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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.

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