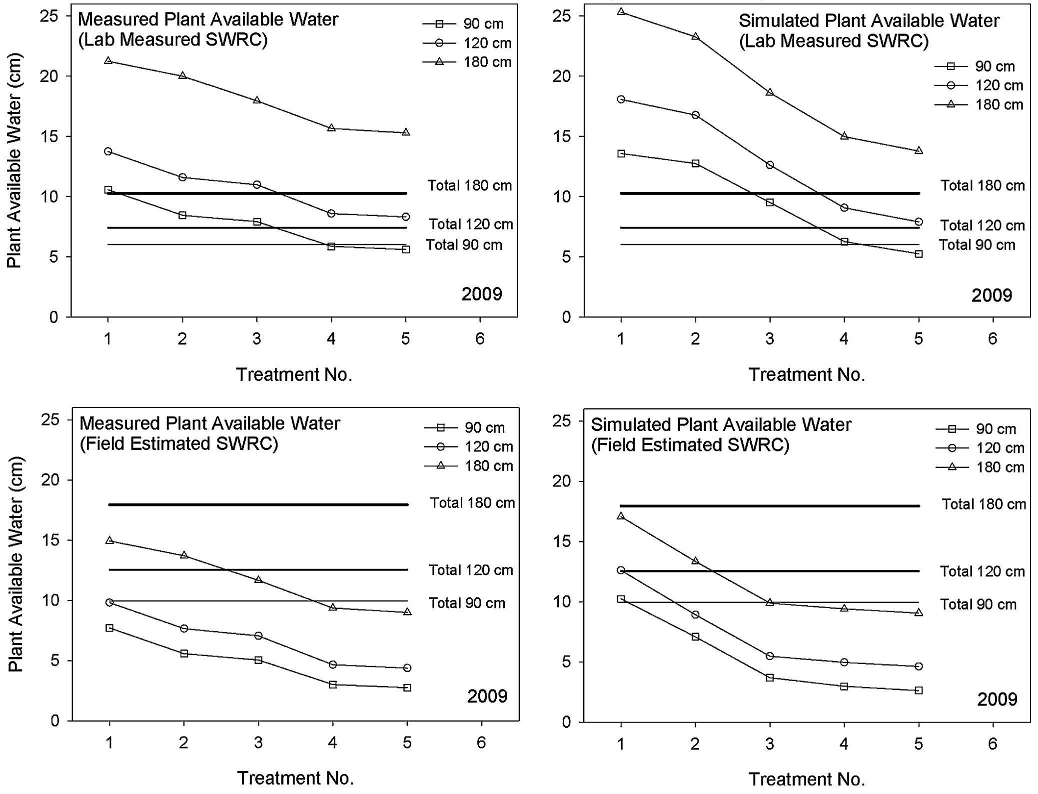

Fig. 6. Measured and simulated average plant available water (PAW) during the growing season from laboratory and field estimated SWRC in 2009. The horizontal lines are total plant available water (TPAW) in the 90, 120, and 180 cm soil profiles.

but considerably over-predicted biomass for the other treatments with overall RMSD of 2439 kg ha^{-1} (Fig. 7). Simulated LAI had an RMSD of 0.99 and total profile soil water was simulated reasonably well with an RMSD of 3.9 cm. However, simulated soil water content deviated from measured values much more in 2010 than in 2008 and 2009 with RMSD of 0.058 cm^3 cm^{-3}.

4.3. Automated calibration of plant parameters

Due to the less than satisfactory simulation for 2010, we optimized the plant parameters to see whether we could improve the 2010 simulation results while maintaining the good prediction for 2008 and 2009, since the presumption of the study was to use measured or estimated soil parameters without calibration. Field-estimated $\theta_{1/3}$ was used for SWRC as above (Table 3) and the plant parameters were varied within a range around the calibrated values with a total of 14,068 sets of plant parameters (Table 2). This seems to be a large number of simulation runs, but it does not take too much time to set it up and can be done in a few days. Since soil water content, profile soil water, and anthesis date did not vary much for all the 14,068 combinations, we selected the best plant parameters based on yield first (RRMSD < 10%), followed by biomass (RRMSD < 10%), LAI (RMSD < 1.0), and maturity date (within 7 days). There were 1199 combinations that provided acceptable calibration results for the full irrigation treatment (#1) in 2008, of which 133 also simulated the other four treatments well in 2008. 94 of the 133 sets of plant parameters simulated well for the five treatments in 2009. Among the 94 sets of parameters, 23 provided yield simulation with RRMSD < 10% in 2010, but none of them simulate biomass well with RRMSD < 10% in 2010. Among the 23 sets of parameters, we selected one set, listed in Table 2, that provided overall best simulation for all the three years. These values were very close to the manual calibration values except for PHINT.

The new set of plant parameters simulated maize yield with RRMSD of 6.5% for 2008 and 7.1% for 2009, and maize biomass with RRMSD of 8.5% for 2008 and 5.7% for 2009. Simulated LAI had a RMSD of 0.92 for 2008 and 0.98 for 2009. The RMSDs for soil water content were 0.037 cm^3 cm^{-3} for 2008 and 0.030 cm^3 cm^{-3} for 2009 and those for profile soil water were 3.9 cm for 2008 and 2.4 cm for 2009. For year 2010, simulated maize yield had a RRMSD of 7.6%, but a simulated biomass RRMSD of 18.7%. Simulated RMSD was 0.67 for LAI, 0.058 cm^3 cm^{-3} for soil water content, and 3.6 cm for total profile soil water in 2010.

Lack of prediction for biomass in year 2010 might be due to spatial variability in soil properties, because maize was planted in three different blocks in the three years. The field capacity was the average from the 2008 and 2009 plots and data from 2010 were not available until simulations were completed for 2008 and 2009. Using the PEST optimization program (Doherty, 2010; Nolan et al., 2011) to calibrate the soil parameters, Ma et al. (under review) did improve biomass simulation with a RRMSD of 11% for year 2010.

4.4. Use of RZWQM2 for irrigation scheduling

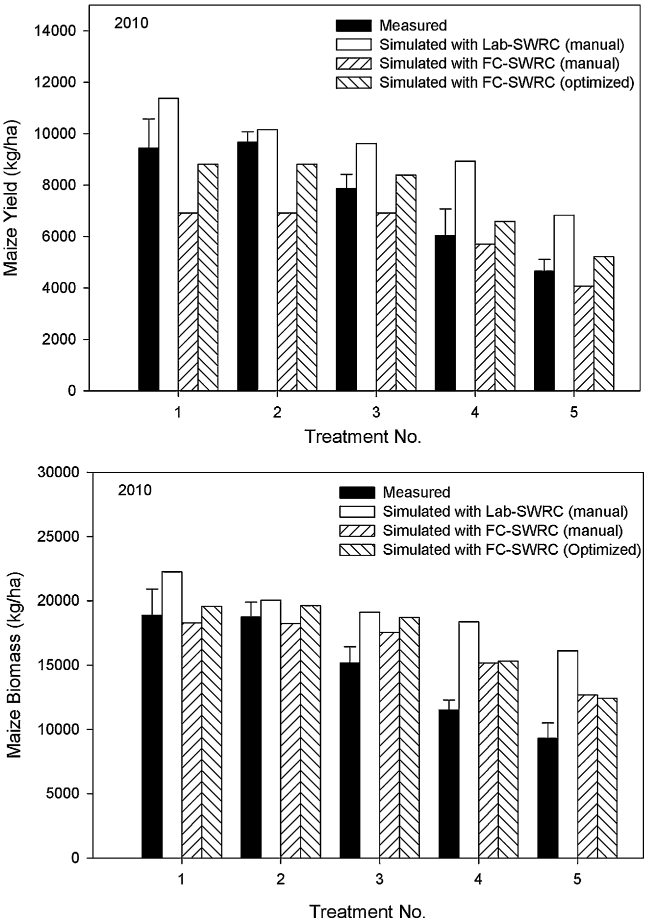

Fig. 7. Measured and simulated maize yield and biomass with field and laboratory measured soil water retention curves (SWRC) and plant parameters calibrated manually and automatically in 2010.

The parameterized model based on the three years of data was then used to explore the possibility of using the model as a tool for irrigation scheduling based on ETc requirements. In the previous model runs, irrigation events on each day were used as input. Therefore, it is of interest to know (1) how well the model simulates irrigation amount in the three crop seasons based on crop ET requirement in comparison to what was implemented in the field; and (2) which crop ET should be used to calculate irrigation amount in RZWQM2. In the field experiments, daily reference ET was calculated using the ASCE Standardized Reference ET method (Allen et al., 2005) and then multiplied by a crop coefficient derived for each day from a reference table for maize in Allen et al. (2007). This estimated transpiration from the reference ET and crop coefficient approach was close to RZWQM2 simulated transpiration based on the Shuttleworth–Wallace equation with $r^2 = 0.93$ (Fig. 8), except for the wettest two treatments in 2010 when the estimated transpiration was higher than simulated. Simulated actual transpiration accounted for 64–100% of potential transpiration (PT) estimated by the Shuttleworth–Wallace equation in RZWQM2 in 2008 and 55–100% in 2009, but only 46–90% of PT was simulated in 2010 (Fig. 9). These simulated transpiration values were very close to the

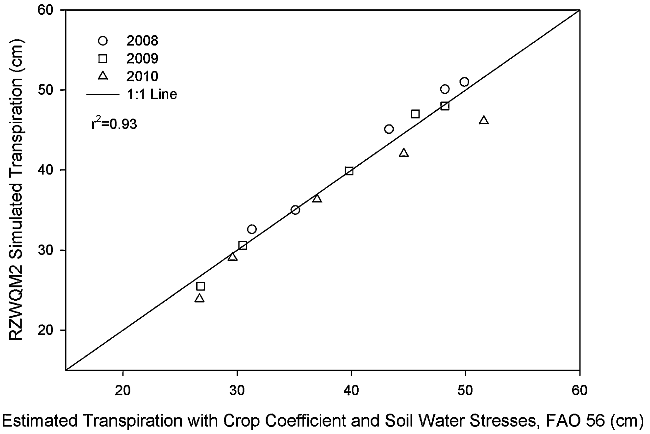

Fig. 8. Simulated versus field estimated crop transpiration in 2008, 2009, and 2010.

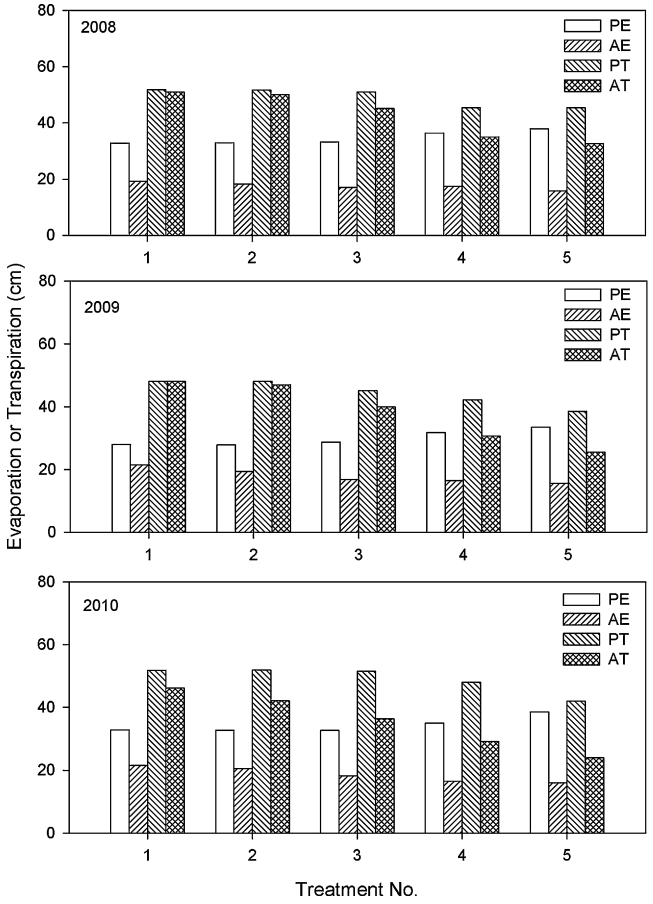

Fig. 9. Simulated potential evaporation (PE), potential transpiration (PT), actual evaporation (AE) and actual transpiration (AT) in 2008, 2009, and 2010.

field estimated transpiration for the three years (63–100% in 2008, 56–100% in 2009, and 52–100% in 2010). The only discrepancy was the wettest treatment in 2010 where the model simulated only 90% of PT, which was in agreement with the simulated water stress in early June and lower simulated yield in RZWQM2.

Thus, the model should be capable of scheduling irrigation events based on ETc requirements. As a test case, we used the calibrated model to schedule weekly irrigation amounts for the five ETc treatments of 100%, 85%, 70%, 55%, and 40% – the same as in the field experiment except that there was no 20% hold back of the projected irrigation amounts during the vegetative stage for use in the reproductive stage. Since RZWQM2 does not simulate ETc using the FAO 56, the Shuttleworth–Wallace PET was used instead. Weekly irrigation amount was determined in the model to meet a certain percentage of the weekly Shuttleworth–Wallace PET of previous week less the rainfall during the same period of time. However, unlike the field irrigation schedule where approximately 20% of the prescribed irrigation amount for the stressed treatments were withheld during the vegetative stage and added back during reproductive stage (with some flexibility from week to week), the stressed treatments in the model were uniformly irrigated based on the Shuttleworth–Wallace PET throughout the growing seasons. As shown in Fig. 10, simulated irrigation amounts were very close to the actual amounts applied in the field with $r^2 = 0.92$. In addition, simulated yield and biomass were also close to those simulated with actual irrigation amounts with $r^2 = 0.92$ and 0.93, respectively (Fig. 11), especially at high ETc treatments. For the low ETc treatments (stressed treatments), the simulated irrigation amount under-predicted yield and biomass somewhat, which implied that redistributing 20% irrigation water from the vegetative stage to the reproductive stage in the field experiment increased yield at low ETc treatments, but not at high ETc treatments.

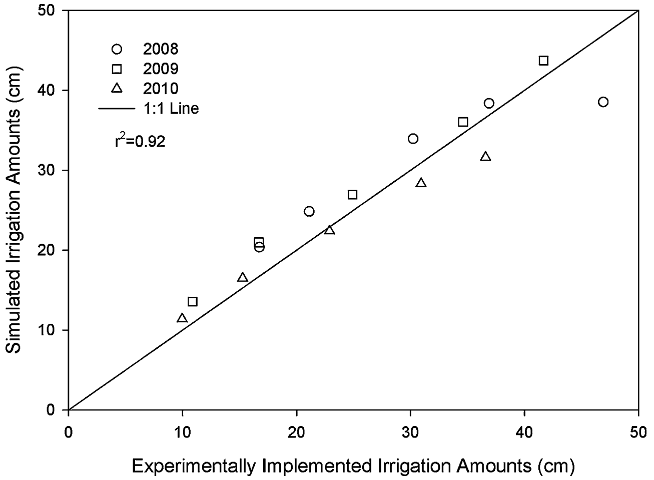

Fig. 10. Irrigation amount as simulated by RZWQM2 and as scheduled in the field in 2008, 2009, and 2010.

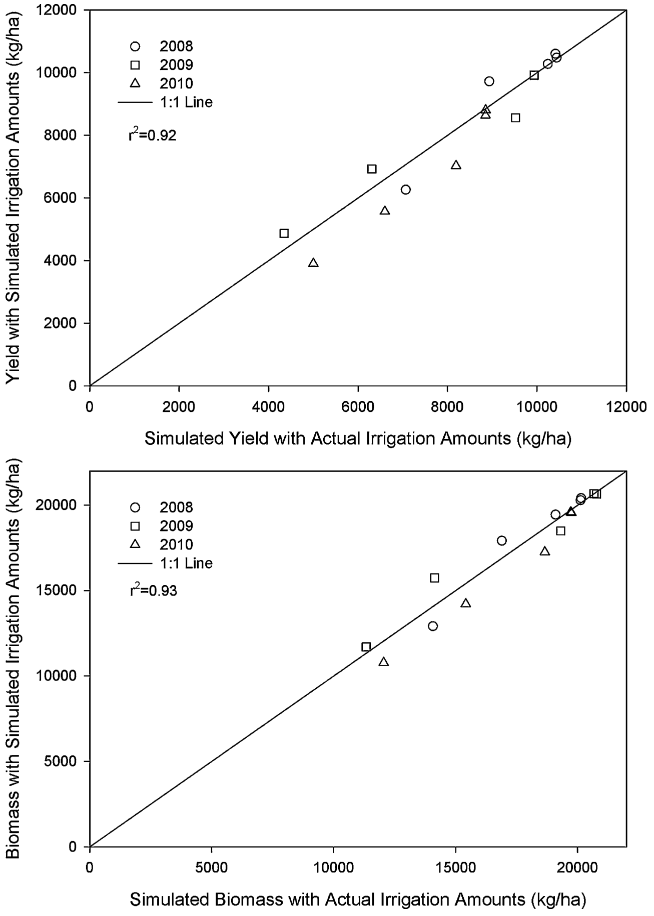

Fig. 11. Simulated yield and biomass with simulated irrigation events and actual irrigation events.

5. Conclusion

This study showed that laboratory-measured SWRCs were not capable of simulating plant water responses. However, using field-estimated SWRCs, the model simulated the response of yield and biomass to all irrigation levels adequately in both 2008 and 2009, and reasonably well in 2010. Without the deficit irrigation treatments and measured soil water content, this limitation would not have been apparent. Therefore, users should be cautious in evaluating and selecting appropriate input data (e.g., SWRC) in a model by cross checking the input data against field-measured soil water contents as was done in this study. This study also demonstrated a step-by-step procedure to parameterize a system model by selecting the correct soil parameters (laboratory-measured versus field-estimated SWRC) and then calibrating the plant parameters.

Since there are many combinations of parameters that can provide acceptable simulation results for a limited dataset, it may be necessary for a model to be parameterized with multiple treatments and multiple years of data so that the calibrated parameters can be transferred to other soil and management conditions. The results also demonstrated that, once RZWQM2 was parameterized for the crop and soil conditions, it was capable of scheduling irrigation amount based on ETc requirement, and that the Shuttleworth–Wallace PET might be used as a surrogate for FAO 56 ETc for ETc based irrigation in RZWQM2.

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