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Simulating cotton yield response to deficit irrigation with the FAO AquaCrop model

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Abstract

The Food and Agriculture Organization has reflected the importance of predicting yield response to water by developing the AquaCrop model. During three growing seasons (2007-2009), a field experiment was conducted in the South-East of Damascus (Syria) to assess the response of drip irrigated cotton grown under full (FI) and deficit irrigation (80, 65, 50% of FI). Input data and comparisons between simulated and observed canopy cover (CC), biomass production at harvesting, final seed cotton yield, and soil water content using data sets of the 2007 season, were used for model calibration. The calibrated model was validated using data sets of the 2008 and 2009 seasons, getting accurate simulation results for CC [root mean square error (RMSE) = 6.5%] and actual evapotranspiration-ETa (RMSE = 25 mm, index of agreement = 0.99). The predicted seed cotton yields were within 6% of measurements. The model predictions of soil water content in the 0.60 m profile were close in the general trend to the measurements. In spite of the good prediction of ETa and seed cotton yield for each treatment, there is an apparent tendency for AquaCrop to over-estimate water use efficiency (WUE) under water-deficit conditions. Therefore, in cases of limited input data, the AquaCrop could be a promising model for estimating crop productivity under deficit irrigation conditions.

Additional key words: canopy cover; crop yield modeling; water productivity; water stress.

Resumen

Simulación de la respuesta del rendimiento del algodón al riego deficitario con el modelo AquaCrop de la FAO

Por lo importante que es predecir la respuesta del rendimiento al riego, la FAO ha desarrollado el modelo AquaCrop. Se llevó a cabo durante tres temporadas (2007-2009) un experimento de campo en el sureste de Damasco (Siria) para evaluar la respuesta del algodón cultivado con riego por goteo, bajo riego total (FI) y deficitario (80, 65, 50% del FI). Para la calibración del modelo se utilizaron los datos *input* y las comparaciones entre los valores simulados y observados de cobertura del dosel (CC), producción de biomasa en la cosecha, rendimiento final de semilla de algodón, y contenido de agua en el suelo, utilizando conjuntos de datos de la temporada 2007. Se validó el modelo calibrado utilizando conjuntos de datos de las temporadas 2008 y 2009, obteniéndose resultados precisos de simulación para CC [error cuadrático medio (RMSE) = 6,5%] y la evapotranspiración real ETa (RMSE =25 mm; índice de concordancia = 0,99). Los rendimientos de semilla previstos estuvieron dentro del 6% de las mediciones. Las predicciones del modelo para el contenido de agua en el perfil de 0,60 m se acercaron a la tendencia general de las mediciones. A pesar de la buena predicción de la ETa y del rendimiento de las semillas para cada tratamiento, hay una clara tendencia de AquaCrop a sobreestimar el uso eficiente del agua (WUE) en condiciones de déficit hídrico. Por lo tanto, en los casos de datos *input* limitados, el AquaCrop podría ser un modelo prometedor para estimar la productividad de los cultivos bajo condiciones de riego deficitario.

Palabras clave adicionales: cobertura de dosel; estrés hídrico; modelización del rendimiento de los cultivos; productividad del agua.

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Abbreviations used: DSW (soil water content change); ETa (actual evapotranspiration); ETo (reference evapotranspiration); FI (full irrigation treatment); HI (harvest index); NWP (normalized water productivity); p (soil water content threshold); SWC (soil water content); Tr (transpiration); WUE (water use efficiency);$\%\theta_v$ (volumetric water content).

Introduction

Increasing the efficiency of water use by crops continues to be a topic of concern because of growing competition for water and the need to face the food crisis in developing countries. In this context, the Food and Agriculture Organization (FAO) has developed a new water productivity model named AquaCrop (Raes *et al.,* 2009; Steduto *et al.,* 2009). The newly developed model is a user friendly and oriented to practitioner-end user type. The model keeps an optimal balance between output accuracy, robustness, simplicity, and requires a relatively limited number of parameters. It has a water-driven growth engine that converts daily transpiration (Tr) directly to daily biomass production, using daily reference evapotranspiration (ETo) and normalized water productivity (NWP), a conservative (nearly constant) parameter specific to a crop species.

In the model, water stress is triggered through the soil water content in the root zone, including three stress response functions; canopy growth reduction, stomatal closure, and acceleration of canopy senescence. The partition of biomass into yield is simulated by means of a dynamic harvest index (HI), which develops during the yield formation stage until reaching a maximum value. Water stress can either increase or decrease HI value depending on the timing and intensity of the stress and crop growth pattern (Steduto *et al.,* 2009). More information on the concepts underlying the model, its structure and algorithmic solutions are found in Steduto *et al.* (2009) and Raes *et al.* (2009).

The goal of the FAO project is to calibrate AquaCrop for each important crop species with respect to all its key parameters, termed as conservative parameters, which are applicable across a wide range of conditions regardless of location and can be used with various cultivars. The location, cultivar, weather data, irrigation events, and planting density, are to be entered by the user. Careful and extensive calibration of the conservative parameters has been achieved for maize only (Heng *et al.,* 2009; Hsiao *et al.,* 2009). Preliminary parameterization for cotton has been done (Farahani *et al.,* 2009) using single location data sets. Data from other locations, having different climate and soil conditions, are needed to do more complete parameterization of this crop.

Cotton responses to deficit irrigation have been reported in some earlier works (Wanjura *et al.,* 2002; Howell *et al.,* 2004; Pettigrew, 2004; Dagdelen *et al.,* 2006; DeTar, 2008; Basal *et al.,* 2009). When adopting deficit irrigation, it is difficult to predict the yield response to irrigation level, being dependent on the stress timing, duration, and severity. An important attribute of the modeling approach is that it permits extension of the field findings to conditions not tested in the field. Thus it is useful in providing practical suggestions that can help in improving irrigation management options. Models, however, need to be calibrated using field and laboratory data before they can be used for solving practical problems. Therefore, our objective was to calibrate and validate AquaCrop model for full and deficit irrigation of cotton in arid area in Syria.

Material and methods

The FAO AquaCrop model was calibrated and validated using data from a 3-year study (2007 to 2009), which was conducted at Der-Alhajar Research Station located in the South-east of Damascus, Syria (33° 21' N, 36° 28' E) at 617 m above sea level. The field experiment had the objective of assessing seed cotton yield and water use efficiency (WUE) of drip irrigated cotton as affected by deficit irrigation. The experimental design was a randomized block design with six replicates in 2007 and 2008 and four replicates in 2009 of four irrigation treatments. AquaCrop (version 3.1, 2010) was calibrated using data from the 2007 growing season. Then, performance of the calibrated model was validated and evaluated by comparing the simulation results of some parameters in the 2008 and 2009 seasons with their measured values. These parameters were seed cotton yield, biomass production, water use, HI and soil water content. The required input data and model parameters are grouped in different files for climate, crop, irrigation, soil and initial soil water content (Raes *et al.,* 2009); these files were prepared using the following data.

Cotton field experiment

The area is located within the arid region with total annual precipitation of 120 mm. The weather data required by AquaCrop are the daily values of minimum and maximum air temperature, daily reference evapotranspiration (ETo), and rainfall (Raes *et al.,* 2009; Steduto *et al.,* 2009). Daily ETo was calculated using Penman- Monteith equation (Allen *et al.,* 1998), and the required climatic data were collected from an automated weather station located in the adjacent field and fitted with six climatic and agricultural sensors for minimum and maximum temperature, dew point, wind velocity at 2 m, solar radiation, and rainfall.

The soil is sandy clay loam in texture, water content at field capacity varies from 30.7 to 36.1% by volume, and wilting point from 11.5 to 17.1%. Soil bulk densities ranges from 1.11 to 1.21 g cm^{-3} throughout the 0.6 m soil profile. The total available soil water within the top 0.6 m of the soil profile is 114 mm. Nine soil cores were taken randomly in the field in the beginning of each season to determine initial soil water content (SWCini) to a depth of 1.05 m. Each core sample was 0.15 m in height and 0.07 m in diameter. The SWCini on volume basis is the product of gravimetric water content multiplied by the bulk density.

Cotton seeds (*Gossypium hirsutum* L. cv. Allepo-33) were planted on April 23rd, 13th and 16th for 2007, 2008 and 2009 seasons, respectively. Plants were thinned to achieve a population density of 9-10 plants m^{-2}. Irrigation was initiated immediately thereafter with an irrigation interval of 3-4 days.

Treatments were designated as full irrigation (FI, which received 100% of the soil water depletion) and those that received 80, 65 and 50% of the amount received by treatment FI on the same day (treatments DI-80; DI-65 and DI-50, respectively). For the FI irrigation scheduling was carried out using the neutron probe method. Two plots of 2.5 × 2.5 m, one of them surrounded by dikes from all sides, were prepared before sowing for neutron probe calibration. An aluminum access tube of 0.051 m internal diameter was installed in the center of each plot to 1.05 m depth. After liberal irrigation for the plot with dikes, it was covered with a plastic sheet. Two days later, readings were taken with neutron probe (CPN 503); using a surface adapter (plastic Teflon parallelepiped block) for surface readings (0.15 m) (Arslan *et al.,* 1997). Three soil cores were taken around each tube to determine volumetric water content (%θ_v). The %θ_v in these soil samples were correlated with the neutron probe count ratio. Soil water content was always taken the day before each irrigation event using the on-site calibrated neutron probe. Aluminum access tubes were installed in the center of each plot, and 0.12 m from the crop row. Neutron probe measurements were made for each 0.15 m layer in the soil profile to a depth of 0.60 m. The active root depth for drip irrigated cotton was given two fixed values (Janat, 2004); after thinning the active root depth was considered 0.30 m until peak flowering, and then it was increased to 0.60 m till termination. It was also observed by Du *et al.* (2008) that the main wetting layer for the drip irrigated cotton was ~ 0.40 m below the soil surface in the full-irrigated treatment plots. Seasonal full irrigation amount was 753, 792, and 815 mm in the 2007, 2008, and 2009 seasons, respectively. The wetted soil surface area by the drip system changed as a function of irrigation level, corresponding to estimates of 30% for DI-50 and DI-65 treatments and 40% for DI-80 and FI treatments.

The experimental unit was 20 × 3.75 m (5 rows/plot). A 2.0 m space between each plot was maintained in order to minimize water movement among treatments. The 16-mm drip laterals were placed on the soil surface along every crop row with emitters (4 L h^{-1} discharge) spaced every 0.30 m on the laterals. Volumes of water applied by irrigation were measured by an in-line flow meter. Nitrogen fertilizer (120 kg N ha^{-1}) was injected in six equally split applications through the drip system as a solution of urea (46% N) using proportional-type injector.

Equation [1] was used in the determination of canopy cover percent (*CC* %):

$$CC\% = \frac{pcd}{rd} \quad 100 \qquad [1]$$

where *pcd* is the plant crown diameter (mm) and *rd* is the inter-row distance (mm). Dry matter yield was calculated at physiological maturity stage on the basis of total dry weight of the aboveground vegetative portion only. Seed cotton yield of each plot was determined by two hand pickings of all treatments on early October, the second picking was about 10-15 days later. All the harvested seed cotton was weighed for each plot as final yield. Harvest index (HI) was calculated as the ratio of seed cotton yield to total aboveground biomass. Water use efficiency (WUE) was determined using the following formula:

$$WUE = Y / ETa \qquad [2]$$

where *Y* is the total seed cotton yield (kg ha^{-1}), and *ETa* is the seasonal cotton evapotranspiration (m^3). ETa was calculated using the water balance equation:

$$ETa = I + P \pm DSW - Dp - Ro \qquad [3]$$

Where *I* is the amount of irrigation water applied (mm), *P* the precipitation (mm), *DSW* the soil water content change (mm) in the 0.60 m soil profile, *Dp* the deep percolation (mm), and *Ro* is the amount of runoff (mm). Since the amount of irrigation water was controlled, runoff was assumed to be zero. In this study, the access tubes were installed up to 1.05 m, sufficiently deep to detect any potential percolation after increasing the active root depth to 0.60 m. Examination of the water content measurements in the experimental plots of the FI treatment revealed that deep percolation was negligible below 0.60 m depth.

AquaCrop calibration

Calibration is the fine tuning of certain model parameters to obtain good matching between estimated and measured values at the given location. Correct simulation of CC is a key factor for AquaCrop performance, as it affects the transpiration rate and consequently biomass production. Parameters affecting CC are: canopy growth coefficient (CGC), referring to the daily percentage increase in CC during growth; canopy decline coefficient (CDC), referring to the daily percentage decline in CC during late season and the coefficients for triggering water stress affecting leaf expansion and early canopy senescence.

AquaCrop calculates daily CC using equations [4] and [5] during canopy development, and equation [6] during late season canopy decline (Steduto *et al.,* 2009):

$$CC = CCo \quad e^{(CGC \;\; t)} \qquad [4]$$

If CC ≤ CCx/2:

$$CC = CCx - \left(CCx - CCo \times e^{(-CGC \times t)}\right) \qquad [5]$$

If CC > CCx/2:

$$CC = CCx\left(1 - 0.05\left(e^{\frac{CDC}{CCx \times}t} - 1\right)\right) \qquad [6]$$

where *t* is the number of days after sowing and *CCo* is the initial canopy cover. Water stress impact on canopy development and transpiration rate is considered by *p* values; calibrated soil water content thresholds (Raes *et al.,* 2009). Actual value of *p,* defined as the ratio of actual to total available water, is assessed and compared with the threshold *p* values on a daily basis in AquaCrop. Stress starts when the upper threshold *p* value (p_{upper}) is reached. With depletion of soil water the stress increases according to a shape factor (f_{shape}) toward the lower threshold (p_{lower}) indicating maximum stress (Raes *et al.,* 2009). The f_{shape} is the route (linear or nonlinear) from the p_{upper} to the p_{lower}, and it depends on the crop sensitivity to the stress and the intensity and duration of the stress as well.

The work done by Farahani *et al.* (2009) was the first to parameterize and test AquaCrop performance for cotton under full and deficit irrigation in the semiarid environment of north-western of Syria. Their study provided the first estimate for cotton parameters values, but since model parameterization is site-specific, the applicability of key calibrated parameters must be reevaluated under different conditions. AquaCrop was calibrated for cotton using data from the 2007 growing season. Data from fully irrigated treatment as well as those from the deficit irrigation treatments were used for calibration by first matching the performance of various treatments in terms of canopy cover (Fig. 1), and then checking the ETa, biomass and yield (Table 1). During the course of this study it was found that it is essential to include data from the DI treatments for sound parameterization of the stress levels in AquaCrop that control leaf expansion, stomatal closure, and early canopy senescence. The following cotton parameters were obtained from field observations and measurements: time

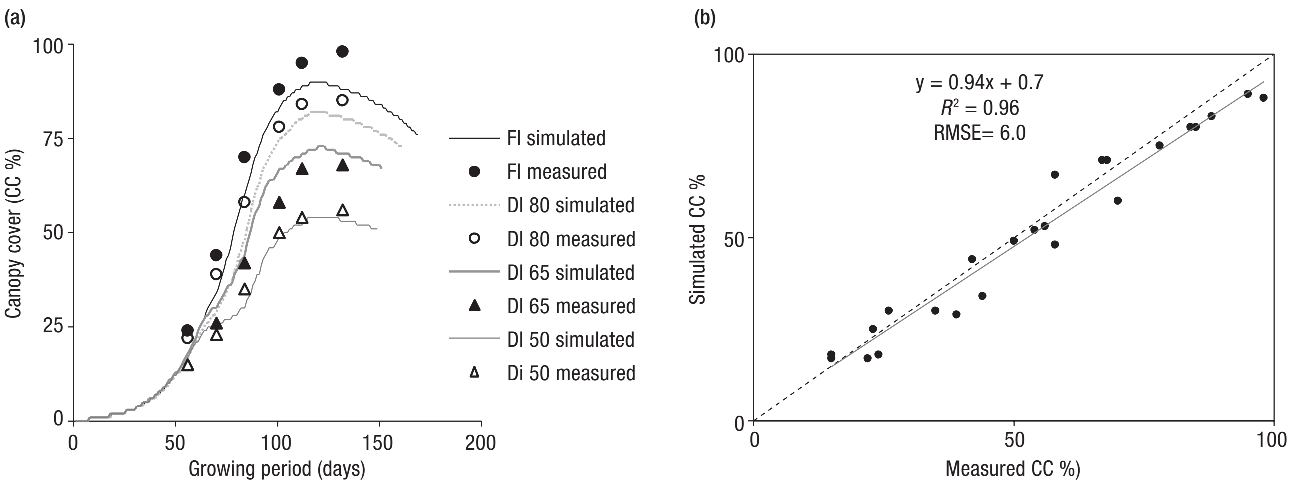

Figure 1. Simulated and measured canopy cover (CC %) for the full- and deficit-irrigated treatments in the 2007 growing season. Each dot represents an average of 18 measurements.

Table 1. Simulated (sim) versus measured (meas) values for biomass (t ha^{-1}), seed cotton yield (t ha^{-1}), harvest index (HI), seasonal evapotranspiration (ETa, mm), and water use efficiency (WUE, kg m^{-3}) for different treatments

Year	Treatment	Biomass		Seed cotton yield		HI		ETa		WUE	
		meas	sim	meas	sim	meas	sim	meas	sim	meas	sim
2007	FI	16.2 ± 0.1[a]	16.1	5.0 ± 0.2	5.2	0.31 ± 0.001	0.32	762 ± 16	766	0.65 ± 0.03	0.67
	DI80	13.0 ± 0.6	13.2	4.6 ± 0.2	4.4	0.35 ± 0.015	0.33	652 ± 11	659	0.7 ± 0.03	0.67
	DI65	10.0 ± 0.4	10.6	3.6 ± 0.2	3.7	0.36 ± 0.014	0.35	556 ± 19	541	0.65 ± 0.04	0.68
	DI50	8.3 ± 0.5	8.0	2.9 ± 0.1	2.8	0.35 ± 0.022	0.35	463 ± 8	438	0.62 ± 0.02	0.64
2008	FI	17.0 ± 0.5	17.0	5.2 ± 0.2	5.4	0.31 ± 0.009	0.32	797 ± 13	788	0.65 ± 0.03	0.68
	DI80	13.7 ± 0.4	13.8	4.8 ± 0.2	4.5	0.35 ± 0.010	0.33	671 ± 21	681	0.72 ± 0.04	0.67
	DI65	10.8 ± 0.3	10.9	3.7 ± 0.2	3.7	0.35 ± 0.010	0.34	576 ± 16	551	0.65 ± 0.03	0.68
	DI50	8.8 ± 0.5	8.5	3.0 ± 0.3	2.9	0.34 ± 0.019	0.35	466 ± 15	451	0.64 ± 0.05	0.65
2009	FI	16.6 ± 0.4	16.3	5.1 ± 0.3	5.2	0.31 ± 0.007	0.32	758 ± 21	727	0.67 ± 0.04	0.72
	DI80	13.2 ± 0.3	13.3	4.5 ± 0.2	4.4	0.34 ± 0.008	0.33	628 ± 19	627	0.71 ± 0.04	0.71
	DI65	10.0 ± 0.4	10.4	3.5 ± 0.2	3.5	0.35 ± 0.014	0.34	526 ± 9	510	0.66 ± 0.03	0.69
	DI50	7.6 ± 0.7	7.2	2.6 ± 0.1	2.5	0.35 ± 0.032	0.34	425 ± 17	399	0.62 ± 0.03	0.62

[a] Standard deviations (SD; values immediately following the ± sign) are available for the measured values only.

from sowing to emergence (7 d), to flowering (65 d) and duration of flowering (40 d); to maximum canopy cover (CCx = 98%) (113 d), to senescence (123 d), to maturity (169, 161, 151, and 149 d for the 100, 80, 65, 50% irrigation levels, respectively). Giving the maximum rooting depth (Z_x) a value of 0.60 m as used in the experiment resulted in no simulated yield. Therefore the Z_x was considered (1.30 m) at (113 d) after sowing as suggested by Farahani *et al.* (2009).

Measurements for some parameters were not available, therefore model default values or developers' suggestions were used: CC per seedling (7.0 cm^2); soil depth contributing to seed germination (0.15 m); root deepening shape factor (the expansion rate of the root zone from planting to the time when the maximum rooting depth is reached) (1.2); and mid-season crop coefficient Kc_{top} (1.10). One of the most important parameters in AquaCrop is the normalized biomass water productivity (NWP), which is typically constant for a given crop species (Steduto *et al.,* 2009). After normalization for atmospheric CO_2 concentrations and climate, recent findings suggest NWP value of 15 – 20 g m^{-2} for C3 species like cotton and 30 – 35 g m^{-2} for C4 species like sorghum (Raes *et al.,* 2010). This parameter was varied until satisfactory results were obtained for different treatments in 2007. The corresponding value of NWP was 15.8 g m^{-2}.

AquaCrop is a water-driven crop growth model (Raes *et al.,* 2009; Steduto *et al.,* 2009). It is therefore essential to get accurate simulation of ETa for sound prediction of biomass. Once a good match for measured CC was obtained, the threshold *p* value for stomatal closure and its shape were the key calibration parameters for simulating ETa and aboveground biomass. Values of soil water depletion threshold (p_{upper}) for stomatal closure at 0.55 with f_{shape} of 0, found earlier by Farahani *et al.* (2009), were also found suitable here.

Data analysis

Two statistical measures of the performance of the model were calculated, comparing simulation results with measured data. One is RMSE:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(Si - Oi\right)^2} \quad [7]$$

where *Si* and *Oi* are the simulated and observed values for the corresponding parameter, respectively, and *n* is the number of observations. The unit for RMSE is the same as that for *Si* and *Oi*; and a model's fit improves as RMSE approaches zero. The other is the index of agreement (*d*) of Willmott (1982):

$$d = 1 - \frac{\sum_{i=1}^{n}\left(Si - Oi\right)^2}{\sum_{i=1}^{n}\left(\left|Si - \overline{O}\right| + \left|Oi - \overline{O}\right|\right)^2} \quad [8]$$

where $\overline{O}$ is the mean of the *n* observed values. The value of *d* ranges from –∞ to 1.0; and the model's fit improves as *d* approaches unity.

Results and discussion

Model calibration (2007 season)

Adopting a trial and error approach, cotton canopy development was reproduced properly using a value of 7.2% daily increase of CGC, and a value of 3% decline per day for CDC during the late season. The values of p thresholds and their shapes found earlier by Farahani *et al.* (2009) have been confirmed to be suitable in this study. For leaf expansion the p_{upper}, p_{lower}, and f_{shape} were 0.25, 0.70, and 4.0 respectively. While, for early canopy senescence p_{upper} was 0.75 with f_{shape} of 1.0. AquaCrop could simulate accurately the CC development in 2007 growing season in different irrigation levels as presented in Figure 1a. There was a slight mismatch in the last measured CC value, owing to the delayed decline compared with simulated CC, except for the DI-65 treatment. The low RMSE (6%), calculated for all treatments, obtained in this study indicated a good agreement. Strong linear regression ($CC_{simulated}$ = 0.94 $CC_{measured}$ +0.7, R^2 = 0.96, n = 24) between simulated and measured values was also in accordance (Figure 1b).

Results showed that AquaCrop simulated ETa accurately with a maximum deviation of 5.4% of the measured values for the different irrigation levels (Figure 2). The fit was good, with R^2 = 0.998 (n = 4), the slope had value close to one, and the intercept was relatively small (Figure 3a). Accordingly, the highest deviation

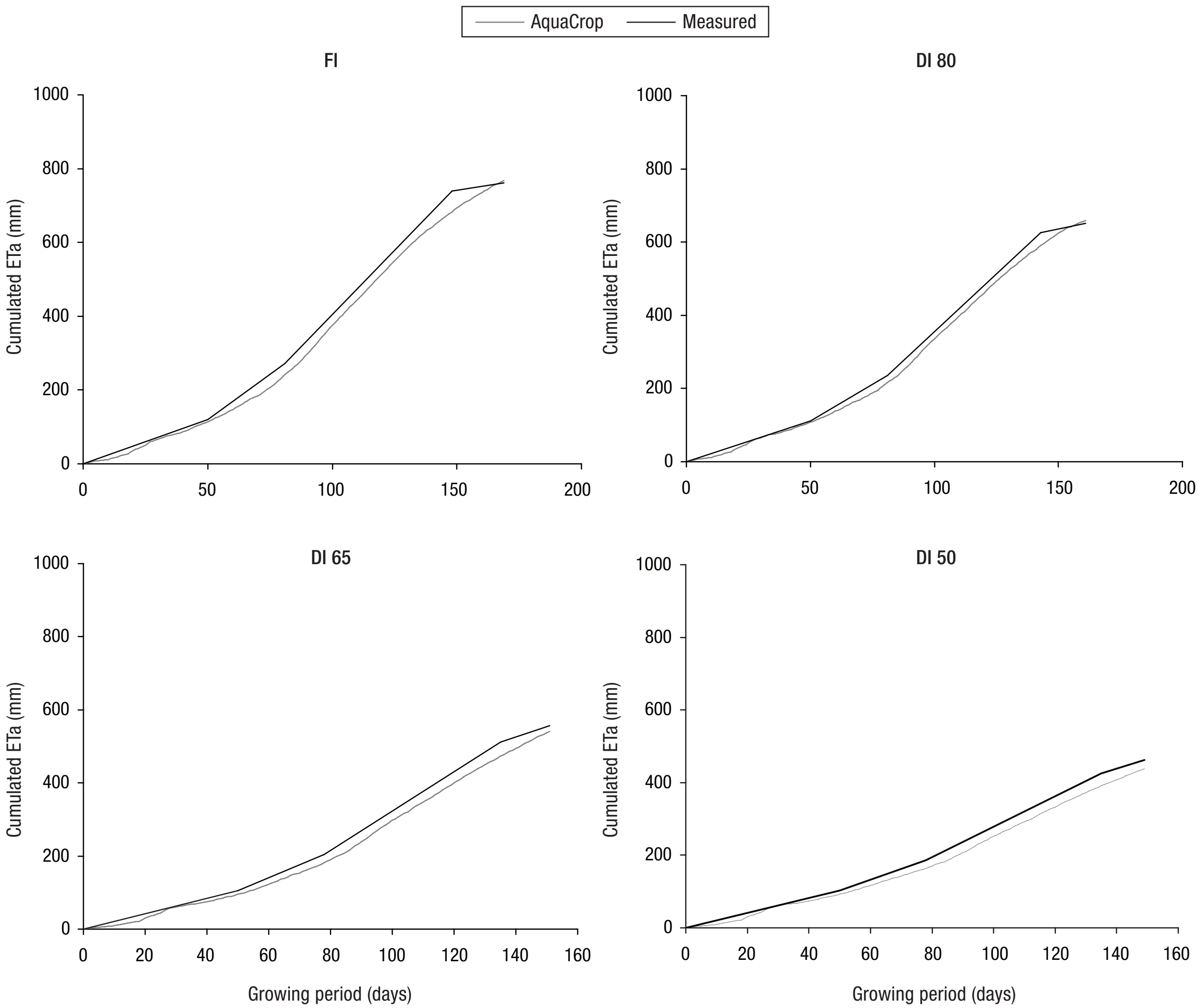

Figure 2. Measured and simulated cumulative actual evapotranspiration (ETa) for the 2007 growing season.

Table 2. Root mean square error (RMSE) and index of agreement (d) for biomass (t ha^{-1}), seed cotton yield (t ha^{-1}), seasonal evapotranspiration (ETa, mm), water use efficiency (WUE, kg m^{-3}), and harvest index (HI) for all treatments

	Final biomass		**Seed cotton yield**		**ETa**		**WUE**		**HI**	
	RMSE	**d**	**RMSE**	**d**	**RMSE**	**d**	**RMSE**	**d**	**RMSE**	**d**
2007	0.48	0.99	0.22	0.99	20	0.995	0.04	0.65	0.02	0.67
2008	0.38	0.996	0.27	0.99	22	0.995	0.05	0.58	0.02	0.63
2009	0.48	0.995	0.20	0.99	27	0.99	0.03	0.82	0.02	0.69

(5.6%) was in the DI-65 treatment (Table 1), and the final biomass production for all treatments was simulated precisely (d = 0.99, RMSE = 0.48 t ha^{-1}), as presented in Table 2.

Seed cotton yield is obtained by multiplying biomass by HI. Starting from flowering, the increase of HI is slow (lag phase) then it is simulated by a linear increase with time up to physiological maturity (Raes *et al.,* 2010; Steduto *et al.,* 2009). The reference harvest index (HIo), the endpoint for the linear increase, obtained in this study was 0.30. The HIo value for cotton was also found as 0.30 by Farahani *et al.* (2009), whereas it was given a value of 0.35 by Garcia-Vila *et al.* (2009). The adjustment of HI to water stress depends on the timing and severity of water stress during the growing season. The values of 1.5 and 2 were assigned to the coefficients a and b, respectively. These coefficients describe the positive and negative impact of water stress on HI during yield formation stage. Fereres and Soriano (2007) suggested that HI can be enhanced by preanthesis water stress which could be related to the relative reduction in preanthesis biomass. This effect is included in the model, but no increase in HI was assumed here due to the water stress occurred before flowering (Raes *et al.,* 2009). The simulated versus observed values for HI showed fairly satisfactory agreement (Table 1). Simulated and measured cotton yields were well correlated (R^2 = 0.97), as shown in Figure 3b, with deviation less than 5% [RMSE = 0.22 t ha^{-1}, d = 0.99 (Table 2)].

The model could reproduce the temporal variations in soil water content in the 0.60 m profile (Figure 4), where the maximum deviation in all treatments was around 2%. This is an indication of satisfactory estimation of the *ETa* of cotton in the soil water balance component of the model. However, there was a trend for overpredicting SWC under deficit irrigation conditions which had minimal effects on the simulated *ETa* in the form of underprediction. Same trend was reported by Farahani *et al.* (2009), where a detailed analysis of soil water profile revealed that the model tended to overpredict SWC in the surface layer and to

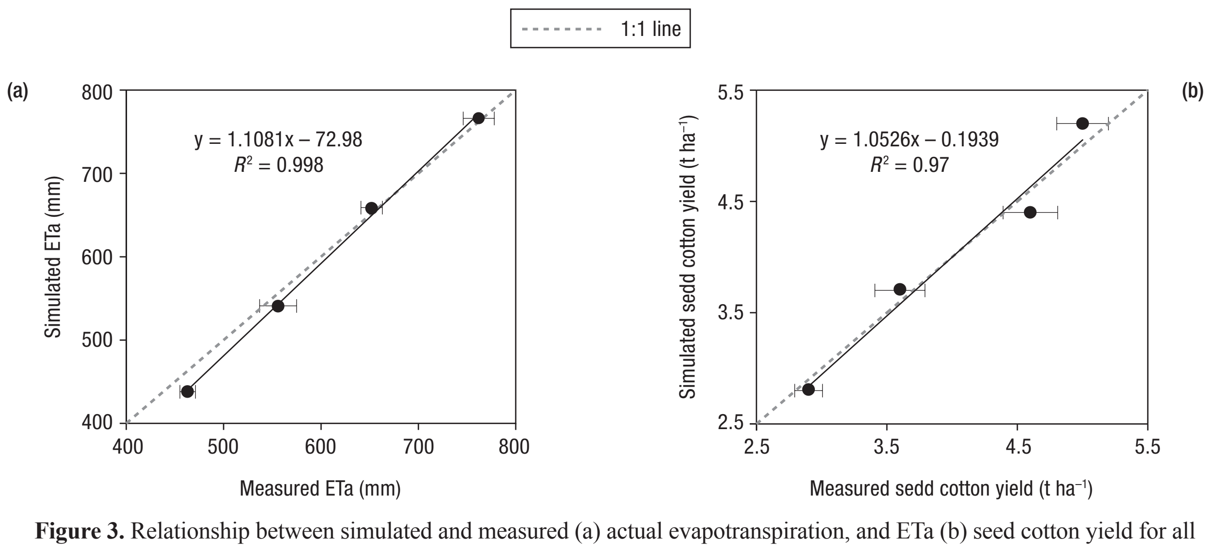

Figure 3. Relationship between simulated and measured (a) actual evapotranspiration, and ETa (b) seed cotton yield for all irrigation treatments in the 2007 season. Each dot represents an average of 6 replications and horizontal bars are ± 1 SD.

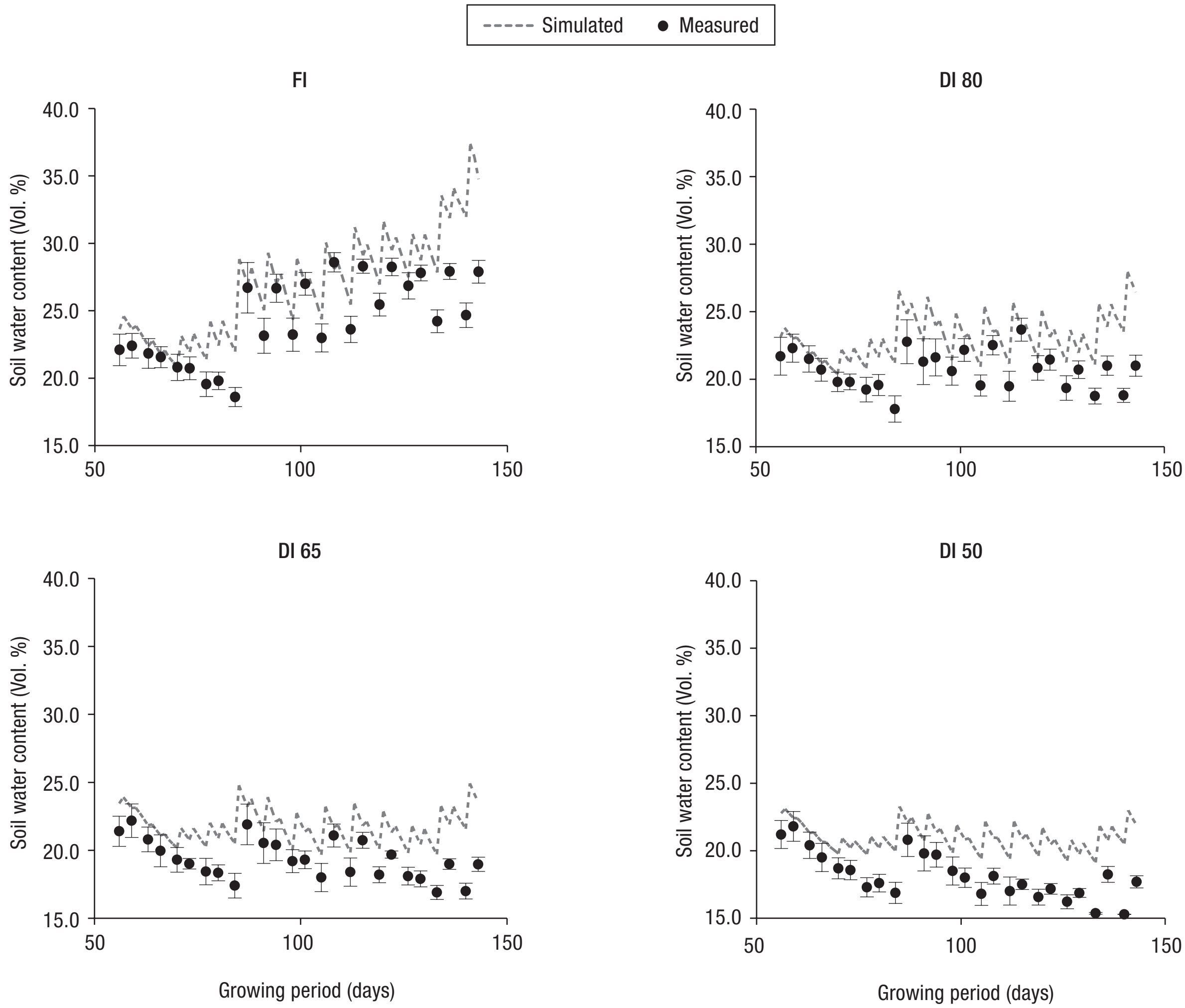

Figure 4. Measured and simulated soil water content (vol %) in the 0.60 m profile in the 2007 season. Each dot represents an average of 6 replications and vertical bars are ± 1 SD.

underpredict it in the deeper layers. The model simulated no deep percolation under different irrigation treatments in the 2007 season, the results were in agreement with the measured soil water content through the soil profile in the plots of the full-irrigated treatment.

Model validation and evaluation (2008 and 2009 seasons)

The calibrated model was validated using the 2008 and 2009 data sets. Actually no big differences were found between the data sets obtained through the three consecutive seasons of experimentation. Virtually, the validation runs with the calibrated AquaCrop for cotton showed good results for the simulated canopy cover as indicated by R^2 and RMSE values in Figure 5 (R^2 = 0.92 and 0.94; RMSE = 6.3 and 6.6% in 2008 and 2009, respectively). Furthermore, regarding *ETa*, the simulated versus measured results were well correlated, as shown in Figure 6, good fit is illustrated by slopes very close to one and small intercepts with high R^2 values (R^2 = 0.99 in both growing seasons). The RMSE values for *ETa* were small and *d* (index of agreement) values were very close to one in both growing seasons (Table 2).

The evolution of final aboveground biomass was simulated accurately in both seasons, as shown in Table 2. The AquaCrop model could reproduce precisely seed cotton yields for different irrigation levels in both seasons (Figure 7), *d* values were not less than 0.99 (Table 2). The largest error was around 5% un-

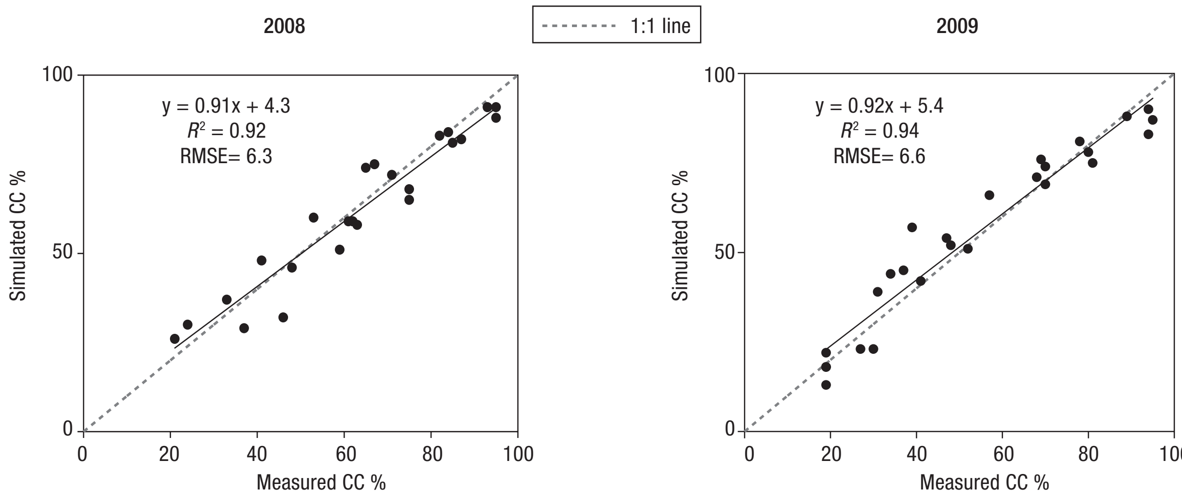

Figure 5. Relationship between simulated and measured green canopy cover (CC %) at different times for all treatments in the 2008 and 2009 seasons. Each dot represents an average of 18 measurements in 2008, while it represents an average of 12 in 2009.

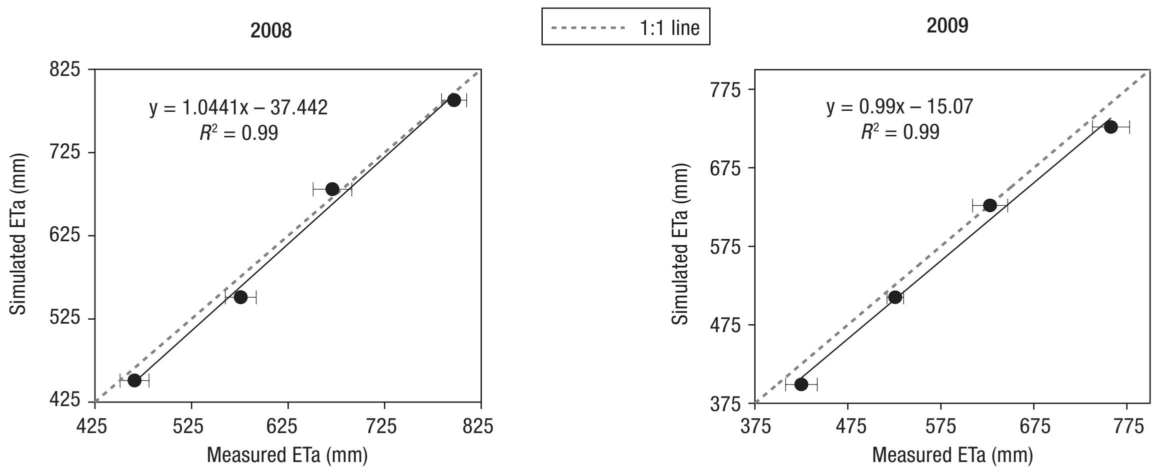

Figure 6. Relationship between simulated and measured seasonal evapotranspiration (ETa) for all treatments in the 2008 and 2009 seasons. Each dot represents an average of six replications in 2008, while it represents an average of four in 2009. Horizontal bars are ± 1 SD.

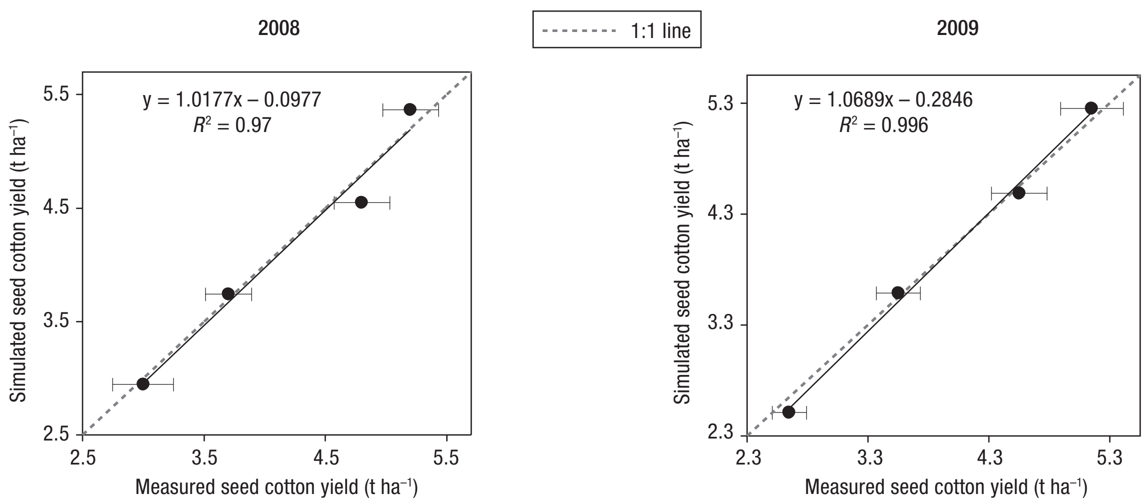

Figure 7. Relationship between simulated and measured seed cotton yield for all treatments in the 2008 and 2009 seasons. Each dot represents an average of six replications in 2008, while it represents an average of four in 2009. Horizontal bars are ± 1 SD.

derprediction of seed cotton yield in the DI-80 and DI-50 treatments in the 2008 and 2009 growing seasons, respectively. The results of simulating HI were relatively, fairly acceptable; the *d* values were more than 0.60 (Table 2). Temporal variations in soil water content under different irrigation treatments using the calibrated model in 2008 and 2009 followed the same trend observed in 2007. The model simulated drying cycles and irrigation events in general, but there was a deviation in the absolute values (Figure 8). However, mismatching the absolute values of SWC had little effect on *ETa* estimates for the different treatments.

Farahani *et al.* (2009) modeled seed cotton yield and water use with AquaCrop model, and found good agreement between measured and simulated values of both for one year. Their data showed that WUE was estimated reasonably well in one season, though not for the other season; due to overestimation of yield and underestimation of evapotranspiration, which led to simulated values of WUE that were larger than measured ones. Garcia-Vila *et al.* (2009) reported that the model tended to overestimate WUE for conditions of severe water stress due to the fact that the model uses a constant value for normalized WUE. On the other hand, AquaCrop performed well as compared with

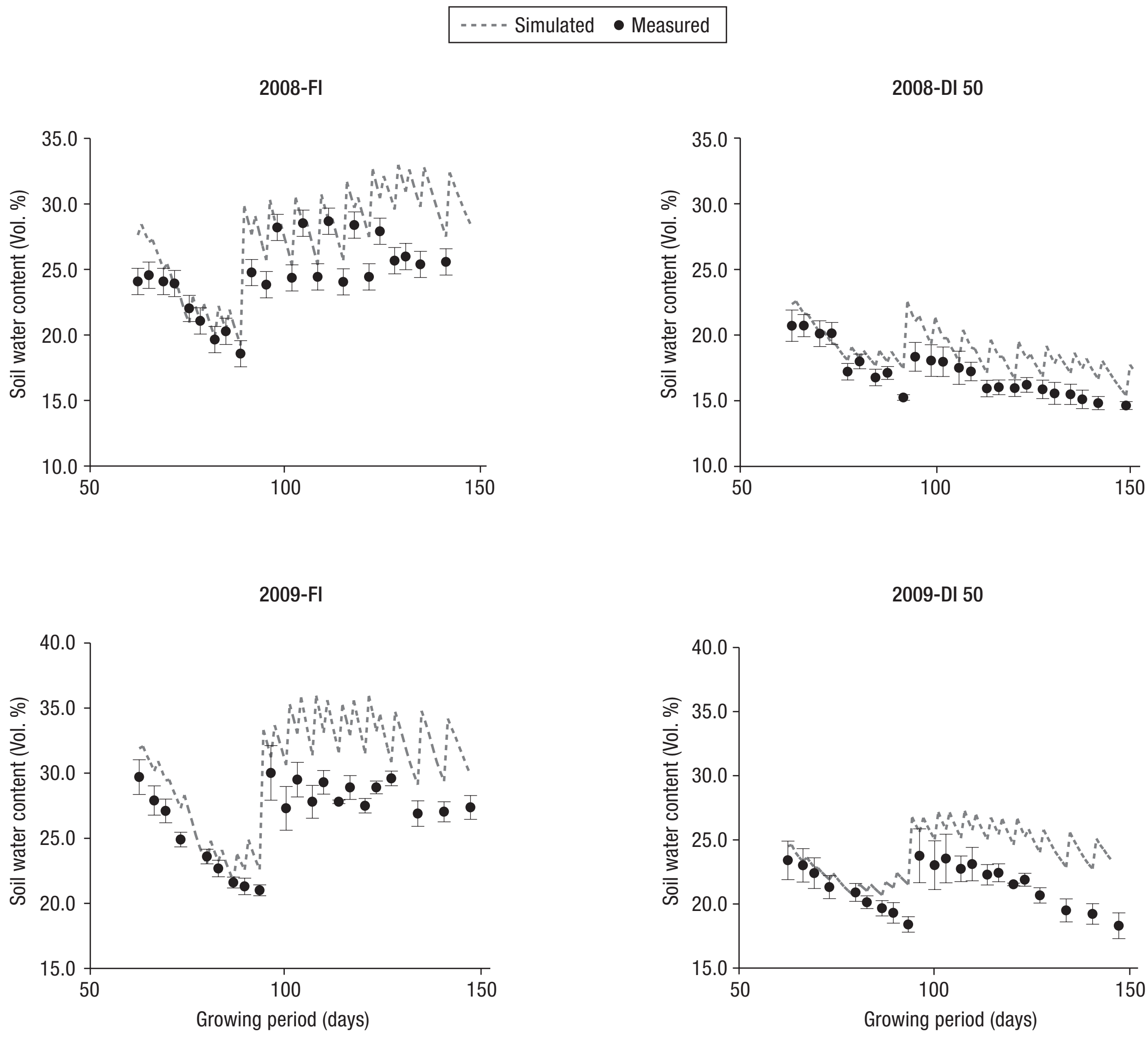

Figure 8. Measured and simulated soil water content (vol %) in the 0.60 m profile in the 100 (FI) and 50% (DI-50) irrigation treatments in the 2008 and 2009 seasons. Each dot represents an average of six replications in 2008, while it represents an average of four in 2009. Vertical bars are ± 1 SD.

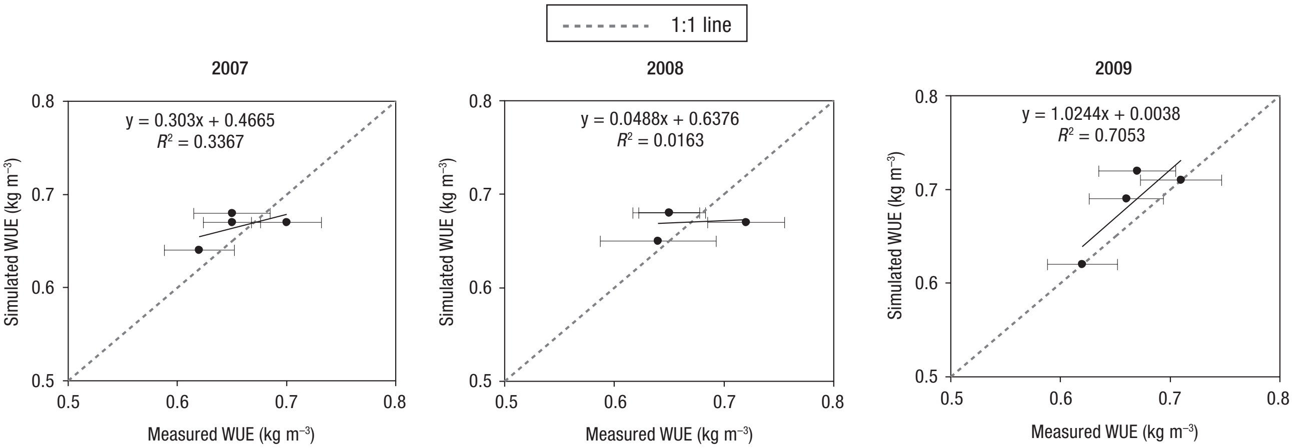

Figure 9. Relationship between simulated and measured water use efficiency (WUE) for all irrigation treatments. Each dot represents an average of six replications in 2007 and 2008, while it represents an average of four in 2009. Horizontal bars are ± 1 SD.

more complicated models (Todorovic *et al.,* 2009). In this study, values of WUE increased first as *ETa* decreased, reached a maximum, and then declined again as more severe water deficits reduced *ETa* further. The highest WUE was obtained for the DI-80 in the three growing seasons. The AquaCrop model had an apparent tendency for overestimating WUE in all treatments, with the exception of the DI-80 in the three seasons (Figure 9). In spite of that, it could simulate seed cotton yield and water use accurately. Therefore, in cases of limited input data and for management purposes using a simple model like AquaCrop should be encouraged.

Conclusion

The AquaCrop model was calibrated for drip-irrigated cotton and its performance was tested in hot and dry climate in the eastern Mediterranean region. Good simulated results of ETa, total biomass, seed cotton yield and soil water across four irrigation levels are promising considering the simplicity owing to its required minimum input data. Worthy noting is the limited number of the required parameters to be adjusted in model calibration when compared with more complicated models. Although the cotton variety used in this study (Allepo-33) has a relatively long growing season (170 d), while the key parameters suggested earlier by Farahani *et al.* (2009) for Allepo-118, a relatively short growing season variety, still applicable here.

This study suggests that it is essential to calibrate the model using data from both full- and deficit-irrigated treatments to capture the crop response to water stress properly. It seems that the most logical method for AquaCrop calibration to start by sound prediction of green canopy development. Key input parameters in this aspect are those defining canopy cover development and the threshold soil water depletion levels for water stress indices. The AquaCrop is a model balanced between the limited parameterization and good accuracy, and it is therefore a powerful tool to study different scenarios and management conditions of cotton crop grown in the dry areas.

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