PARAMETERIZATION OF THE FAO AQUACROP MODEL FOR IRRIGATED COTTON IN THE HUMID SOUTHEAST

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Abstract

Simulation crop models help complement field experimentation and predict the impact of environmental stresses and alternate irrigation management strategies on crop responses. The Food and Agriculture Organization (FAO) of the United Nations has developed AquaCrop, a yield response to water stress model, for this purpose. AquaCrop has been parameterized for a number of crops, but not for cotton in a humid region. Replicated tests were conducted during the 2009 to 2011 growing seasons to meet the following objectives: (1) determine water productivity (WP) and in-season plant growth parameters of cotton in the humid Southeast and (2) parameterize and validate the AquaCrop model for cotton production under both field and controlled environment conditions. Testing the parameterized model with independent field data, we found that the model accurately simulated canopy cover, biomass, and cumulative ET. Therefore, AquaCrop, if properly parameterized and validated, can be used to optimize irrigation under intermittent drought stress and variable weather conditions in the humid Southeast.

Introduction

The 2012 drought in the USA caused devastating economic losses to producers and has provided evidence of how vulnerable our current agricultural production systems are to drought. Cotton growers in the southeastern USA are particularly vulnerable to drought due to poor distribution of rainfall during the growing season. In addition, southeastern Coastal Plain soils have extremely low water holding capacity due to predominantly sandy texture with very low organic matter contents. Therefore, even relatively short drought periods will have devastating effects on crop yields and farm profits.

Traditionally, the focus of irrigation water management for cotton has been to fully irrigate the crop, aiming at maximizing yield. As water becomes limited, full irrigation is no longer a viable water management strategy for many growers and other options, which allow some level of crop water stress, should be tested. However, field experiments could be lengthy and expensive. Simulation crop models have been used for decades to analyze crop responses to environmental stresses and to test the effects of alternate irrigation management practices on crop responses rather than conducting actual lengthy and expensive field tests.

Recently, the Food and Agriculture Organization (FAO) of the United Nations developed AquaCrop, a yield response to water stress model, which evolved from basic yield response to water algorithms (Raes et al., 2009; Steduto et al., 2009). Although AquaCrop has been tested for various crops, including cotton (Farahani et al., 2009), its performance under a humid climate, different irrigation regimes, and sandy Coastal Plain soils is unknown. The objectives of this study were to (1) determine water productivity (WP =Biomass/Normalized Transpiration) and in-season plant growth parameters of cotton in the humid Southeast and (2) parameterize and validate the AquaCrop model for cotton production under both field and controlled environment conditions.

Materials and Methods

Replicated field experiments were conducted at the Edisto Research and Education Center of Clemson University near Blackville, South Carolina, during 2009 to 2011 to determine WP and growth parameters of cotton under different irrigation regimes ranging from no irrigation (dryland) to full irrigation (meeting 100% of full cotton water requirements) (Qiao, 2012). Experiments in 2009 and 2010 were conducted on a typical coastal plain soil (Barnwell loamy sand) in a field called "E5". In 2011, tests were conducted in a field with Wagram sand under an automated rainout shelter that covered the plots during rainfall events (Fig. 1). The shelter was moved by two independent, twin-drive mechanisms and could cover the whole experiment in one minute. The cotton variety DP 0935 B2RF was planted in 2009 and 2010 and DP 0924 B2RF, in 2011.

Figure 1. Automated rainout shelter.

Cotton growth development was monitored in terms of growth stages, canopy cover, and aboveground dry biomass. Canopy cover was monitored weekly with AccuPAR LP–80 (Decagon Devices, Inc.) and with digital images (Qiao, 2012). Volumetric soil water content (SWC) was measured at 6 in. depth intervals with a 503DR Hydroprobe neutron probe. Readings were taken in the mid-morning and before irrigation. For field E5, readings were taken weekly to a depth of 36 in. For the rainout shelter experiment, readings to a depth of 24 in. were taken weekly for all treatments, except for the 100% treatment, which was measured twice a week.

For this study, the AquaCrop V3.1 software was used, which required inputs related to climate, crop, soil, irrigation, and initial soil water content. The model was first parameterized using the 2009 dataset (2009-E5). The 2011 dataset from the rainout shelter experiment (2011-RS) was used to refine the model, mainly because it was more detailed than the other datasets and uncertainties created by rainfall were eliminated. The model was then validated using the independent dataset from 2010 (2010-E5). Model parameterization was performed by first matching the measured and simulated canopy cover of the fully-irrigated treatment. This procedure was repeated to ensure accurate model predictions of ET, biomass, and yield. Default AquaCrop parameters were initially used and were adjusted based on the results from the above adjustment steps. The model was refined in 2011 based on simulation results of the deficit irrigation treatments (33% and 66% of full irrigation). To evaluate the performance of AquaCrop, linear regression was used to correlate observed and simulated values of crop canopy cover (CC), biomass (B), seasonal ET, and yield. The measured ET was determined as:

$$ET_a = P + I - D - R - \Delta SW \quad (1)$$

Where P = precipitation, I = irrigation, D = deep percolation below the root zone, R = runoff, ΔSW = the change in stored soil water, and D and R were assumed to be negligible. AquaCrop simulates crop ET assuming that it is directly related to CC. Therefore, correct simulation of CC is central to AquaCrop's performance as it affects the rate of transpiration and consequently biomass accumulation (Farahani et al., 2009). AquaCrop segregates ET into soil evaporation (E) and crop transpiration (Tr). E is calculated as:

$$E = Kr \times K_e \times ETo \quad (2)$$

Tr is calculated as:

$$Tr = Ks_{sto} \times CC^* \times Kcb_x \times ET_o \quad (3)$$

Where Kr = evaporation reduction coefficient, K_e = soil water evaporation coefficient, Kcb = crop coefficient, ETo = reference evapotranspiration, CC^* = adjusted CC, and Kcb_x = crop coefficient when canopy is fully developed. When there is water stress, transpiration is directly adjusted by a stress factor Ks_{sto}, and indirectly adjusted by stress factors Ks_{exp}, and Ks_{sen}, which are the stress coefficients for stomatal conductance, canopy expansion, and canopy senescence, respectively. The range of these coefficients varies between 0 and 1 depending on soil water depletion. AquaCrop calculates biomass (B) from water productivity (*WP*), *Tr* and *ETo* as:

$$B = WP \times \Sigma\, (Tr/ETo) \tag{4}$$

Crop yield (*Y*) is then estimated from B and harvest index (HI) as:

$$Y = B \times HI \tag{5}$$

The HI can be adjusted for water stress, failure of pollination, and inadequate photosynthesis based on a reference harvest index (HI_o).

Results and Discussion

Model Parameterization

Canopy Cover (CC): Adopting a trial and error approach, changes were made to the default parameters from Cordoba, Spain for cotton. After parameterization, canopy growth coefficient (CGC) was increased to 12% from the default value of 10% and canopy decline coefficient (CDC) was increased to 6.3% from the default value of 2.9%. Figure 2 shows simulated versus measured CC values for the 100% irrigation treatment. AquaCrop accurately simulated CC for the 100% irrigation treatment, but overestimated CC beyond 51 DAP (day after planting) for both the 33% and 66% irrigation treatments. Similar results were reported by Heng et al. (2009) in which simulated CC declined faster than measured CC values for rainfed treatments. They concluded that AquaCrop was not able to simulate slowing down of stress-induced early senescence when there was rainfall or irrigation.

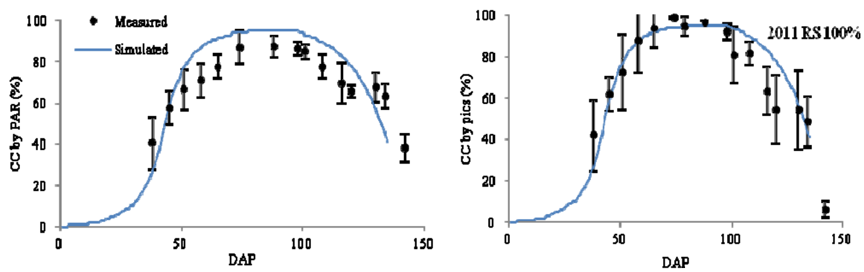

Figure 2. Simulated versus measured CC for 2011-RS experiments (CC measured by AccuPAR sensor [left] and by digital images [right]).

Evapotranspiration (ET): Only the crop coefficient (Kcb) was changed during parameterization, from a value of 1.1 to 1.2 based on Bellamy (2009) who reported that the Kcb for cotton in South Carolina was about 1.24 for the mid stage. Figure 3 shows simulated cumulative ET versus measured ET for the 2011-RS experiment. Cumulative ET was successfully simulated with measured cumulative ET 33% and 66% irrigation treatments (R^2 = 0.994 and 0.996, respectively). While the simulated and measured cumulative ET values for 100% treatment were highly correlated (R^2= 0.984), the seasonal ET value was 5.9 inches less than the measured ET. From the AquaCrop output, the model did simulate 4.1 in. drainage through the season. Also, it was possible that the shelter failed to move on DAP 128 when rainfall was 2.4 in. These two values could add up to 6.5 in, which could explain the deep seepage of 5.9 in., as predicted by the model.

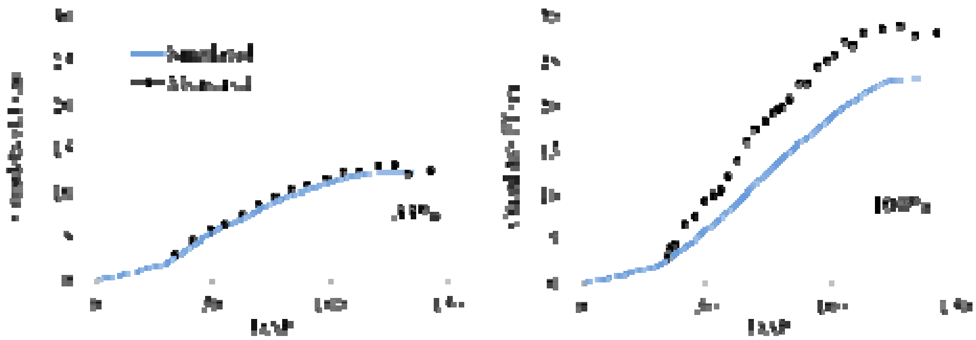

Figure 3. Simulated ET versus measured ET for 2011-RS experiment.

Aboveground Biomass and Yield: Water productivity (WP) is a key parameter in simulating yield and biomass. The measured WP values for cotton under the three experiments were 115, 107, and 113 lb/acre, which were not only similar, but also close to model suggested WP value of 134 lb/acre for cotton. It should be pointed out that due to the difficulty of separating soil evaporation and crop transpiration; the calculated WP values were possibly lower than real values when using ET in place of T. Also, large variation in biomass sampling could induce errors in WP determination. For modeling, the value of WP was adjusted to 129 lb/acre to account for the fact that we used ET in the WP estimation while the model uses WP values based on transpiration. Comparison of simulated and measured biomass values for the different treatments/years showed that AquaCrop accurately simulated biomass accumulation for the 66% and 100% irrigation treatments in 2009 and 2011. The model underestimated biomass for the 33% irrigation treatment in the 2011 rainout shelter experiment, which could be due to observed underestimation of canopy cover

In order to clearly control the parameterization process, water stress effect was only considered in canopy cover development. No stress was induced to harvest index. However, in an effort to ensure correct simulation of the final yield, reference harvest index was slightly adjusted to 27% from the default value of 30%. The regression coefficient of simulated versus measured yield values was 0.909, suggesting satisfactory performance by the model (Fig. 4).

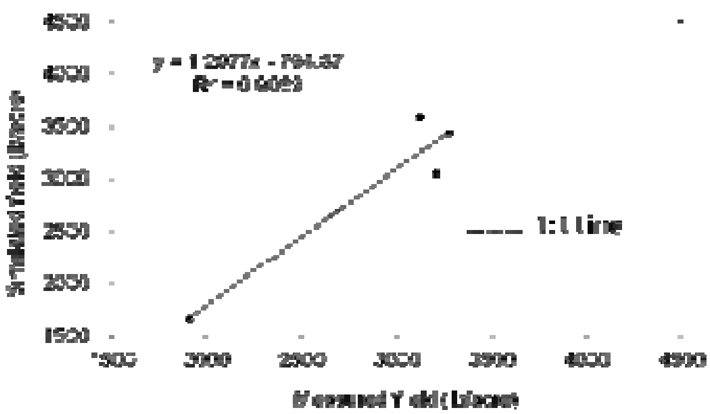

Figure 4. Simulated versus measured seed cotton yields.

__Model Validation__

After successful parameterization of AquaCrop for cotton using the 2009-E5 and 2011-RS datasets, the model was validated using the independent dataset of 2010-E5 in terms of canopy cover, ET, aboveground dry biomass, and yield. As shown in Table 1, the simulated seasonal ET values in the validation run were lower than measured values. It could be seen that the under prediction of seasonal ET for every treatment corresponded to the value of deep percolation simulated by AquaCrop.

Simulated and measured yields are shown in Table 2, where predictions of the 100% treatment were the most accurate, with the least accuracy observed in the dryland treatment. It was questionable that the actual measured yield of the 75% irrigation treatment was higher than the 100% irrigation treatment. This could be due to the fact that yields of some cotton cultivars, including the DP 0935, could decrease above certain total water application level (Bellamy, 2009).

Table 1. Simulated and measured evapotranspiration (ET) values for the 2010-E5 experiment.

Irrigation Treatment	Simulated ET (in)	Measured ET (in)	ET Difference (in)	Simulated Deep Percolation (in)
0%	18	21	4	4
75%	20	23	4	4
100%	20	24	4	5

Table 2. Simulated and measured seed cotton yields of 2010-E5.

Treatment	Average Measured Yield (lb/acre)	Standard Deviation (lb/acre)	Simulated Yield (lb/acre)
2010 E5 0%	2758	227	2102
2010 E5 75%	3285	744	2938
2010 E5 100%	2958	105	3016

Summary

Cotton seasonal water use ranged from 13 in. for the 33% irrigation treatment to 28 in. for full irrigation. Water productivity in the three years ranged from 118 to 161 lb of seed cotton per acre-in of water applied (irrigation and rainfall). WP normalized for local climate was nearly the same during the three years, averaging 112 lb/acre. Cotton WP and water use values quantified in this study are useful for modeling yield response to water stress and evaluating effects of alternate irrigation regimes and intermittent drought on cotton productivity. The model was successfully parameterized and its performance was satisfactory in terms of CC, aboveground dry biomass, and yield. Simulated ET values were highly correlated with measured values for all experiments, except that the model consistently produced unexpected deep drainage in a number of treatments. We were unable to verify this because of lack of deep soil moisture readings. Considering the complexity of modeling crop growth and water stress, AquaCrop did a good job of simulating cotton growth and soil water dynamics in the humid Southeast. Since the parameterization dataset provided in this study applies to cotton grown in humid conditions of South Carolina, the parameterized model is expected to perform satisfactory in major cotton producing states in the South and Southeast USA. The parameterized model will be a useful tool for irrigation and water use efficiency studies in this region. Additional studies are encouraged to further test the performance of the cotton parameters developed in this study to ensure their regional applicability and transferability.

Acknowledgements

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