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Using the AquaCrop model to assess the cotton yield response to three irrigation schedules in the Río Dulce Irrigation System, Santiago del Estero, Argentina

Uso del modelo AquaCrop para evaluar la respuesta del rendimiento del algodón a tres programaciones de riego en el Sistema de Riego del Río Dulce, Santiago del Estero, Argentina

Uso do modelo AquaCrop para avaliar a resposta da produtividade do algodão a três programas de irrigação no Sistema de Irrigação Rio Dulce, Santiago del Estero, Argentina

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Abstract

This work evaluates the cotton response to irrigation scheduling using AquaCrop, in the Río Dulce Irrigation System (SRRD), Santiago del Estero, Argentina. The model was calibrated and validated to simulate the cotton´s growth and yield for the SRRD, where most of the cotton is grown in a cropping system called narrow rows (0.52 to 0.76 meter between rows, 200,000 to 220,000 plants per hectare). The model adaptation to different cultivars and agronomical practices was noteworthy. Then, the impact of three different irrigation schedules on cotton production was assessed using a series of 35 years of daily climatic data. The irrigation scenarios were defined based on the farmers' practices and on the rotational water delivery of the SRRD. The highest yields were attained when irrigation was applied at 25 and 55 days after sowing (DAS), followed by 55 DAS, and, finally, 55 and 85 DAS. Considering both the yields and the water use, irrigating at 25 and 55 DAS would be the best option for a normal season in the SRRD. This work shows the usefulness of combining the use of crop simulation models, field measurements and long-term weather data to analyze yield trends and irrigation water use under different scenarios.

Keywords: irrigation, cotton, yields, AquaCrop, Argentina

Resumen

Se evaluó la respuesta del algodón a la programación del riego utilizando AquaCrop en el Sistema de Riego Río Dulce (SRRD), Santiago del Estero, Argentina. El modelo se calibró y validó para el algodón en el SRRD, donde se cultiva en un sistema llamado surco estrecho (0,52 a 0,76 metros entre filas, 200.000 a 220.000 plantas por hectárea). Se destacó la adaptación del modelo a diferentes cultivares y prácticas agronómicas. Luego, se evaluó el impacto de tres programaciones de riego en el rendimiento del algodón, usando 35 años de datos climáticos diarios. Los escenarios de riego se definieron considerando los hábitos de los agricultores y la forma de entrega de agua del SRRD. Los mayores rendimientos se obtuvieron cuando se regó a los 25 y 55 días después de la siembra (DDS), seguido de 55 DDS y, por último, 55 y 85 DDS. Regar a los 25 y 55 DDS sería la mejor opción en un año de lluvias medias. Este trabajo muestra la utilidad de combinar el uso de modelos de simulación, mediciones de campo y datos meteorológicos de largo plazo para analizar las tendencias de los rendimientos y el uso del agua de riego en diferentes escenarios.

Palabras clave: riego, algodón, rendimientos, AquaCrop, Argentina

Resumo

Esse trabalho avaliou a resposta do algodoeiro ao manejo da irrigação com AquaCrop, no Sistema de Irrigação Río Dulce (SRRD), Santiago del Estero, Argentina. O modelo foi calibrado e validado para simular o crescimento e rendimento do algodão para o SRRD, onde é cultivado em um sistema de cultivo denominado "linha estreita" (0,52 a 0,76 metros entre linhas, 200,000 a 220,000 plantas por hectare). Destacou-se a adaptação do modelo a diferentes cultivares e práticas agronômicas. Logo, avaliou-se o impacto de três programas de irrigação no rendimento de algodão utilizando 35 anos de dados climáticos diários. Os cenários de irrigação foram definidos considerando as práticas dos agricultores e a metodologia de entrega de água do SRRD. As maiores produtividades foram obtidas quando irrigadas aos 25 e 55 dias após a semeadura (DAS), seguida de 55 DAS e, finalmente, 55 e 85 DAS. Irrigar aos 25 e 55 DAS foi a a melhor opção em um ano con chuvas médias. Esse trabalho mostra a utilidade de combinar o uso de modelos de simulação, medições de campo e dados meteorológicos de longo prazo para analisar tendências de rendimentos e o uso de água de irrigação em diferentes cenários.

Palavras-chave: irrigação, algodão, produtividade, AquaCrop, Argentina

1. Introduction

Agricultural production is usually vulnerable to climate risk and uncertainty. Therefore, predicting crop yields to a given water supply is important to cope with uncertainty and to elaborate water allocation strategies, mainly in dry years. For that, crop simulation models are helpful: its main function is to predict the production of crops depending on climate, soil, and agronomic management. There are numerous crop simulation models, which vary in their complexity, input data requirements and kind of outputs. Some of the most used are CERES[1], GOSSYM[2], WOFOST[3], the decision support system DSSAT[4], APSIM[5], CropSyst[6], and AquaCrop[7]. Gowda and others[8] made an ample review of the most used crop simulation models.

The AquaCrop model[9] is driven by a relationship linking the biomass (B) produced to the water transpired (Tr). The input data required by AquaCrop are weather parameters, crop and soil characteristics, and crop management. The model has been used to simulate the performance of maize[10-15]; wheat[16-19]; and cotton[20-27], among the major crops.

The initial AquaCrop parameterization for cotton was performed by Farahani and others[20] using experiments in northern Syria, in a warm, dry and windy climate (average annual rainfall of 350 mm, concentrated in autumn and early spring). Qiao[22] and Qiao and others[24] have applied the model to a humid climate in South Carolina (USA); Heidariniya and others[28] have simulated cotton production in Iran under a Mediterranean-type climate; while García-Vila and others[21] have calibrated and validated the model at Córdoba, Spain (a warm and semiarid climate with a dry summer and an annual rainfall of 550 mm). Linker and others[29] simulated the cotton response to a deficit irrigation scheduling for two contrasting seasons (rainfall of 268 and 97 mm) in Greece. Voloudakis and others[23] also investigated the impact of climate change on cotton yields in seven sites in Greece. All these seven areas have the normal rainfall pattern of a Mediterranean-type climate, having minimal rainfall between May and October, i.e. during the cotton-growing season. By contrast, Li and others[26] used AquaCrop to optimize cotton irrigation scheduling in the North China Plain where the annual rainfall is 507 mm, concentrated from June to September, and mean annual evaporation is 1000 mm. Masasi and others[30] calibrated and validated AquaCrop for two sites in the Southern Great Plains, United States. In the experimental site in Texas, the climate is semi-arid with an average rainfall during the cotton season of 391 mm (May-September), while the site in Oklahoma has a sub-humid climate, with hot and dry summers and an average rainfall of 508 mm during the growing season.

The major cotton production area in Argentina is located in the province of Santiago del Estero, where the cropping system and cultivars differ from the other areas described above, where AquaCrop has been previously calibrated. In the majority of those areas, the planting density varied between 70,000 and 120,000 plants ha^{-1}, and the row spacing was generally 1 m and the cultivars planted were of medium to long season, lasting 150-180 days[(20-22)(28)]. Cotton production in Santiago del Estero is characterized by high planting densities, from 200,000 to 220,000 plants ha^{-1} and narrow rows, varying from 0.52 m to 0.76 m. Cultivars are short season, of about 140 days and growth regulators are intensively used, producing short plants (of about one-meter height) with a limited number of bolls (four to seven). This intensive growing system facilitates mechanization, reduces production costs and increases yields[(31)]. In Santiago del Estero, 156,000 ha of cotton were planted in 2021, mostly under the narrow row system, out of which around 50,000 ha are located in the Río Dulce Irrigation System (SRRD). The SRRD is a collective irrigation network; 100,000 ha can be irrigated, and 80,000 ha are presently cropped. Its climate is semi-arid, mesothermal, with a mean annual rainfall of 598 mm, concentrated during spring and summer (October-March semester). The mean annual evapotranspiration (ETo) is 1,300 mm. The water balance is negative in an annual and monthly basis. The mean annual maximum temperature is 27.5 ºC and the mean annual minimum temperature, 12.7 ºC. The rainfall is highly variable between and within years. In the SRRD, the water runs under a rotational delivery schedule that has an irrigation frequency between 25 and 30 days. The flow rate delivered at every farm outlet is 300 l s^{-1}, and the theoretical run time is 50 min per hectare, which is equivalent to an irrigation depth of 90 mm for a single irrigation. Basin/border irrigation is the most common irrigation method, although furrow and drip irrigation are also used in vegetables. In cotton, a pre-sowing irrigation is given. During the crop cycle, the farmers´ most usual irrigation practices are irrigating at 55 DAS (flowering) or at 55 and 85 DAS (flowering and boll development)[(32-33)]. However, farmers may use other irrigation turns within the standard water delivery arrangement in the SRRD, and this is why it is pertinent to examine alternative strategies and their potential returns in terms of increased yields, using less or similar amounts of water.

The objectives of this work were to calibrate and validate the FAO-AquaCrop model for cotton in the agro-ecological conditions of the SRRD, Santiago del Estero, Argentina, and to assess the cotton yield response to three different irrigation schedules.

2. Materials and methods

2.1 Study area

The SRRD is located in the province of Santiago del Estero, Argentina (27º 27´59.53” to 28º 18´16.42” S and 64º 15´35.30” to 63º 42´ 26.72” W). The irrigated area is situated on a plain alluvial cone with a general slope of 1$_{0/00}$. The climate is semi-arid, mesothermal, with a mean annual rainfall of 598 mm, concentrated in spring-summer (October-March). The mean annual evapotranspiration (ETo) is 1,300 mm, the mean annual maximum temperature is 27.5 ºC, and the mean annual minimum temperature, 12.7 ºC. The predominant soils are deep, of silty loam texture and total available water (TAW) of 170-180 mm m^{-1}. The Río Dulce water is of good quality (electrical conductivity-EC 0.60 dS m^{-1}). Major crops are cotton, alfalfa, maize and vegetables.

2.2 Calibration and validation of AquaCrop

Calibration and validation of AquaCrop were performed using experiments conducted at INTA (National Institute for Agricultural Technology), Experimental Station Santiago del Estero, located at 28º 01' 30'' South latitude and 64º 14' 55'' West longitude, 169 meters above sea level. The soil is silty loam, having a sequence of horizons A1-AC-C1-C2, belonging to the series "La María". The profile is deep, with no compacted layers that would limit root development. The total available water (TAW) is 170-180 mm m^{-1}. Natural fertility is low: organic matter content ranges between 0.5 and 1.5%, and the average nitrogen content is 0.08%, varying between 0.05 and 0.11%. The detailed soil characteristics of the experimental site, used for the AquaCrop soil file, are described in Angella[(34)]. Daily meteorological data were obtained from the automated weather station (Davis Vantage Pro®), located at the INTA experimental field. Input data to run the model were daily maximum and minimum temperatures, rainfall and ETo calculated by the FAO Penman-Monteith equation[(35)]. The climate data for the years of the experiments is presented in Table 1.

Table 1. Main meteorological variables during the experiments

	Av. Tmax. (ºC)	Abs. Tmax. (ºC)	Av. Tmin. (ºC)	Abs. Tmin. (ºC)	Rainfall (mm)	Av. ETo (mm day^{-1})	Max. ETo (mm day^{-1})
2010/2011	30.1	40.0	17.6	5.3	466	4.0	7.9
2011/2012	32.8	43.0	17.8	7.0	461	5.1	8.3
2012/2013	32.9	43.8	18.5	6.6	237	5.1	8.5

Av. Tmax.: average maximum temperature; Abs. Tmax.: absolute maximum temperature; Av. Tmin.: average minimum temperature; Abs. Tmin.: absolute minimum temperature; Av. ETo: average Eto; Max. ETo: maximum ETo

2.3 Calibration process

The experiments used for AquaCrop calibration were carried out in the 2010-11, 2011-12 and 2012-13 seasons. A set of experiments was conducted to assess cotton response to regulated deficit irrigation (RDI), while one additional experiment evaluated conditions of excess water in the soil. In the experiments used for calibration, the cotton did not experience water stress. AquaCrop calibration was done in two groups of experiments, as described below. These experiments are described in Prieto Angueira and others[36].

2.4 Experiments A

The treatments were identified as 2010/2011 RD0 and 2011/2012 RD0 and they were the control plots (replicated four times) of an experiment in which the cotton response to RDI was studied. The plant population was 220,000 plants ha^{-1}, and the crop was kept free of pests and diseases throughout the whole cycle. The experimental unit (EU) consisted of 12 rows of 10 meters in length. The distance between rows was 0.52 meters. Plant phenology was surveyed weekly in 10 plants per EU and the main phenological stages were identified: first bud (FB); first flower (FF); end of effective flowering (EEF, moment in which the number of nodes above the last white flower in first position was less than six); first open bud (FOB) and maturity (HM). The actual evapotranspiration (ETa) was determined by means of the water balance (Equation 1) from sowing to harvest:

$$ETa(mm)=\Delta SM+P+Ir-R-Dp \quad (1)$$

where ETa is the actual evapotranspiration of the crop, ΔSM is the variation in soil moisture considering a depth of 3 meters, P is the accumulated rainfall during the crop cycle, Ir is the total irrigation depth, R is surface runoff, and Dp is deep percolation. Drip irrigation was used and Ir was measured by using flow meters in each treatment. Soil moisture was sampled weekly up to 2 m depth. Runoff was avoided due to a controlled irrigation; moreover, the plots were delimited by bunds. The Dp was considered negligible based on water content observations below the root zone (one-meter depth). Eight square meters were harvested in each plot to determine yield (fiber weight + seeds). The canopy cover (CC) was determined with photographs taken with a digital camera kept horizontally above the canopy, at noon. Two photographs were taken per EU and processed with the software Green Crop Tracker[37] and the canopy cover values of the two photographs were averaged. The biomass was obtained by harvesting the above ground material of 2 m^2 which was dried in an oven at 60 °C for 96 hours. The harvest index (HI) was calculated as the ratio between the reproductive and the total biomass.

2.5 Experiments B

These treatments are identified as ALG 2011/2012 T1 and ALG 2012/2013 T1 and they were part of an experiment aimed at characterizing the response of cotton to soil water excess. The experimental unit was of 8 lines by 10 meters long, the cultivar *Nu Opal RR* was planted in 0.52 m rows and a density of 220,000 plants per hectare. This variety is like the one planted in Experiment A. Treatment 1 (T1) followed a common irrigation practice in the Río Dulce Irrigation System (three irrigations: the first one at pre-sowing and two more during the crop cycle), plus extra water application (whenever necessary) to reach the average within season rainfall (480 mm for October planting date). Surface irrigation was used, registering the date and the application depth. Growth regulators were applied, taking the mean internode length as a reference (when the mean length of the internode exceeded 4.5 cm, a regulator was applied in variable doses, according to phenological state). All plant measurements in this experiment were identical to those described for Experiment A. Soil moisture was sampled weekly up to a depth of 2 m. Table 2 presents the cultivar, plant density, sowing and harvesting dates and irrigation of the experiments used for calibration. Some non-conservative parameters were adjusted; the changes done in the non-conservative parameters can be seen in Table 3.

Table 2. Main information of the experiments used for cotton calibration with AquaCrop

Calibration experiments	Cultivar	Plant density (pl ha^{-1})	Sowing date	Harvest date	Irrigation (mm)
2010/2011 RD0	Guazuncho 2000 RR	220,000	7/12/2010	9/5/2011	170
2011/2012 RD0	Guazuncho 2000 RR	220,000	25/10/2011	23/3/2012	320
ALG 2011/2012 T1	Nu Opal RR	220,000	3/11/2011	19/3/2012	260
ALG 2012/2013 T1	Nu Opal RR	220,000	31/10/2012	25/3/2013	245

Table 3. Non-conservative parameters of cotton that changed compared to their original values in AquaCrop

Parameter	Adopted value	Original AquaCrop value
Canopy growth coefficient (CGC, % GDD-1)	0.846	0.65
Canopy decline coefficient (CDC, % GDD-1)	0.620	0.247
Time to flowering (GDD)	675	602
Duration of flowering (GDD)	747	720
Length of building up of HI (GDD)	1,020	1,388
Time to senescence (GDD)	1,364	1,707
Time to physiological maturity (GDD)	1,880	1,956
Harvest index (%)	41	35

For the adjustment of the non-conservative crop parameters, attention was paid on how well the simulated results agreed with the observed values. This was done not only for the results at maturity, but also throughout the crop growing cycle. For that, simulations were done, using (first) estimated parameter values and comparing measured and simulated results. The parameters were adjusted during the process and then other simulations were run. This was done several times until the simulated results closely agreed with the experimental data. To make this procedure more efficient, the comparison between measured and simulated results of the main variables was done in this order: canopy cover, biomass and yield. The “control” during the crop growing cycle was performed not only by using the numerical output table, but also the graphical display of the model. In this way, it was possible to check when and where the adjustments were needed. In previous works, adjustments of non-conservative parameters were also done. Qiao(22) changed the CGC and CDC and, also, some semi-conservative parameters, such as the thresholds for water stress on canopy expansion and senescence. All these parameters were increased from the default values. Voloudakis and others(23) slightly adjusted the normalized water productivity at 15.2 g m^2 (default value 15.0), the harvest index at 27% (default value 31%) and the maximum canopy cover at 94% (default value 98%). Garcia-Vila and others(21) made similar changes, but also modified the stress thresholds for canopy expansion (from 0.20 to 0.27), for stomata control (from 0.75 to 0.50) and for canopy senescence (from 0.70 to 0.75). The harvest index was increased up to 35%. Li and others(26) adjusted the maximum canopy cover, the time from planting to emergence, to flowering, to senescence and to maturity, the length of the flowering stage, the maximum rooting depth and the reference harvest index. The values of these parameters were changed up and down 5 and 10% during the process of calibration. Masasi and others(30) adjusted the canopy growth coefficient (CGC), the canopy decline coefficient (CDC), the time from sowing to emergence, to maximum canopy cover, to flowering, to senescence and to maturity, the length of flowering, among other. The adjustments of the selected crop parameters done by Masasi and others(30) are similar to the ones performed in this work.

2.6 Validation process

The experiments used for AquaCrop validation are described below.

2.6.1 Dataset A

Datasets used were 2010/2011 RD and 2011/2012 RD, being part of the experiment aimed to determine the cotton response to deficit irrigation. Drip irrigation was used, and the treatments replenished

75% of ETc, 50% ETc, 25% ETc and rainfed (T1 to T4, respectively). The experimental design, plot size, crop variety, plant density, and plants and soil measurements were the same as those described in the experiments used for model calibration (2010/2011 RD0 and 2011/2012 RD0). The applied irrigation depths varied between 0 to 255 mm amongst treatments[(34)].

2.6.2 Dataset B

Datasets used were ALG 2011/2012 T2, ALG 2011/2012 T3, ALG 2012/2013 T2 and ALG 2012/2013 T3, which were part of a 2-year experiment done to determine the cotton response to soil water excess. The general characteristics, objective, experimental design, agronomic management and field measurements were the same to those described in the experiments used for model calibration (ALG 2011/2012 T1 and ALG 2012/2013 T1). In addition to the T1 (already described), two more treatments were used, T2 and T3, designed to simulate wet seasons. T2 received the same as T1 plus extra water application to reach a seasonal total of 530 mm (i.e., 40% of probability of exceedance). T3 received the same as T1 plus extra water application for a seasonal total of 620 mm (i.e., 20% of probability of exceedance). For additional information see Angella[(34)].

2.6.3 Model evaluation

The performance of AquaCrop was evaluated using statistical indicators, considering the following variables: canopy cover (CC), biomass (B) and yield (Y). The statistical indicators were coefficient of determination (R^2), the Willmott Index, *(d)*[(38)], the mean absolute error (MAE), the root mean square error (RMSE), and the normalized root mean square error (NRMSE). A comprehensive analysis of the main characteristics, advantages and disadvantages of these statistical indicators is done by Raes and others[(39)].

2.6.4 Assessing irrigation scenarios with AquaCrop

After calibration and validation, AquaCrop was used to evaluate the cotton response to different irrigation scenarios, which were designed considering both the SSRD water supply characteristics (fixed irrigation turns every 25-30 days) and the farmers' irrigation habits. The most common irrigation schedule in the SRRD are: a single application at 55 DAS (flowering, named ISa) and two applications at 55 and 85 DAS (flowering and boll development, named ISb)[(32-33)]. A third scheduling, not usually implemented by the farmers, was also assessed (25 and 55 DAS, bud formation and flowering, named ISc). In all cases, the net application depths were those needed to get the soil moisture content back to field capacity in the root zone (1m). As a pre-sowing irrigation is usually done in the SSRD, the initial soil moisture content was set close to field capacity[(34)]. Thirty-five years of daily meteorological data (1988-2022) collected at INTA-Experimental Station, Santiago del Estero, were used in the simulations. Sowing date was set on October 15th every year. Regarding soil fertility, the model was run with the option "unlimited soil fertility". The crop file used was the one generated after the calibration and validation of AquaCrop (Table 3), and the soil file was the same as that used in calibration.

3. Results and discussion

3.1 AquaCrop performance

3.1.1 Calibration

Figures 1, 2, and 3 present the observed and simulated results for canopy cover, biomass and yield, respectively for the calibration exercise. Biomass and canopy cover data were not available for 2011/2012 RD0.

Table 4 shows the statistical indicators for canopy cover, biomass and yield in the experiments used for calibration.

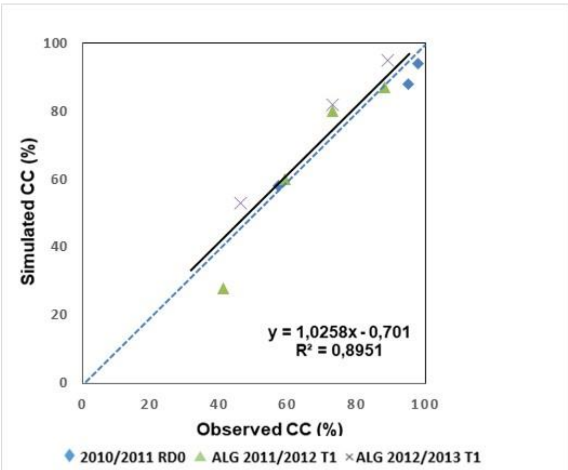

Figure 1. Observed and simulated canopy cover in the experiments used for calibration

Full line: fit line; dotted line: 1:1 relationship. Each dot represents the average of four replications.

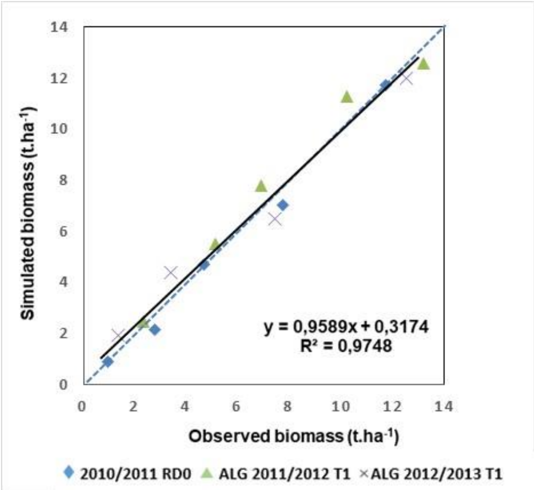

Figure 2. Observed and simulated biomass in the experiments used for calibration

Full line: fit line; dotted line: 1:1 relationship. Each dot represents an average of four replications.

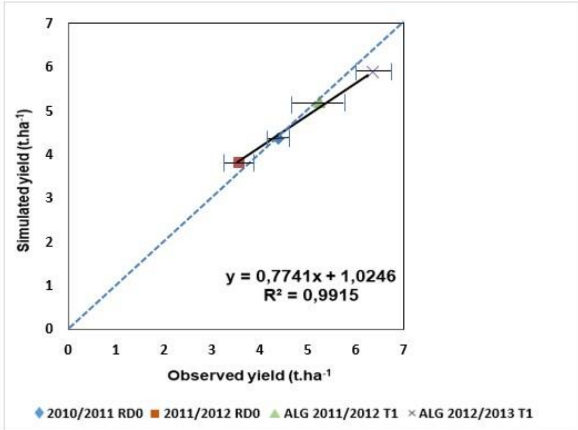

Figure 3. Observed and simulated yield in the experiments used for calibration

Full line: fit line; dotted line: 1:1 relationship. Each marker represents the average of four replications and the horizontal bars represent the standard deviation (SD) of observed yields.

Table 4. Statistical indicators for canopy cover, biomass and yield (experiments used for model calibration)

	n	R^2	*d* Index	MAE	RMSE	NRMSE
Canopy cover %	11	0.895	0.970	5.727	6.749	9.2
Biomass (t ha^{-1})	14	0.974	0.993	0.541	0.646	10
Yield (t ha^{-1})	4	0.991	0.980	0.186	0.257	5.3

The agreement between observed and simulated values of canopy cover (Figure 1, Table 4) is good, although it would have been desirable to have more observations in the early stages of the crop. From the available data, it appears that the evolution of the canopy cover is simulated better during the mid-season (between 60 and 90 days). AquaCrop precisely simulated the biomass evolution, as can be seen in Figure 2 and in Table 4: R^2 and *d* Index very close to 1, while MAE, RMSE and NRMSE had low to very low values. For the final biomass, the average standard deviation of the data sets used for calibration was -2.9%, being the smallest value 0.2% (2010/2011 RD0) and the highest -4.4% (ALG 2011/2012 T1 and ALG 2012/2013 T1). The model predicted yields very well (Figure 3, Table 4); the average standard deviation of the data set was -0.7%. R^2 and the *d* Index had values very close to 1, while MAE, RMSE and NRMSE were low. AquaCrop adequately simulated a wide range of yields, including those higher than 5 t ha^{-1}, although there was some yield underestimation at the highest observed values (Figure 3).

3.1.2 Validation

The observed and simulated canopy cover, biomass and yield of the experiments used for validation are shown in Figures 4, 5 and 6, respectively. Biomass and canopy cover data were not available for 2011/2012 RD0.

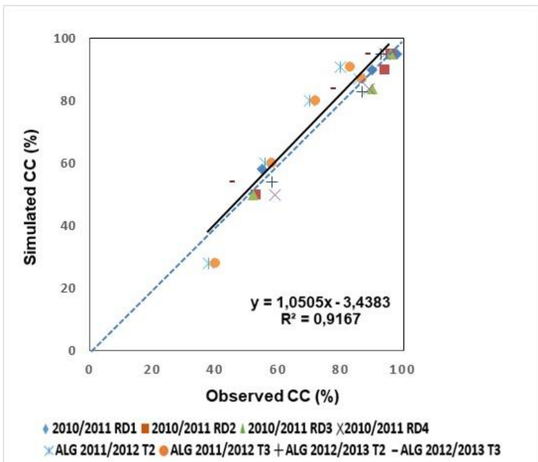

Figure 4. Observed and simulated canopy cover in the experiments used for validation

Full line: fit line; dotted line: 1:1 relationship. Each marker represents an average of four replications.

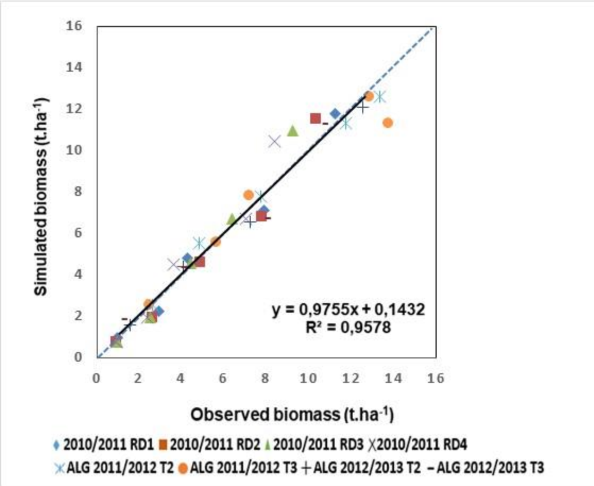

Figure 5. Observed and simulated biomass in the experiments used for validation

Full line: fit line; dotted line: 1:1 relationship. Each dot represents an average of four replications.

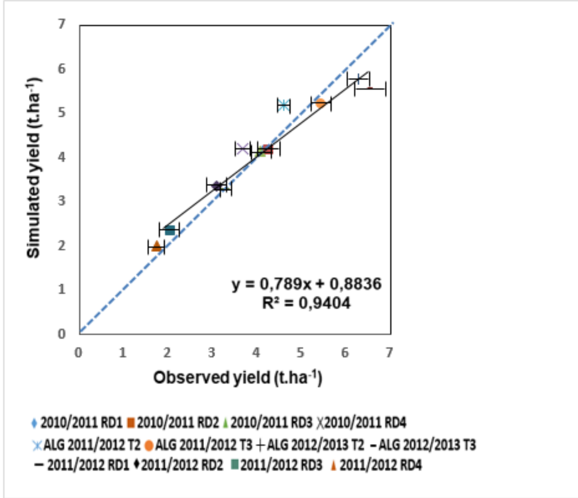

Figure 6. Observed and simulated yield in the experiments used for validation

Full line: fit line; dotted line: 1:1 relationship. Each dot represents an average of four replications and the horizontal bars represent the standard deviation of observed values.

Table 5. Statistical indicators for canopy cover, biomass and yield (experiments used for model validation)

	n	R^2	*d* Index	MAE	RMSE	NRMSE
Canopy cover %	28	0.916	0.976	4.893	6.039	8.1
Biomass (t ha^{-1})	38	0.957	0.989	0.590	0.801	13.2
Yield (t ha^{-1})	12	0.940	0.974	0.317	0.413	10.1

Table 5 shows the statistical indicators for canopy cover, biomass and yield in the experiments used for model validation.

In the validation exercise, AquaCrop simulated very well the evolution of the canopy cover (Figure 4, Table 5): R^2 and *d* index were very close to 1, while MAE, RMSE and NRMSE were low. Similar performance occurred for biomass (Figure 5, Table 5). For the final biomass, the average standard deviation of the data set used for validation was 6.9%, being the smallest value 1.7% (ALG 2011/2012 T3) and the highest, 24.7% (2010/2011 RD4). The model predicted the yield very well (Figure 6, Table 5). The average standard deviation of the data set was 2.9%, R^2 and *d* Index had values very close to 1, while MAE, RMSE and NRMSE were low. AquaCrop had a slight overestimation of the lowest yields (treatments that suffered important water stress, e.g., 2011/2012 RD3 and 2011/2012 RD4) and under-estimated the highest yields (ALG 2012/2012 T2 and ALG 2012/2012 T3). The overestimation of stressed treatments has also been reported in other works. Farahani and others[20] evaluated AquaCrop for cotton under full (100% ET) and deficit (40%, 60%, and 80% of full ET) irrigation regimes in northern Syria. AquaCrop simulated cotton yields within 10% of the measured yields for the 40% and 100% irrigation regimes, while the errors increased to 32% for the 60% and 80% regimes. Garcia-Vila and others[21] calibrated and validated AquaCrop to generate the yield response of cotton to variations in available irrigation water (AIW), using experiments conducted in Córdoba, Spain. They reported that the yield was very well simulated by AquaCrop in the treatments with the highest AIW (80 and 100% of ET), while it was overpredicted in the treatment with the lowest AIW (60% of ET). The largest error was around 5% underprediction of cotton yield in the more stressed treatments. Tan and others[27] studied the performance of AquaCrop for cotton growth simulation under film-mulched drip irrigation in Xinjiang, China. One-year dataset was used to calibrate the model and the datasets for three different years were used for the model validation. AquaCrop simulated the changes in CC and aboveground biomass with $r^2 > 0.77$ and $d > 0.92$ and slightly underestimated cotton yield[27].

3.2 Assessing irrigation scheduling with AquaCrop

After calibration and validation of AquaCrop, the impact on yield and on irrigation water use of three irrigation scenarios was analyzed. Table 6 shows the mean, maximum, minimum, standard deviation and coefficient of variation of the rainfall during the cotton crop cycle; the mean, maximum, minimum, standard deviation and coefficient of variation of yield and the net irrigation, for the three-irrigation scheduling. Seasons 1988 to 2022.

Table 6. Mean, maximum, minimum, standard deviation (SD) and coefficient of variation (CV) of rainfall during the cotton crop cycle. Mean, maximum, minimum, standard deviation (SD) and coefficient of variation (CV) of yield and net irrigation (Net Irr.) for the three irrigation scheduling. Seasons 1988 to 2022

		ISa 55 DAS		ISb 55 and 85 DAS		ISc 25 and 55 DAS	
Season	Rainfall (mm)	Yield (T ha^{-1})	Net irr. (mm)	Yield (T ha^{-1})	Net irr. (mm)	Yield (T ha^{-1})	Net irr. (mm)
Mean	447	4.93	79	4.85	183	5.06	111
Max.	784	5.52	143	5.35	335	5.51	182
Min.	181	3.79	0	4.03	50	4.23	25
SD	147	358	46	301	75	283	44
CV (%)	33	7.26	57.63	6.10	41.32	5.59	39

IS: irrigation scheduling. a) irrigation at 55 days after sowing (DAS); b) irrigation at 55 and 85 DAS; c) irrigation at 25 and 55 DAS.

Figure 7 shows the cotton yield for the seasons 1988 to 2022, simulated by AquaCrop, for ISa, ISb and ISc.

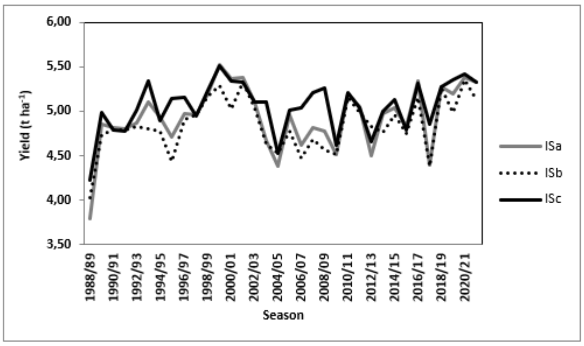

Figure 7. Cotton yield for the seasons 1988 to 2022, simulated by AquaCrop, for ISa, ISb and ISc

Figure 8 shows the average cotton yield for the seasons 1988 to 2022, simulated by AquaCrop, for ISa, ISb and ISc.

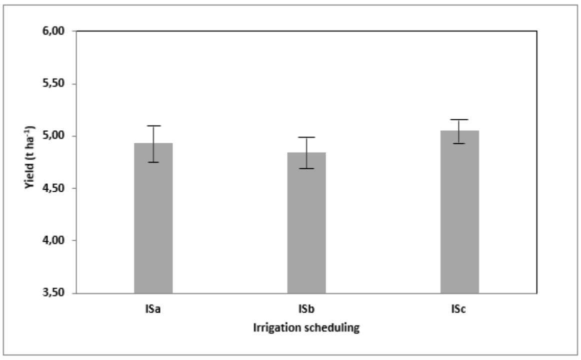

Figure 8. Average cotton yield for the seasons 1988 to 2022, simulated by AquaCrop, for ISa, ISb and ISc. Vertical bars represent the standard deviation (SD)

As can be seen from figures 7 and 8, yields are in general good to very good in all scenarios (extreme values of 3.79 and 5.52 t ha^{-1}). The small differences in average yields between scenarios can be explained by four main factors: the rainfall influence during the crop cycle; the pre-sowing irrigation, that provides a good soil water content from cotton emergence to first stage; the high-water holding capacity of the soil (170 mm m^{-1}), and the lack of limiting layers for root deepening. The model was run under the "unlimited soil fertility" option, thus being water the only limiting factor for crop production. Despite the high yields in all scenarios, it is worthy analyzing the relative differences and the variation throughout the years. We start the analysis by comparing the ISa and ISb. ISb has two irrigations (55 and 85 DAS) and ISa, only one (55 DAS); the yield slightly falls 0.085 t ha^{-1} in ISb. In both ISa and ISb scenarios, the irrigation at 55 DAS ensures a good water status during flowering. Also in both cases, a (positive) water stress occurs after flowering and during yield formation, which results in a harvest index (HI) increase[9]. Nevertheless, the HI increase is higher in ISa: from 0.41 to 0.46 (average for all seasons), while increases from 0.41 to 0.43 in ISb. This explains the lower yield of ISb compared to ISa. Therefore, it appears that a second irrigation at 85 DAS would not be necessary. Yields are the highest in ISc (irrigation at 25 and 55 DAS). The impact of the irrigation at 25 DAS seems to be crucial, since adequate water status is critical for a good canopy expansion and flower bud formation. The irrigation at 55 DAS has the same positive effect, already mentioned, while the lack of irrigation at 85 DAS maintains (and even strengthens) the positive influence of a controlled stress during yield formation, increasing the HI up to 0.47. Similar conclusions were obtained in the SRRD for Prieto and

Angueira[40]. The importance of irrigation at 25 DAS is related to the slow root growth during this period[36] and to the rainfall pattern: in November, the average rainfall is 58 mm and the 25-days irrigation is vital for the flower bud formation. In the rest of the months, the average rainfall is higher: December 105 mm, January 111 mm, and February 98 mm. Hence, the irrigation during these months (although important to sustain the critical periods of flowering and boll formation) has a relatively lower impact, compared to the irrigation during flower bud formation.

The simulated cotton response to these irrigation schedules sustains the well-known relationships between cotton yield and soil water availability. The vegetative/reproductive growth ratio is highly dependent on soil water status: high water content promotes vegetative growth and hampers reproductive growth. Adequate water is essential for vegetation growth prior to and during flower bud formation. On the other hand, abundant rainfall or irrigation late in the cycle can boost vegetative growth at the expense of boll maturation and fiber development. However, severe water stress at reproductive stage causes flowers and bolls abscission. The relationships between cotton yield, soil water content, irrigation timing and water stress were analyzed, among others, in Steduto and others[9], Prieto Angueira and others[36], Prieto and Angueira[40], Li and others[26], Ünlü and others[41], Perry and Barnes[42], and Constable and Bange[43].

For practical irrigation management in the SRRD, in an average rain season (447 mm during the crop cycle), the ISc appears to be the most suitable choice for balancing the positive and negative effects of water availability on cotton production. The irrigation at 25 DAS guarantees a good water status during vegetative growth and flower bud formation; the irrigation at 55 DAS benefits the adequate flower retention, while the lack of late irrigation (85 DAS) helps to control the excessive vegetative growth during boll's formation and development.

4. Conclusions

This work demonstrates that AquaCrop can precisely simulate cotton growth, development and yield in Santiago del Estero, Argentina. The same conservative crop parameters, as defined in the original parameterization of cotton, were used. However, some non-conservative crop parameters, related to canopy growth, phenology and harvest index, were adjusted in order to adapt the default AquaCrop cotton file to the characteristics of the cultivars used in the experiments. For both the calibration and validation processes, the agreement between observed and simulated values of canopy cover, biomass and yield was very good. For validation, the statistical indicators were the following: evolution of the canopy cover: R^2 0.916, *d* index 0.976, MAE 4.893, RMSE 6.039 and NRMSE 8.1; for biomass: R^2 0.957, *d* index 0.989, MAE 0.590, RMSE 0.801 and NRMSE 13.2; for yield: R^2 0.94, *d* Index 0.974, MAE 0.317, RMSE 0.413 and NRMSE 10.1. Yields were slightly over-estimated in the treatments having higher water stress and were moderately under-estimated in those treatments that had a better water availability. It is worth mentioning the model adaptation to the agronomic conditions of the experiments: drip and surface irrigation, deep silty-loam soils, short-season cotton varieties, narrow rows (0.52 m distance), high crop density (200,000 plants per hectare) and intensive use of chemical regulators to control excessive vegetative growth.

Besides the calibration and validation of AquaCrop, another purpose of the work was to analyze the effect on cotton yields of three irrigation scenarios, within the standard water delivery arrangement in the SRRD. In the analyzed climatic series, the yields varied from a minimum of 3.79 t ha^{-1} to a maximum of 5.52 t ha^{-1}. Considering both crop yields and water use, the recommended scheduling would be to give two irrigations, at 25 and 55 DAS, for an average rain season (447 mm during the crop cycle). In this scenario, the timing of irrigations is different to the traditionally performed by farmers, that usually irrigate at 55 DAS or at 55 and 85 DAS. This work shows the usefulness of combining the use of crop simulation models, field measurements and long-term weather series to analyze trends of crop yield and irrigation water use under different situations.

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Transparency of data

Data not available: The data set that supports the results of this study is not publicly available.

Author contribution statement

Angella G. A., Prieto Angueira S., Fereres E.: Conceived and designed the analysis.

Angella G. A., Prieto Angueira S., Prieto D.: Collected the data.

García-Vila M., Prieto D.: Contributed to data or analysis tools.

Angella G. A., Prieto Angueira S., Fereres E.: Performed the analysis.

Angella G. A., Fereres E.: Wrote the paper.

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