Water Productivity of Cotton in the Humid Southeast - FAO AquaCrop Modeling

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Abstract: *Robust crop models help complement field experimentation and predict the impact of alternate management on production. Recently, the Food and Agriculture Organization (FAO) of the United Nations developed the AquaCrop, a yield response to water stress model. AquaCrop has been parameterized for a number of crops, but not for cotton in a humid region. Using field data, AquaCrop was parameterized and tested for cotton under both open field and a rainout shelter at the Clemson University, Edisto Research and Education Center, near Blackville, SC. Parameterization was less demanding than expected, requiring adjustments of a few model parameters. Using the parameterized model with independent field data, the model simulated canopy cover, soil water content, and cumulative ET values that were highly correlated with measured values with coefficient of determination (R^2) values greater than 0.79. The properly parameterized AquaCrop provides the necessary tool to study irrigation optimization under intermittent drought stress and climate variability in the humid Southeast.*

Keywords: AquaCrop, Water Productivity, modeling, cotton, evapotranspiration, irrigation

Introduction

Simulation models have been used for decades to analyze crop responses to environmental stresses and to test alternate management practices. Modeling complements field experimentation and help limit lengthy and expensive field tests. Crop yield response to water has been framed in a few simple equations in the past, while more sophisticated simulation models have been developed in recent decades. The tradeoff between simplicity and accuracy of the models remains an issue of concern if their broad application is to be achieved. Model has to be simple enough to be comprehensible by others, but complex enough to be comprehensive in scope (Monteith, 1996).

Recently, the Food and Agriculture Organization (FAO) of the United Nations addressed this concern by developing the AquaCrop model. AquaCrop evolved from the basic yield response to water algorithm in FAO Yield Response to Water (FAO-33) to a daily-step, process-based crop growth model with limited complexity than other models (Raes *et al.*, 2009; Steduto *et al.*, 2009; Todorovic *et al.*, 2009).

AquaCrop was recently tested for various crops, including cotton, across a wide range of climate, soil types, water deficit, and management conditions (Farahani *et al.*, 2009; Geerts *et al.*, 2009; Hsiao *et al.*, 2009; Karunaratne *et al.*, 2011; Salemi *et al.*, 2011; Stricevic *et al.*, 2011; Zeleke *et al.*, 2011). The model did a good job of simulating canopy cover, yield, and water productivity. AquaCrop simulated well Bambara groundnut with field observations originating in three zones in semi-arid Africa with R^2 values of 0.88, 0.78 and 0.72 for the canopy cover (CC), aboveground dry biomass (B), and yield (Y), respectively (Karunaratne *et al.*, 2011). Farahani et al. (2009) tested this model for cotton under Mediterranean climate, resulting in accurate prediction of ET (<13% error), canopy cover (9.5% error) and yield (<10% error). Salemi et al. (2011) used AquaCrop to study winter wheat yield performance under deficit irrigation in an arid region. However, the transferability of the existing cotton parameters developed in Mediterranean environments to humid climate with different climate regimes, soils, irrigation methods, and field management is unknown. Hence, our objectives were to parameterize and validate AquaCrop for cotton growth in the humid Southeast U.S.A.

Material and Methods

Site Condition

Data used for modeling purposes were detailed in Qiao (2012) and in a companion paper (Farahani et al., 2012; in this proceedings). Three irrigated cotton experiments were conducted at Edisto Research and Education Center of Clemson University (EREC), Blackville, SC. In-season variations in cotton growth parameters and water use as well as water productivity (WP) were quantified under different irrigation regimes ranging from dryland (i.e., no irrigation) to full irrigation. The climate is subtropical with hot and humid summer and mild to chilly winter. Annual precipitation is abundant, ranging from 1000 to 1700mm, while drought and excessive rainfall make it hard for irrigation management. Rainfall distribution in the Southeast U.S.A. is very uneven. For example in South Carolina, there is a probability that in one out of three years, a twenty one consecutive day period during the growing season will occur with total rainfall of less than 53mm; and every year a period of fourteen days will occur with total rainfall of less than 35mm (Linvill, 2002). An automated weather station inside the research center measured daily values of minimum and maximum air temperature and relative humidity, precipitation, solar radiation, and wind speed at 2 m height. Daily reference evapotranspiration (ET_o) was computed using the Penman-Monteith approach (Allen *et al*., 1998).

AquaCrop Modeling

AquaCrop was first parameterized using the cotton datasets from 2011 experiment under an automatic rainout shelter (2011 RS for short) and from 2009 experiment at E5 field (2009 E5 for short), The model was then validated using an independent dataset from the 2010 cotton experiment at E5 field (2010 E5). This study used the AquaCrop V3.1. AquaCrop requires the input data files for climate, crop, soil, irrigation, and initial soil water (SW_{ini}) conditions, which were assembled using the field data described above

Model parameterization was performed with two datasets (2009 E5 and 2011 RS) by first matching the measured and simulated canopy cover of fully irrigated cotton crop (2009 E5 data and the 100% irrigation treatment data in 2011 rainout shelter). This procedure was repeated to ensure model predictions of ET, biomass, and yield were satisfactory. Default parameters from AquaCrop were initially used. Default parameters were adjusted based on the results from the above adjustment steps. The model was also parameterized in 2011 based on simulation results of deficit irrigation treatments (33% and 66% of full irrigation). Trial and error approach was used until satisfactory results were gained.

Upon parameterizing the model, the model was validated using the independent 2010 dataset from E5 field. To evaluate AquaCrop performance, a linear regression was used to determine correlations between the observed and simulated values of CC, B, seasonal ET, and yield.

Results and Discussion

Model Parameterization – 2009 E5 and 2011 RS

Adopting a trial and error approach, changes were made to the default parameters from Cordoba, Spain for cotton. Table 1 shows default parameters of cotton as suggested by AquaCrop.

Table 1. Default parameters based on cotton data from Cordoba, Spain

User Adjusted	Units or meaning	Value
Development parameters		
CGC	increase in CC relative to existing CC per GCD, %	10
CDC	decrease in CC relative to existing CC per GCD, %	2.9
CCx	Maximum canopy cover, %	98
Kcb	Crop coefficient when canopy is complete but prior to senescence (Kcb,x)	1.1
Zx	Maximum effective rooting depth, m	1.2
Water stress response parameters		
$P_{exp,upper}$	as fraction of TAW, above this leaf growth is inhibited	0.2
$P_{exp,lower}$	as fraction of TAW, leaf growth completely stops at this point	0.7
f_{exp}	shape of expansion curve, the bigger the more resistant to stress	3
$P_{sto,upper}$	as fraction of TAW, stomata begin to close at this point	0.65
f_{sto}	shape of stomatal curve, the bigger the more resistant to stress	2.5
P_{sen}	as fraction of TAW, canopy beging to senescence at this point	0.75
f_{sen}	shape of senescence curve, the bigger the more resistant to stress	2.5
Crop production parameters		
WP	Water productivity, g/m^2	15
HI_o	Reference harvest index, %	30

Note: CGC is canopy growth coefficient. CDC is canopy decline coefficient. GCD is growth calendar days. $P_{exp,upper}$ and $P_{exp,lower}$ are the upper and lower threshold of soil water depletion factor for canopy expansion, respectively. f_{exp} is shape factor for water stress coefficient for canopy expansion. $P_{sto.upper}$ is the soil water depletion factor for stomata control. f_{sto} is shape factor for water stress coefficient for stomata control. P_{sen} is the shape factor for water stress coefficient for canopy senescence and f_{sen} is the shape factor for water stress coefficient for canopy senescence. Reference Harvest Index (HIo) is the ratio of the yield mass to the total aboveground biomass that will be reached at maturity for non-stressed conditions.

Canopy Cover (CC)

As pointed out in Farahani et al (2009), correct simulation of CC is central to AquaCrop performance, as it affects the rate of transpiration and consequently biomass accumulation. After parameterization, CGC was increased to 12% from the default value of 10% and CDC was increased to 6.3% from the default value of 2.9%. The water stress response parameters were then adjusted where $P_{exp,upper}$ was changed from 0.2 to 0.4 and f_{exp} was changed from 3 to 3.5. For the period of senescence, $p_{sen,upper}$ was changed to 0.8 from the default of 0.75. Figure 1 shows simulated versus measured CC both by AccuPAR LP-80 (Decagon Devices, Inc.) and digital camera. As shown, AquaCrop did a good job of simulating CC for the 66% and 100% irrigation treatments. AquaCrop overestimated CC beyond 51 DAP (Day After Planting) for both 33% and 66% treatments. Between 51 DAP and 82 DAP when canopy was still developing, $p_{exp,upper}$ must have been reached, and therefore, plant could not reach the maximum CC. Also, from 82 DAP to the end of season, p_{sen} was reached so simulated CC declined faster than measured values. Similar results were reported by Heng et al. (2009) in which simulated CC declined faster than measured CC values for nonirrigated treatments. They concluded that AquaCrop was not able to simulate slowing down of the stress-induced early senescence when there was rainfall or irrigation. Also, it could be seen that the model tends to overestimate CC later in season for the 100% irrigation treatment. This could be related to the nature of PAR measurement. Compared to maximum average CC measured by digital camera, maximum average CC measured by PAR was lower.

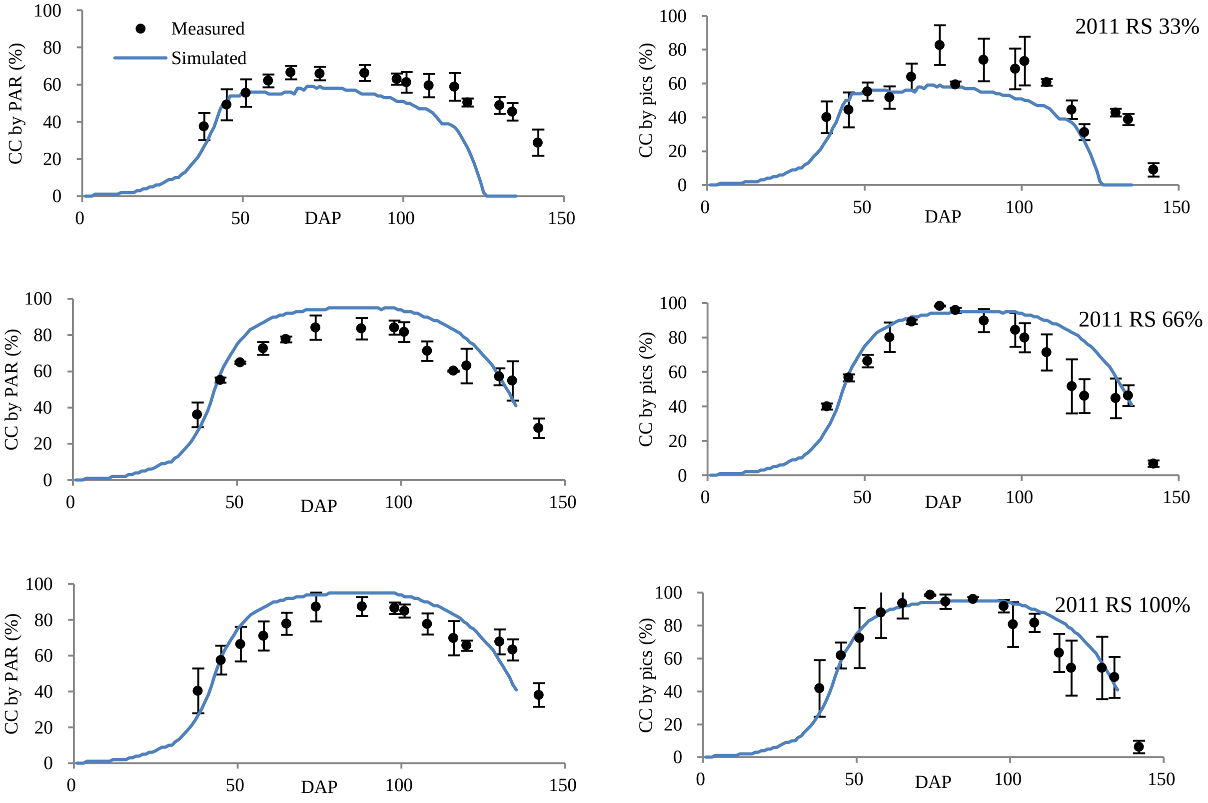


Figure 1. Comparison of simulated versus measured CC for 2011 RS and 2009 E5 experiments (continuous lines are predicted values)

Evapotranspiration (ET)

Crop ET is directly related to canopy cover. After simulating CC successfully, simulated ET values were compared to measured ET values. AquaCrop is able to segregate ET into soil evaporation (E) and crop transpiration (T_r). However, soil evaporation is hard to measure in the field using current equipment, so the total of soil evaporation (E) and crop transpiration (T_r) was used in this study. In AquaCrop, Tr is calculated as:

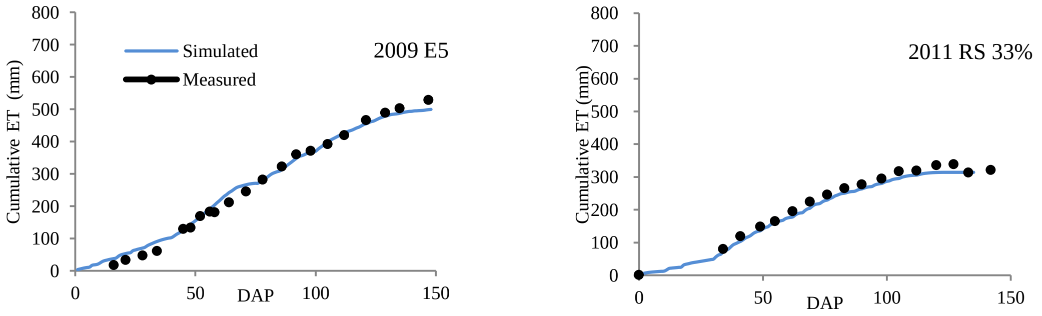
$$Tr = Kcb * ET_o \; with \; Kcb = (CC^* \times Kcb_x) \qquad 1.$$

Where Kcb is crop coefficient, ET_o is reference evapotranspiration, Adjusted CC is denoted as CC^*, and Kcb_x is the crop coefficient when canopy is fully developed. When there is water stress, transpiration is adjusted by a stress factor as:

$$\mathrm{Tr} = Ks_{sto} \times CC^* \times Kcb_x * ET_o \qquad 2.$$

Where Ks_{sto}, Ks_{exp}, and Ks_{sen} 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 how much water is depleted. Only Kcb was changed during the process of parameterization, from a value of 1.1 to 1.2 based on Bellamy (2009) who reported that the crop coefficient for cotton in South Carolina was about 1.24 for mid stage. Figure 2 shows simulated cumulative ET versus measured ET for 2009 E5 and 2011 RS experiments.

Cumulative ET was successfully simulated for 2009 E5, 2011 RS 33%, and 2011 66% which correlated with measured cumulative ET with R^2 of 0.995, 0.994, and 0.996, respectively. While for 2011 RS 100%, simulated cumulative ET correlated with measured cumulative ET with an R^2 of 0.984, the seasonal ET value was 150mm less than measured ET. From AquaCrop output, the model did simulate 104mm drainage through the season. Also, it was possible the shelter failed to move on DAP 128 while the rainfall was 61mm on that day. These two values could add up to 165mm, which could explain the deep seepage of 150mm as predicted by the model. Drainage was expected to be near zero during this experiment under the carefully irrigated drip irrigation, but a few long irrigation durations of the sandy soil could have caused deep seepage.



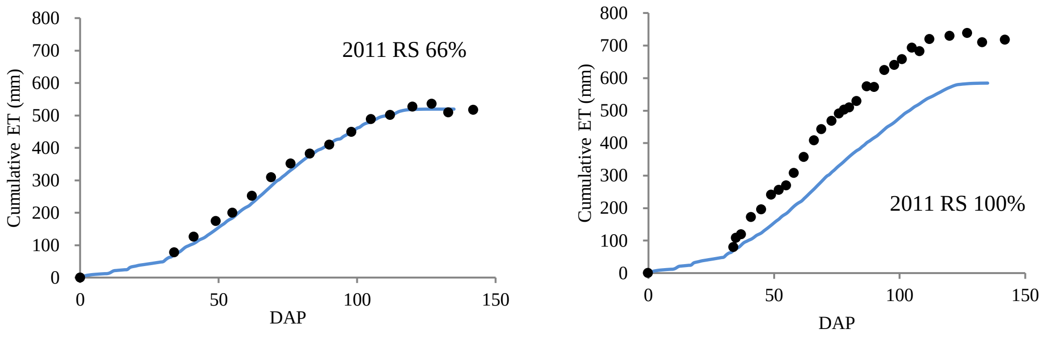


Figure 2. Simulated ET versus measured ET for 2009 E5 and 2011 RS experiments

Aboveground Biomass and Yield

After modeling ET, simulated and measured values of biomass were compared. As stated above, biomass is calculated in AquaCrop using equation

$$\mathrm{B} = \mathrm{WP} \times \sum \left(\frac{Tr}{ET_o}\right) \qquad 3.$$

Water productivity (WP) is the key parameter in yield and biomass computation in the model. It is normalized by climate condition. Crops could be classified into different groups (C3 and C4) with WP values that are nearly twice as large in the C4 than in C3 plants. For C3 crops, literature suggests WP values between 15 to 20 g/m^2. For C4 crops, WP values of 30 to 35 g/m^2 are suggested. WP could be adjusted based on soil fertility level. For this study, the fertility level in all experiments was not limited, thus no simulation of fertility effects was performed.

Simulated biomass values were compared with measured values in different treatments and years (Figure 3). The measured WP values for cotton under the three experiments were 12.9, 12, and 12.7 g/m^2, which were not only similar, but also close to model suggested WP value of 15 g/m^2 for cotton. It should be pointed out that due to the difficulty of separating soil evaporation and crop transpiration (T_r), the calculated WP values were possibly lower than real values when using ET in place of T. Also, large variation in biomass sampling could also induce errors in WP determination. For modeling, the value of WP was adjusted to 14.5 g/m^2 to account for the fact that we used ET in the WP estimation while the model is interested in WP values based on transpiration (or T_r). AquaCrop simulated biomass accumulation rather well for 66% and 100% irrigation treatments in 2011, as well as for the 2009 E5 cotton experiment. The model underestimated aboveground biomass for 33% irrigation treatment in 2011 rainout shelter experiment. This could be the result of the underestimation of canopy cover for the same treatment, as previously shown in Figure 1.

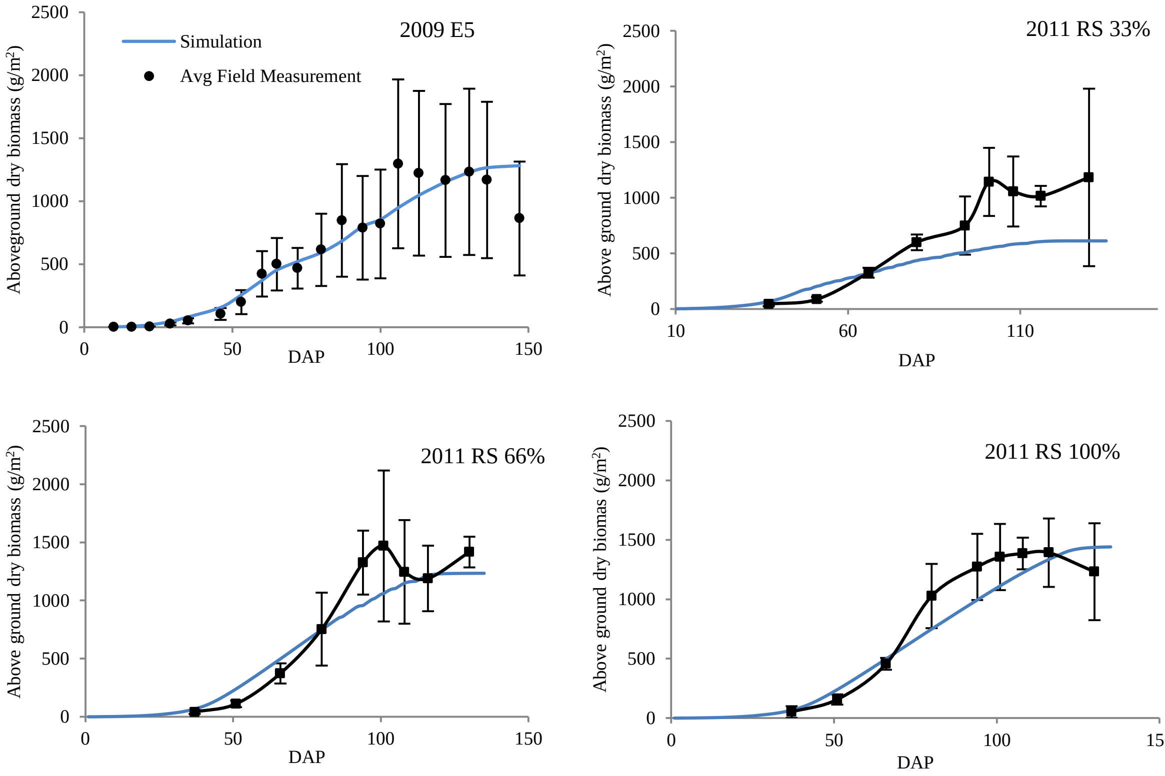


Figure 3. Simulated versus measured aboveground dry biomass

The partition of biomass into yield is simulated by equation:

$$Y = B \times HI \qquad 4.$$

Where HI is harvest index. HI could be adjusted by water stress, failure of pollination, and inadequate photosynthesis based on HI_o (reference harvest index). 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 (Figure 4).

Validation of AquaCrop

After successful parameterization of Aquacrop for cotton using the 2009 E5 and 2011 rainout shelter datasets, the model was validated using the independent dataset of 2010 cotton experiment at E5 in terms of canopy cover, ET, aboveground dry biomass, and yield. Table 2 presents a complete list of Aquacrop crop parameters for cotton grown in the humid region experimented in this study.

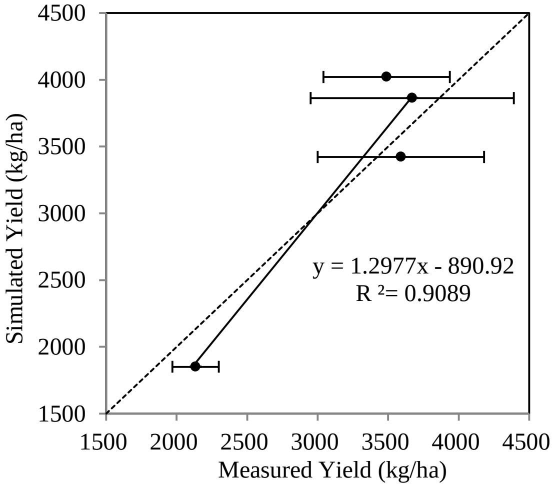


Figure 4. Simulated versus measured yields (seed + lint cotton) for 2011 shelter and 2009 E5 experiment.

Table 2. Parameterized crop parameters for cotton

User Adjusted	Units or meaning	Value
	Development parameters	
CGC	increase in CC relative to existing CC per GCD, %	12
CDC	decrease in CC relative to existing CC per GCD, %	6.3
Kcb	Crop coefficient when canopy is complete but prior to senescence (Kcb,x)	1.2
Zx	Maximum effective rooting depth, m	0.6
	Water stress response parameters	
$P_{exp,upper}$	as fraction of TAW, above this leaf growth is inhibited	0.4
$P_{exp,lower}$	as fraction of TAW, leaf growth completely stops at this point	0.7
f_{exp}	shape of expansion curve, the bigger the more resistant to stress	3.5
$P_{sto,upper}$	as fraction of TAW, stomata begin to close at this point	0.7
f_{sto}	shape of stomatal curve, the bigger the more resistant to stress	2.5
P_{sen}	as fraction of TAW, canopy beging to senescence at this point	0.8
f_{sen}	shape of senescence curve, the bigger the more resistant to stress	2.5
	Crop production parameters	
WP	Water productivity, g/m^2	14.5
HI_o	Reference harvest index, %	27

The validation results show simulated CC values that were well correlated with measured values determined by a digital camera with R^2 values of 0.839, 0.826, and 0.834 for the 100%, 75%, and 0% irrigation treatments, respectively (Figure 5). Simulated CC values were less correlated with measured CC by PAR (R^2 of 0.674, 0.694, and 0.613 for 100%, 75%, and 0% treatments, respectively) simply because PAR measurements do not distinguish between live and senesced and dead leaves.

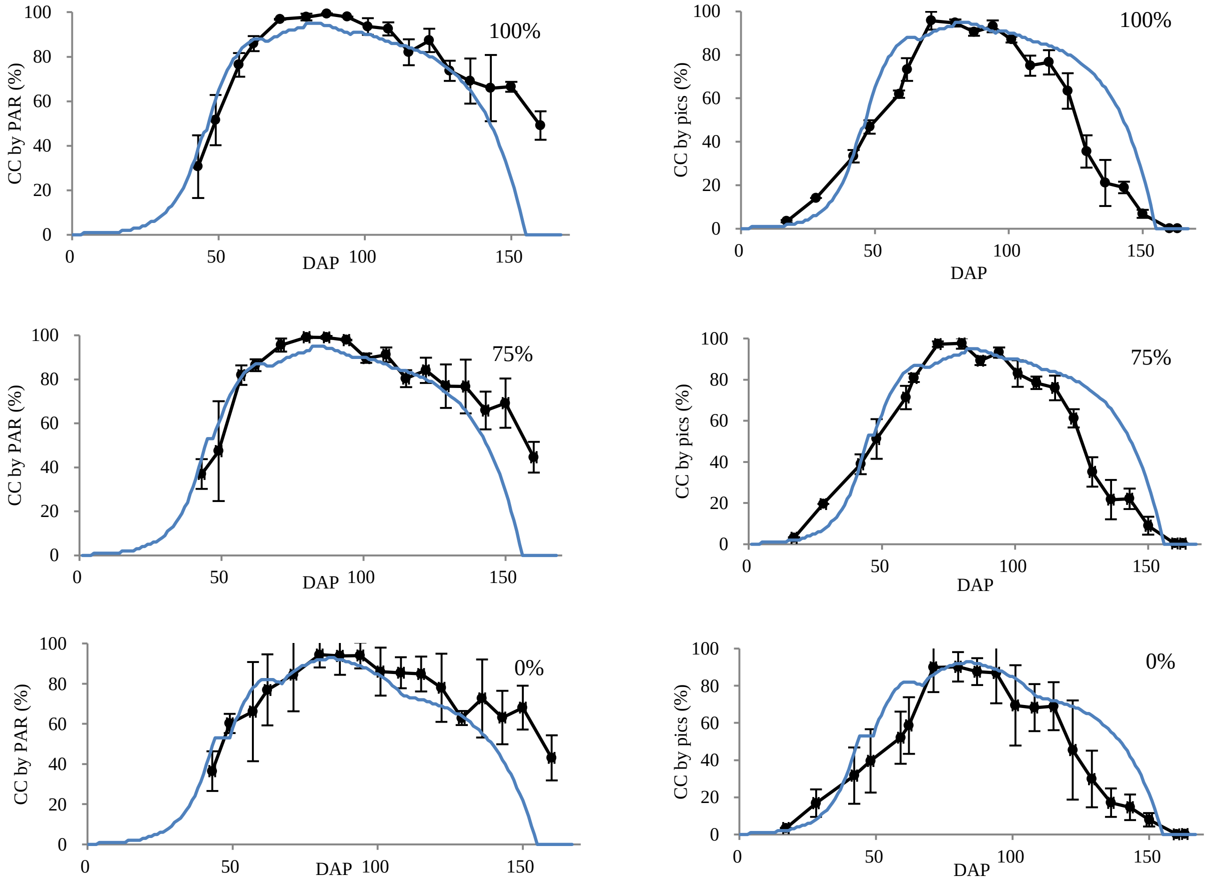


Figure 5. Simulated CC versus measured CC for every treatment of 2010 E5 experiment

As shown in Table 3, the simulated seasonal ET values in the validation run were lower than measured values.

It could be seen that the underprediction of seasonal ET for every treatment correspond to the value of deep percolation simulated by AquaCrop. Since ET was underestimated, final biomass was slightly underestimated except for the dryland plots (0% treatment) (Figure 6).

Table 3. Simulated and measured ET values for 2010 E5 experiment

Irrigation Treatment	Simulated ET	Measured ET	Difference	Model predicted Deep Percolation
	mm	mm	mm	mm
0%	448	538	90	92
75%	500	594	94	112
100%	505	617	112	124

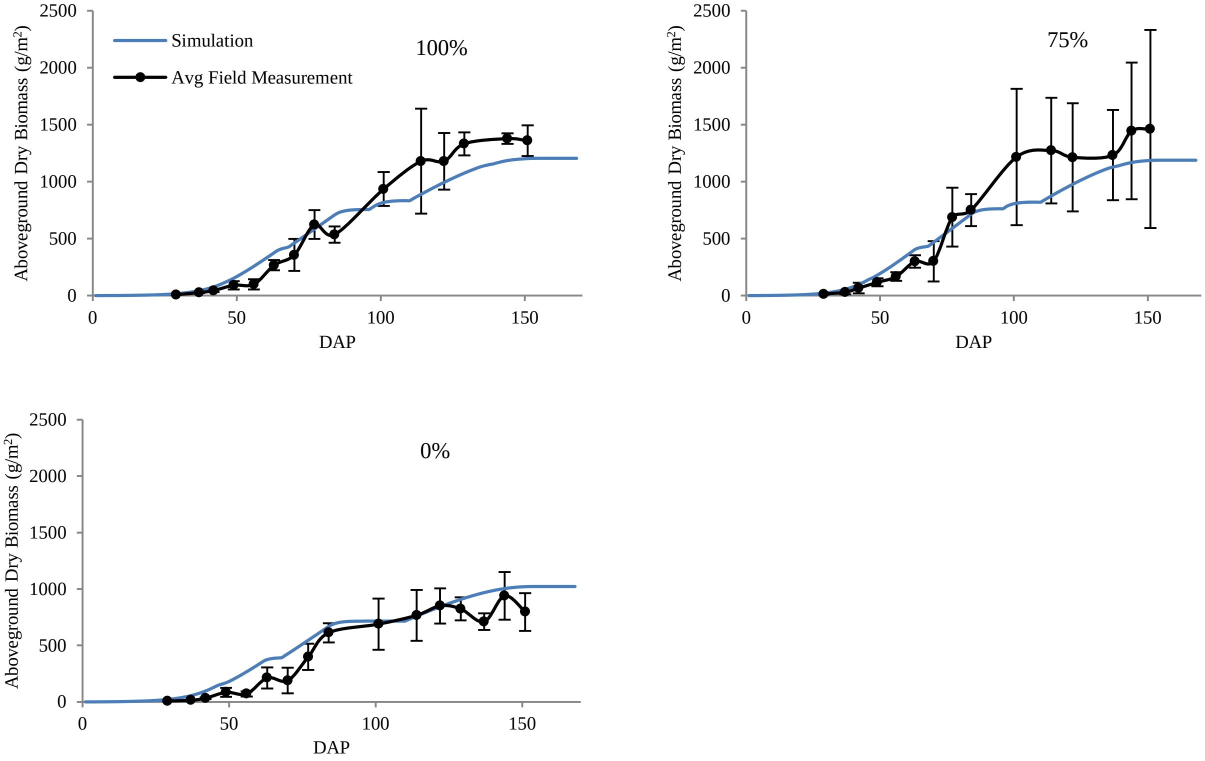


Figure 6. Simulated B versus measured B for every treatment of 2010 E5

Simulated yield values are shown in Table 4, where predictions of the 100% treatment were the most accurate, with least accuracy observed in the dryland treatment. It was questionable that the actual measured yield of 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 4. Simulated and measured yields of 2010 E5

Year	Avg. Seed Cotton Yield	STD. Yield	Simulated Seed Cotton Yield
	kg/ha	kg/ha	kg/ha
2010 E5 0%	3091	254	2356
2010 E5 75%	3682	834	3293
2010 E5 100%	3315	118	3380

Conclusion

The model was successfully parameterized using the 2009 E5 and 2011 shelter data sets, except that calibrating the model to accurately simulate severe water stress or early canopy senescence was difficult. Model 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. The parameterization dataset provided in this study applies to cotton grown in the humid conditions similar to South Carolina. South Carolina climate is quite representative of the Southeast, and thus the parameterized model is expected to perform satisfactory in major cotton producing states in the South and Southeast. 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.

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