Parameterization and Evaluation of the AquaCrop Model for Full and Deficit Irrigated Cotton

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ABSTRACT
Predicting yield is increasingly important to optimize irrigation under limited available water for enhanced sustainability and profitable production. Food and Agriculture Organization (FAO) of the United Nations addresses this need by providing a yield response to water simulation model (AquaCrop) with limited sophistication. In this study, AquaCrop was parameterized and tested for cotton (*Gossypium hirsutum* L.) under full (100%) and deficit (40, 60, and 80% of full) irrigation regimes in the hot, dry, and windy Mediterranean environment of northern Syria. Model parameterization used the 2006 data and was straightforward within the designed user-interface, owing to the limited number of key parameters. Accurate simulation of canopy cover was central to sound prediction of evapotranspiration and biomass accumulation. Key user-input parameters for this purpose were identified as the coefficients defining canopy development and the threshold soil water depletion levels for the water stress indices. The parameterized model was tested using data from the 2004 and 2005 seasons, resulting in accurate prediction of evapotranspiration (<13% error). The predicted yield values were within 10% of measurements, except in the 60 and 80% irrigation regimes in 2004, with errors up to 32%. The model closely predicted the trend in total soil water, but deviation existed for individual soil layers. This study provides first estimate values for cotton parameters useful for future model testing and use. Model parameterization is site-specific, and thus the applicability of key calibrated parameters must be tested under different climate, soil, variety, irrigation methods, and field management.

THE GLOBAL CHALLENGE for the coming decades will be increasing food production with less water. This can be partially achieved by increasing crop water use efficiency (WUE), and is particularly important in countries with increasing shortages of, and competition for, limited water resources used in agriculture. In this context, deficit irrigation is an option that may increase WUE, but would most certainly improve resource sustainability. The loss in production will depend on the extent of deficit, which may be more than compensated when the real value of water is taken into account. In practice, optimal scheduling of deficit irrigation requires a good understanding of crop response to water stress. Crop simulation models can be of great help toward this end.

Simulation models have been used for decades to analyze crop responses to environmental stresses and to test alternate management practices (Boote et al., 1996; Sinclair and Seligman, 1996). Crop yield response to water has been framed in a few simple equations in the past (Hanks, 1974), while more sophisticated and mechanistic simulation models were developed in recent decades (Uehara and Tsuji, 1998; Ahuja et al., 2002). However, the tradeoff between simplicity and accuracy of the models remains an issue of concern if their broad application is to be achieved. Recently, the FAO of the United Nations addressed this concern by developing the AquaCrop model. This simulation model evolved from the basic yield response to water algorithm in Doorenbos and Kassam (1979) to a daily-step, process-based crop growth model with limited complexity. AquaCrop is described in its conceptual framework and algorithmic solutions in Steduto et al. (2009) and Raes et al. (2009).

In many dry areas of the world, like southwestern USA and areas of the Mediterranean, cotton is grown under full irrigation (Janat and Somi, 2001; Grismer, 2002; Ertek and Kanber, 2003). Full irrigation is intended to maximize yield (and presumably profit), but the practice is not sustainable in basins where water is being withdrawn faster than it is being replenished. A more sustainable alternative is a demand management strategy that may include deficit irrigation (Kijne et al., 2003; Farahani et al., 2006). Cotton is an indeterminate perennial shrub that is grown as an annual, with a high crop water use (e.g., mostly reported between 800 and 1100 mm), yet found suitable for conditions of limited water (Mauney, 1986; Oosterhuis, 1990). Past research reports cotton physiological and morphological responses to water, cotton yield–water use relationship, and deficit irrigation strategies (Wanjura et al., 2002; Howell et al., 2004;
Dagdelen et al., 2006; Ibragimov et al., 2007; DeTar, 2008). When adopting deficit irrigation, the loss in crop yield and the impact on WUE is difficult to predict, being dependent on the timing, duration, and intensity of the stress. Local yield–water use functions can be developed experimentally, but that requires extensive field trials. A preferred approach is to use a combination of modeling and targeted experimentation. Modeling is useful to assess the effect of environment and management changes on crop development, to develop deficit irrigation strategies, and to simulate expected yields and WUE in a given soil–field–crop–climate environment. Among existing cotton models (Plant et al., 1998; Soler and Hoogenboom, 2006; Pachta, 2007), some are simpler and more suitable for local conditions, while others are more process-based. Mechanistic models are suited for research and systems analysis, but tend to be technically demanding and input-intensive, and thus are not easily adopted by practitioners.

AquaCrop was developed to achieve a balance between simplicity, accuracy, and robustness. AquaCrop has a relatively limited number of input parameters for ease of use and greater appeal to agricultural extension, consultants, and practitioners. It has a water-driven growth-engine for field crops with a growth-module that relies on the conservative behavior of biomass per unit transpiration (Tr) relationship (Hsiao and Bradford, 1983; Steduto et al., 2007). AquaCrop is a menu-driven program, with a set of input files that describe the soil–crop–atmosphere environment in which the crop develops, in addition to the seasonal field practices. AquaCrop is currently being tested for various crops across a wide range of climate, soil, water deficit, and management conditions. Our objectives were to parameterize and test AquaCrop for cotton under full- and deficit-irrigation in the semi-arid environment of northern Syria.

METHODS AND MATERIALS

AquaCrop Modeling

AquaCrop was parameterized and tested using data from a 3-yr study (2004 to 2006) that was conducted at the International Center for Agricultural Research in the Dry Areas (ICARDA), 35 km south of Aleppo (36°01´ N, 36°56´ E, and 284 m above mean sea level), in northern Syria (Farahani et al., 2008). The drip-irrigated field experiments had the objective of analyzing the effect of water and N stress on cotton growth, water use, and yield. The experimental design was a randomized split plot with four levels of irrigation and three levels of N treatments and was replicated three times each year. The version of AquaCrop (v. 2.4) used in this study is not yet fully configured to model the impact of N on crop growth, and thus N treatments are not simulated herein. For modeling, only the N treatment ensuring adequate fertility was used. AquaCrop was parameterized using data from the 2006 cropping season that provided the most extensive in-season plant measurements. The performance of the parameterized model was tested by simulating cotton yield, water use, and soil water in the 2004 and 2005 seasons, which offered an independent dataset, but arguably not very different than the 2006 season. AquaCrop requires the input data files for climate, crop, soil, irrigation, and initial soil water (SW\textsubscript{ini}) conditions (Raes et al., 2009), which were assembled using the field data described below.

The Cotton Field Experiment

Site Conditions

The experimental site is characterized by a Mediterranean climate with a single rainy season from the fall to early spring, averaging 350 mm with no rainfall during the summer. 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 (Fig. 1). Daily reference evapotranspiration (ET\textsubscript{o}) was computed using the Penman–Monteith approach (Allen et al., 1998). The cotton growing season in northern Syria usually starts in early May and ends in late September, typically a hot and windy season with high evaporative demand ~10 mm d\textsuperscript{-1} of ET\textsubscript{o} (Fig. 2). Soil at the site is deep (1.50 m at least), well-drained clay (montmorillonitic, thermic, Chromic Calcixerert), with a deep water table at depths > 100 m. Volumetric water content values at permanent wilting point (PWP) and field capacity (FC) equal to 22 and 38%, respectively (Ryan et al., 1997), which results in a total available water (TAW, the difference between FC and PWP) of 160 mm per 1 m soil.

Management Practices

The short season cotton variety (Aleppo-118, made available by the local extension office) was sown by hand during the first few days of May [1 May is assumed 1 DAS (day after sowing)], in 0.70-m rows, at a density of 9–10 seeds m\textsuperscript{-2} in 2004 and 2005, and 7–8 in 2006. The plots were 10.0 m wide by 13.3 m long and managed similarly over the 3 yr. The first irrigation...
occurred a few days after seeding, with observed emergence about 4 d later. Field was monitored for pests and weeds, and pesticides were applied as needed. The high N application treatment used in this modeling was 200 kg ha\(^{-1}\) of N (urea at 46% N) in each irrigation treatment, applied one-fifth at planting (surface banded over the rows and just before the first irrigation), with the rest fertigated on three separate occasions during the season. In all years and in accordance with local farm practices, cotton was harvested by hand over two dates in a span of 2 wk in September from an area 10 m long and seven rows wide in the center of each plot.

**Soil Water and Irrigation**

Over the 3 yr, soil water content was monitored using an on-site calibrated neutron probe (Type IH-II, Didcot Instruments, Co., Ltd., Abington, UK) at a minimum of weekly intervals, and always taken the day before and 2 d after each irrigation event. Aluminum access tubes were installed in the center of each plot, and along a crop row, before sowing. Neutron probe measurements were made for each 0.15-m layer in the soil profile to a depth of 1.80 m, except the top 0.15 m that was measured gravimetrically. Analysis of soil profile water identified maximum rooting depth (\(Z_{r}\)) at about 1.30 m, which was reached at beginning of crop senescence (110 DAS).

Cotton was drip irrigated using polyethylene laterals (16 mm inside diameter) that were installed after sowing and placed on the soil surface along every crop row with emitters (4 L h\(^{-1}\) inside diameter) that were installed after sowing and placed on the soil surface along every crop row with emitters (4 L h\(^{-1}\) inside diameter) that were installed after sowing and placed on the soil surface along every crop row with emitters (4 L h\(^{-1}\) discharge) spaced every 0.4 m on the laterals. Four levels of irrigation regimes were used, corresponding to 40, 60, 80, and 100% of full crop water needs. In the full irrigation (i.e., 100%) treatment, irrigation was initiated when soil water in the estimated root zone approached 50% of TAW, refilling the root zone to FC. In the deficit irrigated treatments, irrigation occurred on the same day as the fully irrigated plots, but the duration of irrigation applications were reduced to 40, 60, and 80% of the full irrigation. The irrigation season ended by late August, allowing the soil to dry to expedite boll opening. There were a total of 9, 10, and 9 irrigation events in 2004, 2005, and 2006, respectively, with corresponding seasonal full irrigation amounts of 800, 810, and 760 mm. The mean of all irrigation amounts per event was 85 mm with a mean frequency of 10 d (not including the lengthy 35-d period between the first and second irrigation). The wetted soil surface area by the localized drip system changed as a function of the irrigation treatment, corresponding to visual estimates of 30, 40, 60, and 70% surface wetting for the 40, 60, 80, and 100% irrigation treatments, respectively.

**Cotton Growth Measurements**

During the 2006 season, canopy development was monitored in terms of growth stages, leaf area, and aboveground biomass. On weekly basis, leaf area and aboveground biomass were determined by removing two plants per plot in one replicate only. Before cutting the plants at the ground level, growth stage was recorded. AquaCrop requires identifying generic growth stages of time to emergence, maximum canopy cover, start of senescence, and maturity. This identification does not necessarily correspond to the commonly reported growth stages for cotton, such as those based on node development or others based on stages of growth, like square initiation, first flower, and first boll. For the purpose of AquaCrop simulation, time to emergence, maximum canopy cover, and start of senescence were based on field observations (see below). For the indeterminate cotton, top growth continues if the season is not terminated by severe soil drying or chemical application to induce defoliation or desiccation. This latter method is not used in Syria.

Green leaves from the above two plants were separated and passed through a standard moving belt leaf area meter (Model AAM, Hayashi Denko, Japan) to measure leaf area per plant, which was multiplied by plant density to obtain leaf area index (LAI). Dry biomass of all aboveground plant components were then determined after drying at 65°C for 48 h. Two methods were used to estimate canopy cover (CC): (i) using the ratio of below to above canopy measurements of photosynthetically active radiation (PAR):

\[
CC = 1 - \frac{(\text{PAR}_{\text{below}})}{(\text{PAR}_{\text{above}})}
\]  

and (ii) using digital photos of canopy development taken at about weekly interval. The PAR readings were taken near solar noon (to minimize shading) at four locations within each plot using a quantum bar sensor (AccuPAR LP-80, Decagon Devices, Inc., Pullman, WA). The PAR readings were only available from 6 Aug. 2006 to the end of season, while measured leaf area (and thus LAI) was available for the entire season. For the period of PAR availability, a mean extinction coefficient \(\chi\) value of 0.77 for cotton was determined from

\[
\chi = -\ln(1 - CC)/\text{LAI}
\]

using measured LAI and their corresponding CC values. Using measured LAI and the mean \(\chi\) value, CC values for days with missing PAR data were then computed from

\[
CC = 1 - e^{-\chi \cdot \text{LAI}}
\]

Visual estimates of CC from digital photos proved to be fairly simple and in line with CC values from PAR and LAI data (data not shown), supporting the modelers’ choice of CC as the main crop growth indicator in AquaCrop instead of commonly used LAI. For the fully irrigated cotton, the parameter maximum canopy cover (\(CC_{m}\)) was estimated at 90% that was reached around 90 DAS. For the 2004 and 2005 seasons, in-season crop data were less rigorous than in 2006, with no CC and biomass data, but detail soil profile water and final yield data were available.
Cotton Evapotranspiration

Soil water budget method was used to estimate actual crop evapotranspiration ($ET_a$). This involved measuring or estimating the components of the water balance equation for a control volume defined by soil profile of given root zone depth, and is written as

$$ET_a = P + I - D - R - \Delta SW,$$  \[4\]

where P is precipitation, I is irrigation, D is deep percolation below the root zone, R is runoff, and $\Delta SW$ is the change in stored soil water, with all variables in units of equivalent mm water. The change in stored soil water was determined using the neutron probe (discussed above) at a minimum of weekly intervals. The reliability of $ET_a$ estimates depends on the measurement or estimation accuracy of the variables in the right-hand side of the equation. There was no rainfall during the cotton growing seasons and the drip system produced no runoff, with P and R equaling zero for analysis. Deep percolation is the most difficult variable to detect and quantify, particularly when the depth of access tube is less than the wetting front by irrigation (Wright, 1990). In this study, the access tubes were installed up to 1.80 m, sufficiently deep to detect any potential percolation. Examination of the profile water content measurements revealed limited percolation, if any (Farahani et al., 2008).

AquaCrop Parameterization

Parameterization is a higher-level adjustment of specific model parameters than calibration, although the two are used interchangeably in some literature. Calibration is adjusting certain model parameters to make the model match the measured values at the given location. As for AquaCrop, there were no predetermined parameters for cotton, and thus parameterization was the primary goal. The model was parameterized for cotton using data from the 2006 growing season. This included data from the fully irrigated plots as well as those from the deficit irrigation treatments. Inclusion of data from the deficit treatments were found necessary to correctly parameterize the stress thresholds in AquaCrop that control leaf expansion, stomatal closure, and canopy senescence. The following cotton parameters were obtained from field data: maximum canopy cover (7.0 cm²); age decline in CC during late season, and (ii) $p_{upper}$, $p_{lower}$, and $f_{shape}$ for water stress affecting leaf expansion and early senescence. The change in stored soil water was determined using the neutron probe (discussed above) at a minimum of weekly intervals. The reliability of $ET_a$ estimates depends on the measurement or estimation accuracy of the variables in the right-hand side of the equation. There was no rainfall during the cotton growing seasons and the drip system produced no runoff, with P and R equaling zero for analysis. Deep percolation is the most difficult variable to detect and quantify, particularly when the depth of access tube is less than the wetting front by irrigation (Wright, 1990). In this study, the access tubes were installed up to 1.80 m, sufficiently deep to detect any potential percolation. Examination of the profile water content measurements revealed limited percolation, if any (Farahani et al., 2008).

Canopy Cover

In AquaCrop, the crop response to environmental conditions and to root-zone water balance is captured through four water stress indices, with three affecting CC growth and transpiration, and one impacting HI. The impact of water stress on canopy development and transpiration is controlled by calibrated soil water depletion ($p$) thresholds (Raes et al., 2009). On a daily basis, the soil water algorithm in AquaCrop quantifies the actual value of $p$, defined as the ratio of actual to total available soil water [i.e., $(FC - SW)/(FC - PWP)$, where $SW$ is the simulated soil water content], and compares it with the threshold $p$ values. As long as the upper threshold $p$ value ($p_{upper}$) is not reached, no stress is triggered. As soil water depletes, the stress increases linearly or nonlinearly, according to a shape factor ($f_{shape}$) toward the lower threshold $p$ value ($p_{lower}$) denoting maximum stress (Raes et al., 2009). The $p_{upper}$ and $p_{lower}$ values depend on many factors such as the crop species, the stage of development, the soil characteristics and the evaporative demand of the atmosphere (Steduto et al., 2009). The $f_{shape}$ depends on the crop sensitivity to the stress and the intensity and duration of the stress as well. Identification of the threshold $p$ values and shapes for the stress indices was the core parameterization challenge. Parameterization of the stress indices first concerned adjusting crop key variables to reproduce field observed CC. Correct simulation of CC is central to AquaCrop performance, as it affects the rate of transpiration and consequently biomass accumulation. Parameters affecting CC are (i) the canopy growth coefficient (CGC) corresponding to the daily percentage increase in CC during growth, and the canopy decline coefficient (CDC) corresponding to the daily percentage decline in CC during late season, and (ii) $p_{upper}$, $p_{lower}$, and $f_{shape}$ for water stress affecting leaf expansion and early senescence. AquaCrop calculates daily CC using Eq. [6a] and [6b] during canopy development, and Eq. [7] during late-season canopy decline (Steduto et al., 2009):

$$CC = CC_0 \times e^{(CGC \times t)} \quad \text{if } CC \leq CC_x/2$$

or a WP* value of 19.8 g m⁻² for cotton with a high $r^2$ value of 0.92, reconfirming the expected linearity of biomass versus normalized $ET_a$.

RESULTS AND DISCUSSION

Model Parameterization—2006 Season

Canopy Cover

One of the most important parameters in AquaCrop is the normalized biomass water productivity ($WP^*$), which is typically constant for a given crop species (Steduto et al., 2007, 2009). Specifically, WP* is quantified as the slope of above-ground dry biomass versus cumulated normalized transpiration [i.e., $\Sigma(Tr/ET_a)$]. Literature suggests WP* values of 13–15 g m⁻² for C3 species like cotton and 26–30 g m⁻² for C4 species like sorghum (Steduto et al., 2007, 2009). Since partitioned $ET_a$ values into Tr and soil evaporation ($E$) components were not available from the field data, model developers suggested computing WP* using the cumulated normalized $ET_a$ in place of Tr. Using the 2006 cotton data, the locally developed relationship was

$$Aboveground dry biomass = 19.8 \times \Sigma(ET_a/ET_o) - 223 \quad \text{[5]}$$

$WP^*$ for cotton with a high $r^2$ value of 0.92, reconfirming the expected linearity of biomass versus normalized $ET_a$.
where \( t \) is the number of days after seeding and \( CC_0 \) is the initial canopy cover. Daily values of \( CC \) are then reduced by water stress, if any. For instance, when SW decreases below FC and reaches the threshold \( p_{\text{upper}} \) for leaf expansion, \( CC \) expansion is inhibited, and under severe water stress conditions, canopy senescence accelerates reducing canopy size.

Adopting a trial and error approach, cotton canopy development proved to be properly reproduced using a value of 10.5% increase per day for \( CGC \), and a value of 6.5% daily decline during the late season for \( CDC \). Calibration for leaf expansion resulted in \( p_{\text{upper}} \) and \( f_{\text{shape}} \) of 0.25, 0.70, and 4.0, respectively. Suitable soil water depletion threshold \( p_{\text{upper}} \) for anticipated senescence was determined at 0.75 with \( f_{\text{shape}} \) of 1.0. Parameterization led to simulated \( CC \) values for the four irrigation treatments, with a strong 1:1 correlation \( (CC_{\text{simulated}} = 1.05 \times CC_{\text{measured}} - 1.45, r^2 = 0.89, n = 48) \) with measured values, and a RMSE of 9.5% (Fig. 3). Simulation results show between-replication variability in predicted \( CC \) that was traced to variations in season- \( SW_{\text{ini}} \). This behavior reflects model’s sensitivity to \( SW_{\text{ini}} \) in addition to model sensitivity associated with the threshold \( p \) values.

### Evapotranspiration and Aboveground Biomass

Accurate simulation of \( ET_a \) and partitioning into \( Tr \) and \( E \) is critical for biomass prediction since daily biomass is directly calculated from the calibrated \( WP^* \) and simulated \( Tr \). Once \( CC \) was properly simulated, parameterization for \( ET_a \) and biomass were limited to the determination of the threshold \( p \) value for stomatal closure and its shape. Suitable soil water depletion threshold \( p_{\text{upper}} \) for stomatal closure was determined at 0.55 with \( f_{\text{shape}} \) of 0. AquaCrop estimated \( ET_a \) within 11% of the measured values at all irrigation levels (Fig. 4). According to Table 1, simulated \( E \) values changed only narrowly across the four irrigation treatments (about 125 mm per season). This makes the seasonal \( E/ET_a \) ratio nearly twice as large in the 40% irrigation (i.e., 0.28) than in the 100% irrigation (i.e., 0.16), even though surface wetting coverage by drippers was half as large in the 40% as in the 100% irrigation. Because of the large differences in soil surface wetting between irrigation regimes, the simulated narrow range of \( E \) across irrigation regimes is questionable. Irrigation frequency was the same for all irrigation treatments, which led to proportionally larger simulated \( E \) in the deficit treatments, even though application amounts were smaller. The model predicted well the seasonal trend in biomass growth (Fig. 5) at all irrigation treatments. The only exception was an underprediction of the rapid accumulation of the aboveground biomass in the full irrigation regime.

#### Seed Cotton Yield and Sensitivity

In AquaCrop, simulated \( Tr \) is converted into biomass, and subsequently to yield according to \( HI \). Enhanced prediction of seed cotton yield required adjusting the water stress effect on \( HI \). This involved choosing values of 6.0 and 1.5 for the coefficients in the functions describing the positive and negative impact on \( HI \) as a result of water stress during yield formation, and assuming no increase in \( HI \) as a consequence of water stress. Simulation results show between-replication variability in predicted \( CC \) that was traced to variations in season- \( SW_{\text{ini}} \). This behavior reflects model’s sensitivity to \( SW_{\text{ini}} \) in addition to model sensitivity associated with the threshold \( p \) values.

### Table 1. Measured and simulated actual evapotranspiration \( (ET_a) \) and the simulated partitioning into transpiration \( (Tr) \) and soil evaporation \( (E) \) for the 2006 growing season (mean of all replications, with between-plot variation of ±4% in measured \( ET_a \)).

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<th>Irrigation treatment</th>
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of water stress before flowering (Raes et al., 2009). Simulated seed cotton yields, as shown in Fig. 6, were correlated \( r^2 = 0.98 \) with measured values, with errors less than 9% (RMSE = 0.13 Mg ha\(^{-1}\)).

A limited sensitivity analysis was conducted to determine the dependency of simulated yield to changes in a few key parameters. Increasing CGC beyond 10.5% per day, even up to +50%, had minimal effect on yield at all irrigation levels, mainly because crop development was more limited by water availability than the growth potential. Large changes in the threshold \( p \) value for stomatal closure (i.e., up to ± 25%) also had a small effect (less than 10%) on deficit-irrigated yield. On the contrary, changes in the shape of the stress curve \( f_{\text{shape}} \) had larger impact on model simulated final yield. This warrants detailed sensitivity analysis, not pursued herein. Influence of root characteristics on yield was tested by imposing hypothetical variations in the input parameters of \( Z_x \) and the time to reach \( Z_x \). These parameters are not readily known and constitute potential sources of input errors. Changes in \( Z_x \) had varying effect on yield depending on the level of irrigation. Generally, deepening the profile by up to 25% from 1.3 to 1.7 m had minimal effect under greater irrigation depths, but increased the yield by about 15% in the deficit (40 and 60%) irrigations because of the expanded soil volume that increased accessible soil water. Shortening the \( Z_x \) profile by up to 25% had a moderate effect of reducing yield in the greater irrigation depths, but drastic reduction in \( Z_x \) by 50% (i.e., from 1.3 to 0.65 m) often resulted in no simulated yield due to excessive water stress. Sensitivity of yield to ±25% change in the parameter time to reach \( Z_x \) was relatively small, resulting in less than ±7% change in simulated yield as compared with the parameterization results. Similar results were obtained even when time to reach \( Z_x \) was reduced by 50%, reflecting the low sensitivity of yield to this parameter.

### Soil Water Dynamics

All stress thresholds in AquaCrop are direct functions of soil water, making accurate simulation of soil water dynamics of particular importance. The water balance algorithm in AquaCrop is based on the storage capacity of the soil layers, described previously in the models BUDGET (Raes, 1982; Raes et al., 2006) and CROPWAT (Smith, 1990). For each simulation, the soil profile was defined in 10 layers of 0.15 m thick, each with \( SW_{\text{ini}} \) values from the neutron measurements and a value for saturated hydraulic conductivity (100 mm d\(^{-1}\)). Saturated hydraulic conductivity was not measured in the field, and a default value suggested by the model was adopted. For the 2006 season, measured and simulated soil profile water storage is shown in Fig. 7. The model predicted well the trend of soil wetting and drying cycles due to irrigation events, yet the absolute values deviated from measured values. There was a tendency for the model to consistently overpredict soil water storage in the deficit irrigated plots. A more informative

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**Fig. 5.** Measured and simulated aboveground biomass for the 2006 growing season. DAS is days after sowing.

**Fig. 6.** Measured versus simulated seed cotton yield for the 2006 growing season. Graph shows mean and error bars for the three replications.

**Fig. 7.** Measured and simulated total soil profile water (1.30-m depth) in the four irrigation treatments in 2006. Soil water at permanent wilting point and at field capacity are 286 and 494 mm water in the 1.30 m profile, respectively. DAS is days after sowing.
depiction of soil water dynamics is shown in Fig. 8 for individual 0.30-m-thick soil layers. Simulation errors in water content were nonuniformly distributed in the profile, with a tendency to overpredict in the surface layer and underpredict in the deeper layers. AquaCrop simulated no deep percolation in any of the 2006 irrigation treatments, a result that is in accordance with the analysis of soil water measurements. For the entire 2006 season, simulated soil profile water storage per day was 38, 37, 24, and 18 mm higher than measurements in the 40, 60, 80, and 100% treatments, respectively, which is less than 2.5% error.

**Model Testing—2004 and 2005 Seasons**

The parameterized AquaCrop was tested in the 2004 and 2005 seasons. In-season crop data was limited in 2004 and 2005, and testing concentrated on model performance to predict ETₐ, crop yield, and soil water. AquaCrop simulated ETₐ across the irrigation treatments with a RMSE of 61.4 and 23.2 mm in 2004 and 2005, respectively (Fig. 9). For 2004, ETₐ was accurately estimated in the intermediate deficit irrigation treatments. The largest error was a 13% underprediction of ETₐ in the 100% irrigation. The underprediction corresponds to 107 mm of water, which incidentally is the same amount of simulated deep percolation. Although deep percolation was not evident from the field data, it could not be ruled out in 2004 due to late season irrigations. In 2005, seasonal ETₐ was accurately predicted, with errors < 8%, or approximately 37 mm for the season. It is not clear why the model predicted much greater deep percolation in 2004 than in 2005, during which climate and irrigation practices were very similar. Comparison of measured and simulated soil profile water is not shown, but the model performed in a similar manner as was observed in 2006. That is, predicting soil wetting and drying cycles well, yet consistently overpredicting water content in the top layers and underpredicting in the deeper layers. These errors in soil water content estimation had minimal effect on simulated ETₐ as a major component of the soil water balance.

AquaCrop simulated cotton yield across the irrigation treatments and years with a RMSE of 0.4 Mg ha⁻¹ (Fig. 9). Cotton yield in 2005 was simulated within 10% of the measured values for a maximum deviation of 0.33 Mg ha⁻¹ in the 80% irrigated treatment. Yield predictions were also within 10% of the measured values, or approximately 0.21 Mg ha⁻¹, in the 40 and 100% irrigation treatment in 2004. The highest error in yield was observed in the 80% irrigation treatments in 2004, in spite of the fact that the ETₐ was correctly simulated in this treatment. This is traced to higher simulated HI values in 2004 than those in 2005 and 2006. For instance, simulated HI was 0.29 in the 80% irrigation treatments in 2004, while varying between 0.23 and 0.27 in other years. In AquaCrop, yield is calculated as the product of simulated aboveground biomass and HI. Thus errors in the user-input value for WP*, the simulated ETₐ, and the model adjusted HI can cause errors in yield. Although HI is a user-input parameter, AquaCrop adjusts HI during yield formation as a result of water stress. This latter process is not clearly understood and there are no firm guidelines for parameterizing the effect of stress on HI.

**Fig. 8.** Measured and simulated soil water content in each 0.30 m soil layer in the 40 and 100% irrigation treatments. Soil water content at permanent wilting point and at field capacity are 66 and 117 mm in the 0.30-m layer, respectively. DAS is days after sowing.

**Fig. 9.** Measured and simulated ETₐ and seed cotton yield for the 2004 and 2005 growing seasons. Graphs show mean and error bars for the three replications.
The problem was further complicated because of the lack of measured aboveground biomass data in 2004, which made it difficult to determine what the correct HI values were.

CONCLUSIONS

We parameterized AquaCrop for drip-irrigated cotton and tested its performance under a hot and dry climate representative of most of the eastern Mediterranean region. Parameterization was less demanding than other system-wide and mechanistic cropping models, owing to the limited number of key parameters to be adjusted. Model predictions of ET$_a$, total biomass, yield, and soil water across four levels of irrigation regimes are particularly promising considering the simplicity of the model and the limited parameterization. This very early parameterization and testing is site- and climate-specific, and most applicable to short-season, drip-irrigated cotton grown under optimum fertility conditions. Therefore, the parameterized variables need to be further tested under differing climate, soil, variety, irrigation methods, and field management. As pointed out by Sinclair and Seligman (1996), no crop model is universal, and considerable work is needed to make any model account for differences in cultivars, field conditions, and the environment.

This study suggests that the most logical pathway for a systematic calibration of AquaCrop is first and foremost to ensure a sound prediction of canopy cover. Key user-input parameters for this purpose are the coefficients defining canopy development (cover) and the threshold (p) soil water depletion levels for the relevant stress indices, with particular attention to their shapes. Results from this study provide a set of first estimates for these difficult-to-determine parameters for further testing and use of the model at other locations. Of particular importance is the realization that parameterization of a new model requires a sound prediction of canopy cover. Key user-input parameters such as the user-input WP* is only established with cultivars, field conditions, and the environment.

REFERENCES


