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Simulation of sugarbeet growth under different water regimes and nitrogen levels by aqua crop

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Abstract

Precise crop growth models are important tools in assessment the effects of water deficits on crop yield or productivity and predicting yields to optimize irrigation under limited available water for enhanced sustainability and profitable production. Food and Agricultural Organization (FAO) of United Nations addresses this need by providing a yield response to water simulation model (AquaCrop) with limited complexity. The objectives of this study were to evaluate the AquaCrop model for its ability to simulate sugarbeet (*Beta vulgaris* L.) performance under full and deficit water conditions and two nitrogen levels in a dry environment in center of Iran. The AquaCrop model was evaluated with experimental data collected during the field experiment conducted in Markazi province. The AquaCrop model was able to accurately simulate crop biomass, root yield and canopy cover, with normalized Root Mean Square Error (RMSE) less than 18% for non-water-stress or mild water stress condition. The most deviation in simulation of root yield was in treatment of highest water stress and low nitrogen level (I9N100). Canopy cover was simulated good enough in almost all of treatment but same trend as root yield observed. The ease of use of the AquaCrop model, the low requirement of input parameters and its sufficient degree of simulation accuracy make it a valuable tool for estimating crop productivity under rainfed conditions, supplementary and deficit irrigation and on-farm water management strategies for improving the efficiency of water use in agriculture.

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Introduction

Models are generally defined as simplification or abstraction of a real system (Loomis *et al.*, 1979). This is particularly the case for models of biological systems like crops, where the reality is composed of a vast number of components and processes interacting over a wide range of organizational levels (Sinclair and Seligman, 1996). Since the late 1960s, crop growth modeling has been evolving along with the progress of computer technology, supporting the simulation of plant physiological processes and crop growth and development. The evolution of the modeling efforts has been influenced by the changing goals, target users and policies over the years: from models with a strictly scientific insight at leaf and plant scale (explanatory models) to those focused on practical applications and impact of management practices ranging from a single crop to complex agriculturalsystems (Sinclair and Seligman, 2000; Boote *et al.*, 2003). The model presented in this study is a canopy-level and engineering type of model, mainly focused on simulating the attainable crop biomass and harvestable yield in response to the water available. The model focuses on water because it is a key driver of agricultural production and because recent growth in human population and increased industrializationand living standards around the world are demanding a greater share of our finite water resources, making water an increasingly critical factor limiting crop production. Additionally, the crop response to water deficit remains among the most difficult responses to capture in crop modeling, as water deficits vary in intensity, duration and time of occurrence (Hsiao, 1973; Hsiao *et al.*, 1976; Bradford and Hsiao, 1982). The FAO AquaCrop model predicts crop productivity, water requirement and water use efficiency under water-limiting conditions (Raes *et al.*, 2009). This model has been tested for maize (Hsiao *et al.*, 2009; Heng *et al.*, 2009), cotton (Farahani *et al.*, 2009; Garcia-Via *et al.*, 2009), sunflower (Todorovic *et al.*, 2009) and quinoa (Geerts *et al.*, 2009) under different environmental conditions. All of them have illustrated that the model could accurately simulate the crop biomass and yield as well as soil water dynamics under full and water deficit irrigation and soil fertility stress conditions. 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 calibrate and test AquaCrop for sugar beet under different irrigation and nitrogen level in the semiarid environment of central Iran.

Materials and methods

For assessment of AquaCrop model on sugarbeet (c.v. *Brigita*) under different water regimes and nitrogen levels in semi-arid Markazi province weather condition a factorial experiment carry out in form of randomized complete block design with two factor (irrigation and nitrogen) in four replication in a typical farm (33.52 N, 49.94 E, altitude 2065 m above sea level) in 2012. Experimental factors was three different irrigation period include 3 day (I3), 6 day (I6), 9 day (I9) irrigation period and two nitrogen level 100 (N100) and 200 (N200) kg/ha. Irrigation was the same for 70 days after sowing for all treatments. Nitrogen applied in two part (30 and 60 days after sowing) each time half of fertilizer. Each plot compose of six row of 10 m length with 0.5 m space between rows and 0.2 m space between plants in the row that result in 10 plant/m^2 density. Planting and harvest date was 12 June and 29 October respectively. Amount of irrigation was 20 mm each time and sprinkler method used. Seven sampling were done during growth period and each time biomass, root weight and canopy cover measured.

Weather and soil data

The weather data required by AquaCrop are the daily values of minimum and maximum air temperature, ETo and rainfall (Raes *et al.*, 2009, Steduto *et al.*, 2009). The standard procedure is to calculate ETo following the FAO Penman-Monteith equation (Allen *et al.*, 1998), which was done from daily maximum and minimum temperature, dew point, wind velocity at 2 m and solar radiation. The required input soil parameters for AquaCrop are the saturated hydraulic conductivity (K_{sat}), volumetric water content at saturation (θ_{sat}), field capacity (θ_{FC}) and permanent wilting point (θ_{PWP}). These parameters were derived from field measurements.

Model calibration

The model was calibrated for the full irrigation and high nitrogen treatment (3 day irrigation and 200 kg ha^{-1} nitrogen) and validated for five other treatments. The calibration was done through an iterative process using the measured crop growth variables, observed phonological stages; parameters estimated from available data and derived growing coefficients. The final phase of calibration consisted in the refinement of other parameters so that simulated values fit well with observed data. In fact, the parameters were changed manually around the default values until the best fitting with measured data was achieved. The main step in the calibration of AquaCrop was the determination of the crop WP coefficient, which was derived from the linear regression of the relationship between the aboveground biomass and the accumulated crop transpiration normalized for reference evapotranspiration. Crop transpiration was simulated directly by the model by using the measured weather, soil, irrigation and canopy cover data and thereafter it was estimated through an iterative procedure when other crop parameters were calibrated. Other crop input parameters included canopy growth, given as a percentage of canopy cover, yield formation duration, rooting depth growth, soil water extraction pattern, crop coefficients at full canopy, three water stress response functions (for leaf expansion growth, stomataclosure and early canopy senescence), aeration stress and HI adjustment functions.

Model evaluation

Evaluation is an important step of model verification. It involves a comparison between independent field measurements (data) and output created by the model. Dry biomass, root yield and canopy cover were considered in this study for model evaluation. The performance of the calibrated model was evaluated against the independent treatments that were not used for model calibration. Different statistic indices including coefficient of determination (r^2), absolute and normalized Root Mean Square Error (RMSE) and index of agreement (D-index) were employed for comparison of simulated against observed data. The normalized RMSE expressed in percent (Equation 2)), was calculated according to Loague and Green (1991):

$$\mathrm{RMSE} = \left[\sum_{i=1}^{n} \frac{(p_i - o_i)^2}{n}\right]^{0.5} \quad (1)$$

$$\mathrm{RMSE} = \left[\sum_{i=1}^{n} \frac{(p_i - o_i)^2}{n}\right]^{0.5} \times \frac{100}{M} \quad (2)$$

where, Pi and Oi refer to simulated and observed values of the study variables, respectively, e.g., biomass, root yield and canopy cover. M is the mean of the observed variable. Normalized RMSE gives a measure (%) of the relative difference of simulated versus observed data. The simulation is considered excellent with a normalized RMSE is less than 10%, good if the normalized RMSE is greater than 10% and less than 20%, fair if normalized RMSE is greater than 20 and less than 30% and poor if the normalized RMSE is greater than 30% (Jamieson *et al.*, 1991). The index of agreement (D-index) proposed by Willmott *et al.* (1985) was estimated (Equation (3)). According to the d-statistic, the closer the index value is to one, the better the agreement between the two variables that are being compared and vice versa:

$$d = 1 - \left[\frac{\sum_{i=1}^{n}(p_i^2 - o_i^2)}{\sum_{i=1}^{n}\left(|p_i'| + |o_i'|\right)^2}\right] \quad (3)$$

Where:

n = The number of observations

P_i = Predicted observation

O_i = A measured observation $P_i' = P_i - M$ and $O_i' = O_i - M$ (M is the mean of the observed variable)

Results

Crop input parameters used in the AquaCrop model were either calculated or obtained from Raes *et al.* (2011). Crop-specific but non-location-specific parameters for major agricultural crops including sugarbeet have been determined and validated in varying locations by the FAO and are provided as default values in the model. These parameters are referred to as "conservative" because they do not change with geographic location, management practices and time and they were determined with data from favourable and non-limiting conditions but remain applicable for stress conditions via their modulation by stress response functions (Steduto *et al.*, 2009; Raes *et al.*, 2009) (Table 1). The other parameters are cultivar specific or less conservative and are affected by the climate, field management or conditions in the soil profile and thus have to be provided by the user (user-specific) (Table 2). However, if not available, AquaCrop can estimate them (e.g., seeding date, plant density,). In this study, these parameters were determined from site-specific data. Calibrated parameters for fertility stress also presented in Table 3.

Table 1. Conservative parameters used to simulation runs (Raes *et al.*, 2011).

Parameter description	Value	Unit or meaning
Base temperature	5	ºC
Cut-off temperature	30	ºC
Canopy cover per seeding at 90% emergence (CC_o)	1	cm^2
Canopy Growth Coefficient (CGC)	0.0115	Increase in CC relative to existing CC per GDD
Crop coefficient for transpiration at CC = 100%	1.1	Full canopy transpiration relative to ETo
Decline in crop coefficient after reaching CC_x	0.15%	Decline per day due to leaf aging
Canopy Decline Coefficient (CDC) at senescence	0.004	Decrease in CC relative to CC per GDD
Water productivity	18	g (biomass) m^{-2}, function of atmospheric CO_2
Leaf growth threshold p-upper	0.25	As fraction of TAW, above this leaf growth is inhibited
Leaf growth threshold p-lower	0.7	Leaf growth stops completely as this p
Leaf growth stress coefficient curve shape	4	Highly convex curve
Stomatal conductance threshold p-upper	0.65	Above this stomata begin to close
Stomata stress coefficient curve shape	2.5	Highly convex curve
Senescence stress coefficient p-upper	0.75	Above this early canopy senescence begins
Senescence stress coefficient curve shape	2.5	Moderately convex cure

Table 2. Non-conservative parameters adjusted to simulate the growth of sugarbeet.

Parameter description	Value	Unit or meaning
Time from sowing to emergence	65	GDD
Maximum canopy cover (CC_x)	85%	Function of plant density
Time from sowing to start senescence	1845	GDD
Time from sowing to maturity	2150	GDD
Maximum effective rooting depth, Z_x	1	m
Minimum effective rooting depth, Z_n	0.3	m
Time from sowing to maximum rooting depth	920	GDD
Reference harvest index, HI_o	60%	Common for good condition

Biomass

The results show that the model performed very well for simulating Biomass (Fig. 1). The calculated RMSE and normalized RMSE were less than 517 kg ha^{-1} and 15% for all treatments (Table 4). The r^2 and D-index is higher than 99% for all of treatments. The model simulates the biomass in treatments with 9-day irrigation good and other treatments excellent. The graphs show some overestimation in final simulated value of biomass in almost all treatments.

Root yield

In treatments with 3 day and 6 day irrigation in both level of nitrogen model simulate the root yield well enough but in 9-day irrigation treatments the results is relatively poor. The highest RMSE and normalized RMSE belong to 9-day irrigation and 100 kg ha^{-1} nitrogen treatment with 641 kg ha^{-1} and 49% respectively. Thus in water stress condition model has less accuracy than normal condition particularly when there is both water and nutrient stress simultaneously. The model simulates biomass better than roots yield because root yield is the product of biomass and harvest index so the error in simulation of HI result in less accurate root yield.

Table 3. Fertility stress parameters as decrease in growth parameters.

Effects of soil fertility	Reduction
CCx reduction	45%
CGC reduction	25%
Average decline canopy cover	0.25 %/day
WP* reduction	30%

Canopy Cover

The model simulate canopy cover in most treatment with 3 and 6 day irrigation good but in treatment with 9 day irrigation the simulation is fair (Fig. 2) with RMSE and normalized RMSE less than 11 and 27% show relatively good fit in simulation of canopy cover (Table 4). In all treatment the model simulate maximum and final canopy cover well but deviation from observed values increase with increment of irrigation period and reduction of nitrogen fertilizer.

Table 4. Statistical indices derived for evaluating the performance of AquaCrop model in predicting root yield, biomass (t ha^{-1}) and canopy cover.

	Canopy Cover				Biomass				Root Yield			
Treatment	RMSE	$RMSE_{norm}$	r^2	d	RMSE	$RMSE_{norm}$	r^2	d	RMSE	$RMSE_{norm}$	r^2	d
I6N200	5	13	0.97	0.99	279	5	0.99	0.99	233	11	0.99	0.99
I9N200	11	33	0.89	0.99	508	12	0.99	0.99	417	26	0.99	0.99
I3N100	5	13	0.98	0.99	311	7	0.99	0.99	250	11	0.99	0.99
I6N100	6	18	0.97	0.99	328	8	0.99	0.99	156	9	0.99	0.99
I9N100	7	27	0.95	0.99	517	15	0.99	0.99	641	49	0.97	0.99

I6N200: 6 day irrigation and 200 kg ha^{-1} nitrogen, I9N200: 9 day irrigation and 200 kg ha^{-1} nitrogen, I3N100: 3 day irrigation and 100 kg ha^{-1} nitrogen, I6N100: 6 day irrigation and 100 kg ha^{-1} nitrogen, I9N100: 9 day irrigation and 100 kg ha^{-1} nitrogen, norm: Normalized

Todorovic *et al.* (2009) simulate Sunflower yield with RMSE less than 500 $kgha^{-1}$ for all scenarios of water availability in a Mediterranean environment but a general trend of underestimation of yield by AquaCrop was observed under severe water stress conditions. For evaluation of optimal planting date Araya *et al.* (2010) simulate Barley growth and yield in Ethiopia and they found that the model is valid to simulate the barley biomass and grain yield under various planting dates in the study site. Out of the tested planting dates, early sowing was found to maximize barley biomass, grain and water use efficiency. Barley showed slightly lower performance under mild water stress condition compared to full irrigation condition. However, the model has indicated the possibility of obtaining more biomass and grain yield from a relatively larger barley field under (deficit irrigation) mild stress condition. Garcia-villa *et al.* (2009) after calibration found AquaCrop predicted well the yield response trends of cotton to various levels of applied irrigation water under the conditions of southern Spain. Cotton is an indeterminate crop of complex behavior, and previous modeling efforts have produced models which are much more complex and sophisticated than AquaCrop. It is therefore encouraging that this model was capable of predicting cotton yield responses to water. Stricevic *et al.* (2010) use AquaCrop for simulation of maize, sugarbeet and sunflower under rainfed and supplementally irrigation in Serbia.

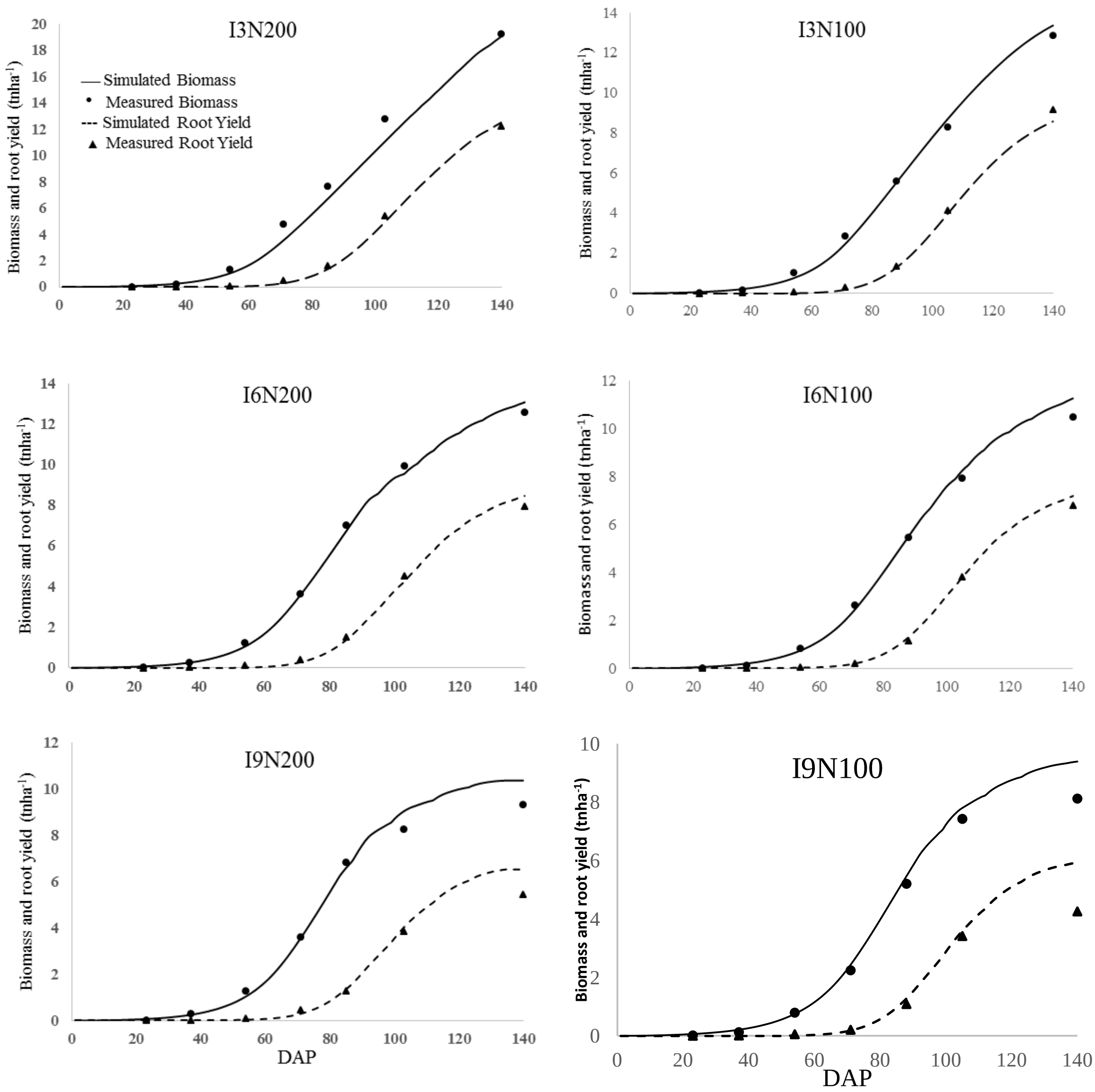

Fig. 1. Simulated versus measured Biomass and root yield of sugarbeet for all treatments I3N200: 3 day irrigation and 200 kg ha^{-1} nitrogen, I6N200: 6 day irrigation and 200 kg ha^{-1} nitrogen, I9N200: 9 day irrigation and 200 kg ha^{-1} nirogen, I3N100: 3 day irrigation and 100 kg ha^{-1} nitrogen, I6N100: 6 day irrigation and 100 kg ha^{-1} nitrogen, I9N100: 9 day irrigation and 100 kg ha^{-1} nitrogen.

Simulated maize yield levels exhibited the greatest departure from measured data under irrigation conditions (3.6 and 3.3% during an extremely dry and an extremely wet year, respectively). Simulated sunflower yield levels varied by less than 10% in 8 out of 10 comparisons. The most extreme variation was noted during the extremely wet year. The difference between simulated and measured values in the case of sugarbeet was from 10.2 to 12.2%. Large differences were noted only in two or three cases, under extreme climatic conditions. Statistical indicators – root mean square error (RMSE) and index of agreement (d) –

for all three crops suggested that the model can be used to highly reliably assess yield and irrigation water use efficiency. It is noteworthy that under wet conditions, the model suggested that sunflower and sugarbeet do not require irrigation, as confirmed by experimental research. These data are significant because they show that the AquaCrop model can be used in impartial decision-making and in the selection of crops to be given irrigation priority in areas where water resources are limited. Heng *et al.* (2009) evaluate the performance of AquaCrop model for maize using data from three studies performed under diverse environmental conditions: Bushland, Texas; Gainesville, Florida; and Zaragoza, Spain .The model performed satisfactorily for the growth of aboveground biomass, grain yield, and canopy cover (CC) in the non-water-stress treatments and mild stress conditions, but the results are relatively poor in simulating critical water-stress treatments, particularly when stress occurred during senescence. In south of Iran AquaCrop model was evaluated with experimental data collected during the three field experiments conducted in Ahvaz by Andarzian *et al.* (2011). The AquaCrop model was able to accurately simulate soil water content of root zone, crop biomass and grain yield, with normalized root mean square error (RMSE) less than 10%.

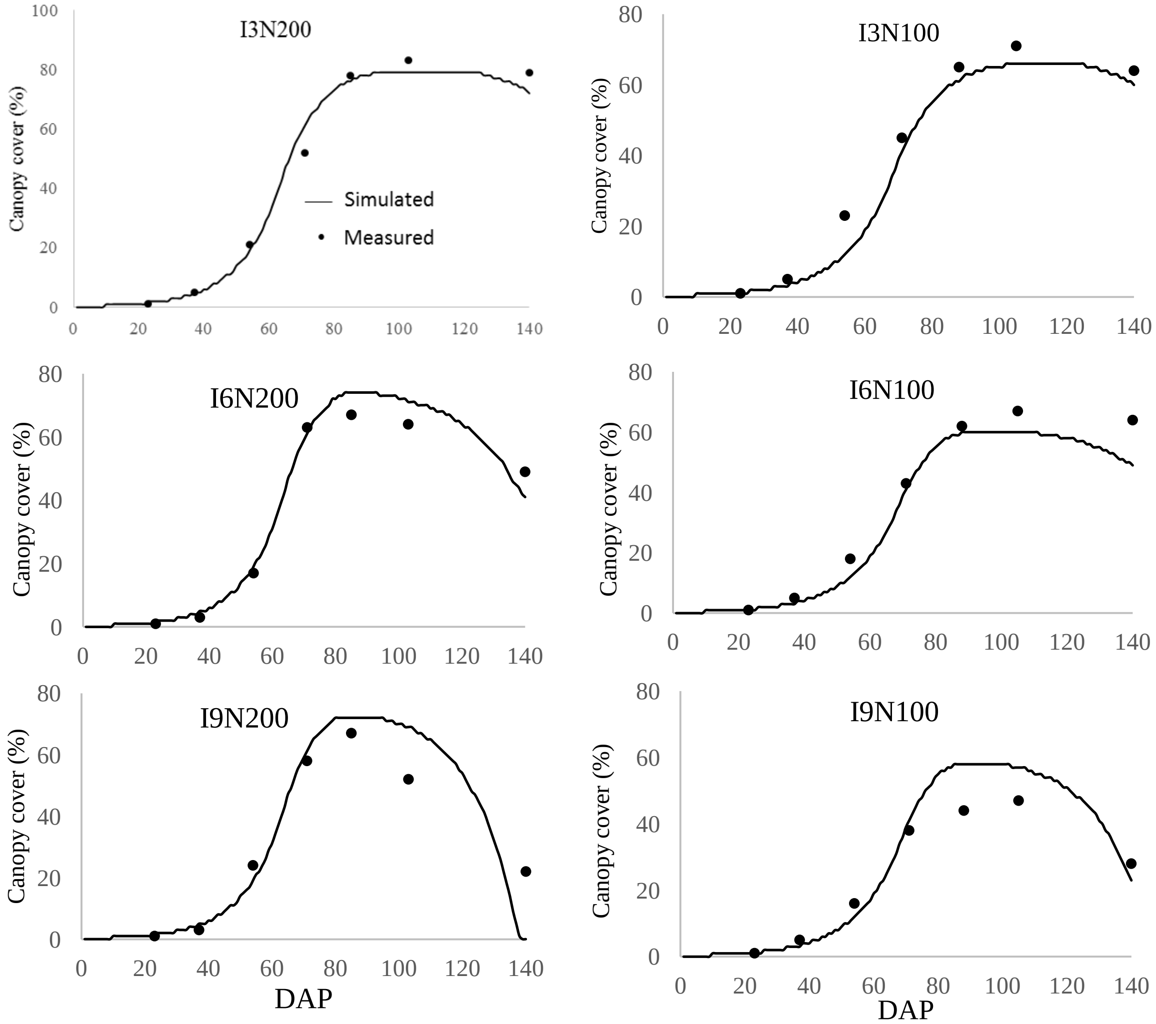

Fig. 2. Simulated versus measured canopy cover of sugarbeet for all treatments I3N200: 3 day irrigation and 200 kg ha^{-1} nitrogen, I6N200: 6 day irrigation and 200 kg ha^{-1} nitrogen, I9N200: 9 day irrigation and 200 kg ha^{-1} nitrogen, I3N100: 3 day irrigation and 100 kg ha^{-1} nitrogen, I6N100: 6 day irrigation and 100 kg ha^{-1} nitrogen, I9N100: 9 day irrigation and 100 kg ha^{-1} nitrogen.

Conclusion

AquaCrop obtained good agreement in simulating the CC, growth of biomass and root yield in the non-water-stress treatments and mild stress conditions. The model was less satisfactory in simulating severe water-stress treatments especially when nutrient stress occurred. The simplicity of AquaCrop due to its required minimum input data, which are readily available or can easily be collected, has made it user-friendly for users.

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