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Aquacrop model validation and calibration for full and deficit irrigation for sugar beets

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To meet the growing food demand of Egypt's expanding population, it is critical to increase crop water productivity and efficiency while minimizing harmful environmental effects in the face of growing water scarcity, declining water quality, and the uncertainties surrounding climate change. Increasing crop output depends on available water for agriculture. The purpose of this research is to boost irrigation water use efficiency by providing farmers with more information on when and how much to apply, which will maximise application efficiency and distribution uniformity through improved system management and the production of more food with less water. To reduce climate change and boost irrigation application efficiency, cor-water models are helpful tools for agricultural water management and effective irrigation scheduling. The aquacrop model was evaluated under irrigated sugar beet crops with different water regimes (100, 80 and 60% potential evapotranspiration (Etp)) throughout the winter growth season, under pressurized irrigation systems (surface drip-irrigation system and fixed-sprinkler irrigation). The crop water productivity for solid-set sprinkler irrigation and surface drip irrigation were about 14.1 and 15.1 g/m2 respectively with an average of about 14.6 g/m2. Model performance was assessed comparing the simulation results with measured data for canopy cover (CC) and biomass (B) and the final yield (Y).

Keywords: Egypt, Drip Irrigation, Sprinkler, Water Productivity, and Simulation Models

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INTRODUCTION

Given variability in the duration, time, and intensity of the water deficit, crop response to it continues to be one of the hardest reactions to accurately simulate through crop modeling, Molden *et al.,* (2001). These days, the competition for limited water is becoming more and more important. The supplies of good water quality are constant and possibilities for increasing it are limited due to the great challenge of the agricultural sector to produce more food with less water. Therefore, it is necessary to find ways to improve the efficiency of water application in agriculture. Pressurized irrigation is one of the most efficient irrigation systems used in agriculture with high-applied water-saving technology, Kemanian *et al.,* (2007).

Crop growth simulation models are also useful instruments for evaluating the consequences of water shortages and optimizing water use in restricted circumstances to boost crop yields. It is necessary to consider the efficient use of the available water given the detrimental consequences of climate change on agriculture, which include a decrease in agricultural water availability. For high-value crops that can be cultivated with irrigation, this is especially crucial, Hsiao, (2000) and Hsiao *et al.,* (2009).

The crop biomass and yield of sugar beet in response to different water application rates were simulated using an Aquacrop model. A minor sugar crop that is increasingly gaining attention in Egypt is sugar beet. It would also be easier to simulate and compute the projected yield and performance of the crop with all input data parameters for the Aquacrop model if the sugar beet model was calibrated under local climate conditions, (Steduto, 2003). To reduce the difference between the amount of sugar used and produced, increasing the area under cultivation for sugar crops and the amount of sugar produced per area are thought to be crucial national targets. In recent years, sugar beet has taken center stage in Egypt's crop rotation, serving as a winter crop on both rich and poor, saline, alkaline, and calcareous soils. This would assist farmers in anticipating the projected results from all model input data factors in advance. Thus, the primary goals of the research were to: Estimate the yield response factor under deficit irrigation in various pressurized irrigation systems; and Validate the Aquacrop model using irrigated sugar beet under full and deficit irrigation regimes.

MATERIALS AND METHODS

Aquacrop water productivity simulation model:

The model employs a green canopy cover in place of the Leaf Area Index; the canopy cover (CC) was determined by analyzing horizontal images taken during the growing season and measuring the height of sugar beet plants. In Aquacrop, inputs were saved in files related to climate, crop, soil type, management (irrigation), and initial soil water condition Raes *et al.,* (2009a). The following formula, provided by (Wu and Gitlin (1975), Abd-Elmabod et al., (2019a,b), was used to determine crop evapotranspirarion. Etc = ETo*K. Where ETo is the reference evapotranspiration (mm/day), Kc is the crop coefficient, and Etc is the evapotranspiration (mm/day). For sugar beet that was irrigated using surface drip and solid-set sprinkler irrigation, three water regime rates were used: 100%, 80%, and 60% of crop potential evapotranspiration.

The Central Laboratory for Agricultural Climate provided the formal data in Table 1, which displays the monthly meteorological data for the research area during the growth period. Air temperature (C^o), dew point temperature (C^o), wind speed (m/sec), and rainfall (mm) are examples of climatic factors. The evapotranspiration (ETo) was calculated with the use of the ETo calculator program depending on the Penman-Monteith equation (Version 3.2, September 2012), Raes *et al.,* (2009b).

Calibration and validation of the Aquacrop model

Figure 1 shows the Aquacrop flow chart for validation and calibration. To get the best possible agreement between the simulated and measured system variables, the model's input parameters are adjusted during the calibration process, (Shaw *et al.,* 2002). In this work, data from field experiments conducted during the 2017–2018 winter season were measured through independent sampling to calibrate the sugar beet Aquacrop model (version 6.1).

During calibration, some characteristics of the measured crops are evaluated (plant height, rootstock, time to reach maximum green canopy cover and physiological maturity). The green canopy cover was measured during the growing season through analysis of horizontal images based on sugar beet plant height.

The soil characteristics (soil texture of the study area, soil water content at the permanent wilting point, field capacity and saturation), field management (irrigation treatments) and meteorological data such as temperature, precipitation, ETo and atmospheric CO_2 for the experimental study area.

After the calibration process, the model was validated using the statistical indexes to evaluate the matching between the simulated and the measured data values. The following was used in this study: The correlation coefficient (r) is the squared value of the Pearson correlation coefficient (R^2). The range of the coefficient of determination is -1 to 1, where values near 1 signify a strong agreement, while in watershed simulation, values above 0.5 are often regarded as satisfactory (Moriasi *et al.,* 2007). If the simulated and measured values are zero or totally independent, that is, they are uncorrelated, Loague and Green (1991).

The root-mean-square deviation (RMSD)

One of the most widely used statistical indicators, the root-mean-square deviation (RMSD) represents the sample standard deviations of the differences between simulated values and measured values and measures the average magnitude of the difference between predictions and observations of a series of n pairs of data. It indicates bad model performance when it is negative infinity and favorable when it is positive infinity. Because it is scale-dependent, RMSD is a measure of accuracy that is used to compare prediction errors of various models on a given set of data rather than between data sets. Larger errors have a disproportionately big effect on RMSD because each error's effect on RMSD is proportional to the amount of the squared error, Pontius *et al.,* (2008), Willmott and Matsuura (2006) and Hyndman and Koehler (2006).

Experimental location and field layout

At the Agricultural Production and Research Station Experimental Farm, National Research Centre (NRC), El Nubaria region, Egypt (latitude 30.87N, longitude 30.17E, with altitude 20 m above sea level), a field experiment was conducted in the winter of 2017–2018. First planted on September 1, 2017, sugar beet (Frieda Dutch species) was harvested on April 10, 2018, using pressurized irrigation systems (surface drip and solid-set sprinkler irrigation) to validate the HydroCalc and Aquacrop models.

Irrigation system schedule and component:

The chemical characteristics of the irrigation water were determined by standard analytical techniques. To ascertain the physical and chemical properties, soil samples were taken at various layer depths (0~15, 15~30, 30~45, and 45~60 cm) in the soil profile. Each main plot was split into three subplots, each of which represented one of the three water treatments (representing 100%, 80%, and 60% of the crop potential evapotranspiration (ETp). The irrigation schedule was designed to meet agricultural water requirements by applying surface drip irrigation and metered solid-set sprinklers at two-day intervals. The rotation depends on a shocking stick, which is a kind of sprinkler that can control its rotation, and it has a nail to deflect the rush of the water path, Eldardiry *et al.,* (2015), and El-Hagary *et al.,* (2015).

Table 1. Average weather data in the study area.

Month	Tmax °C	Tmean °C	Tmin °C	Tdew °C	u(x) m/sec	Rain mm
Spt. 2017	31.50	25.18	19.62	2.08	0.38	0.00
Oct. 2017	28.35	21.88	16.44	5.72	0.45	0.00
Nov. 2017	23.90	17.22	12.14	0.48	0.22	1.89
Dec. 2017	18.45	11.49	6.25	0.64	0.35	2.12
Jan. 2018	17.83	11.36	6.33	0.00	0.45	2.79
Feb. 2018	19.65	12.91	7.42	0.03	0.09	1.60
Mar. 2018	22.11	15.81	10.67	0.00	0.62	1.97

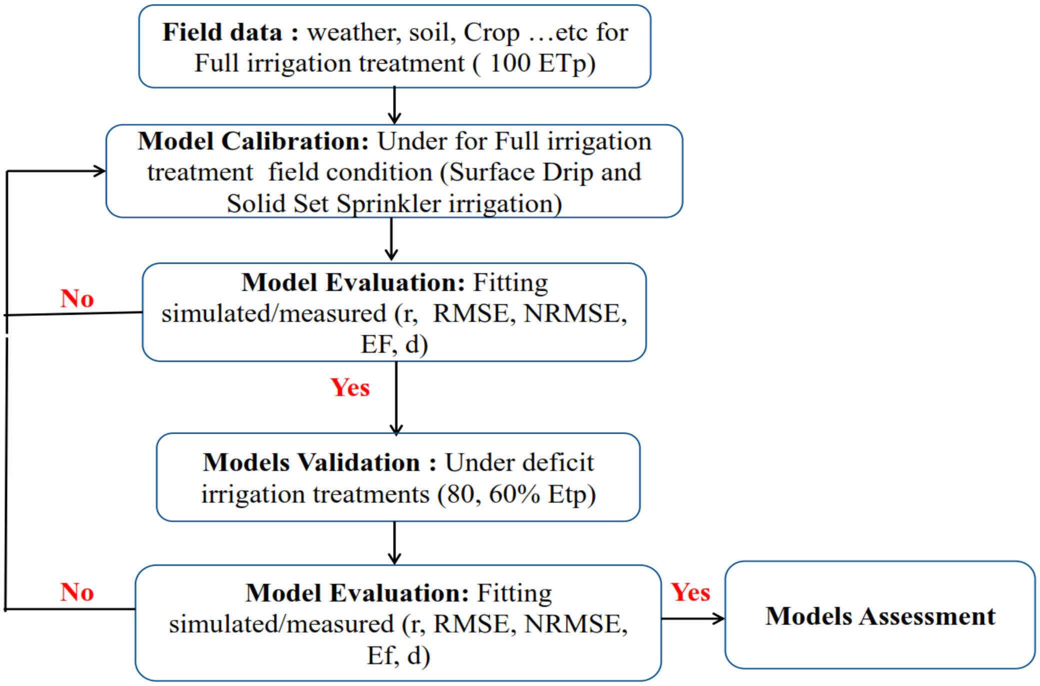

Figure 1. Aquacrop model flow chart processing

Sugar beet growth parameters and productivity measurements

Regardless of the experimental treatments, sugar beet (*Beta vulgaris L.)* was selected for this investigation. Every plot was given the standard and advised care for sugar beet growth as stated in the official agricultural bulletin guidelines. Sugar beet (Frieda Dutch species) was transplanted manually to each line at a 15 cm distance between plant pots. The experiment was cultivated for the growing season on 1st September 2017 and harvested on 10th April 2018. Before cultivation, the soil was plowed 3 perpendicular times at 15 cm depth, leveled and lined into, 100 cm distances apart to extend the lateral tubes of surface irrigation in each experimental plot. Always represented as a function of the crop coefficient, the sugar beet crop coefficient is dependent upon time and growth stage variations, weather changes, and evaporation-induced changes in soil moisture. Table 2 presents the crop coefficient for every growth stage through the growing season of sugar beet in the semi-arid region regarding FAO 56, Allen et al., (1960).

Following a month after planting, all measurements began in October 2107. Three plants that were representative of each plot were taken each month to measure the following growth characteristics: root diameter (cm), height (cm), number of leaves per plant (least one), fresh weight (g) of the top leaves per plant, dry weight (g) of the top leaves per plant, total fresh root weight (g/plant), and total fresh dry weight (g/plant). To achieve a constant weight, plant samples were oven-dried at 70°C using a digital balance with four decimal places. At harvest, a random sample from each plot was taken to determine the sugar beet productivity and juice quality characteristics:

1. Root weight (Kg).
2. Sucrose % was determined by using a saccharometer lead acetate extract of fresh moderated roots, according to Carruthers and Oldfield (1960).
3. Extractable sugar % = Sucrose % - [(0.343*(K + Na) + 0.094 α- amino N + 0.29] according to Reinefeld e*t al.,* 1974.
4. Juice purity% = (Extractable sugar%/sucrose percentage) *100.
5. Impurities% = [0.343*(K+Na)+0.094 α-amino N + 0.29].
6. White sugar yield (ton/ha) = root yield* (extractable sugar % / 100).
7. Root yield (ton/ha) = (root yield (kg/m2)*10000).
8. Crop Water Productivity (CWP): Crop Water productivity is an indicator of the effectiveness of using an irrigation water unit [41, 42].
9. Water productivity of white sugar yield was calculated using the following equation: CWP (kg/m^3) = Total white sugar yield (kg/ha)/(Total applied water amount (m^3/ha).

RESULTS AND DISCUSSION

Reference Evapotranspiration (ETo)

The data displayed in Figure 2 represented the daily reference evapotranspiration (ETo) for irrigated sugar beets from 1 September 2017 to 31 March 2018, which was computed using the ETo calculator application for daily meteorological data using the Penman-Monteith equation. About 2 mm/day/season was the average ETo.

Applied water requirements

The information in Table 3 illustrates the amount of water needed for irrigated sugar beets grown under surface drip and solid-set sprinkler systems with varying water application regimes (100%, 80%, and 60% from crop potential evapotranspiration) at each growth stage. The calculations were made using the crop coefficient factor (Kc) and reference evapotranspiration (ETo). Due to the high evapotranspiration, it is evident that the maximum amount of water applied was around (617 mm) under solid-set sprinkler irrigation, with more than (11%) of surface drip irrigation. The irrigation schedule was designed to meet agricultural water requirements by applying surface drip irrigation and metered solid-set sprinklers at two-day intervals. Due to the high evapotranspiration, it is evident that the maximum amount of water applied was around (617 mm) under solid-set sprinkler irrigation, with more than (11%) of surface drip irrigation. The irrigation schedule was designed to meet agricultural water requirements by applying surface drip irrigation and metered solid-set sprinklers at two-day intervals, Howell et al., 1995.

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Aquacrop calibration

Aquacrop calibration was done based on green canopy measurements and measured crop growth data for the irrigated sugar beet crop under both irrigation systems. The measured field data under full irrigation treatment were used to calibrate the model, while the remaining data under 80 % and 60 % from potential evapotranspiration were used to validate the model. For each of the simulation runs, the weather data, soil characteristics, canopy cover development, sowing date and planting density were entered as input. The plant density, measured maximum rooting depth, time of crop development and crop water productivity (CWP) were used for model calibration. Crop water productivity (CWP) was estimated by the relationship between biomass for sugar beet crop that was estimated from samples taken periodically from the crop through the growing season with simulated accumulated daily transpiration (Tr) and reference evapotranspiration (ETo) Steduto *et al.,* (2007) shown in Figure 3. Crop water productivity for solid-set sprinkler irrigation and surface drip irrigation were about 14.1 and 15.1 g/m^2 respectively with an average of about 14.6 g/m^2. Model performance was assessed comparing the simulation results with the measured data for canopy cover (CC) and biomass (B) and the final yield (Y).

Green canopy cover (CC)

The results on green canopy cover analysis for both irrigation systems are presented in Figure 4 under full irrigation requirement (100 % Etp). As shown, the maximum simulated canopy cover was about 85%, and there was a little bit of variation in the canopy cover between measured (observed) and simulated in the two irrigation systems, but it was clear in solid-set sprinkler irrigation (S100) the maximum measured canopy cover was about 75%, while it was 80% under surface drip irrigation (D100).

Table 2. Crop factor (Kc) of sugar beets in semi-arid regions

Growth stage	**Initial**	**Crop development**	**Mid season**	**Late season**
Duration	1 up to 35	36-95	96-165	166-210
Total days	35	60	70	45
Kc	0.35	1.2	1.2>Kc<0.7	0.5

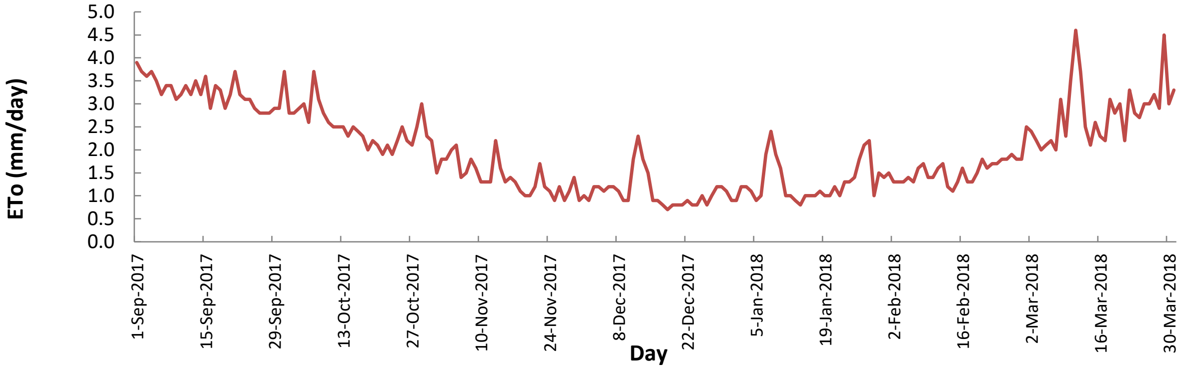

Figure 2. The daily reference Evapotranspiration (ETo)

Table 3. Applied water requirements under surface drip and solid-set sprinkler irrigation

Days from planting	**Growing stage**	**Amount of applied water (mm)**					
		100%		**80%**		**60%**	
		Sprinkler	**Drip**	**Sprinkler**	**Drip**	**Sprinkler**	**Drip**
1	Initial	68.71	60.63	54.97	47.50	41.23	36.38
35							
36	Development	273.60	244.85	218.88	191.13	164.16	144.85
95							
96	Mid-season	176.26	155.52	141.01	124.52	105.75	93.31
165							
166	Late-season	98.40	86.82	78.72	68.66	59.04	52.09
210							
Season total		616.97	616.97	547.82	493.58	431.81	370.18
Water saved (%)		0.00	0.00	11.21	20.00	30.01	40.00

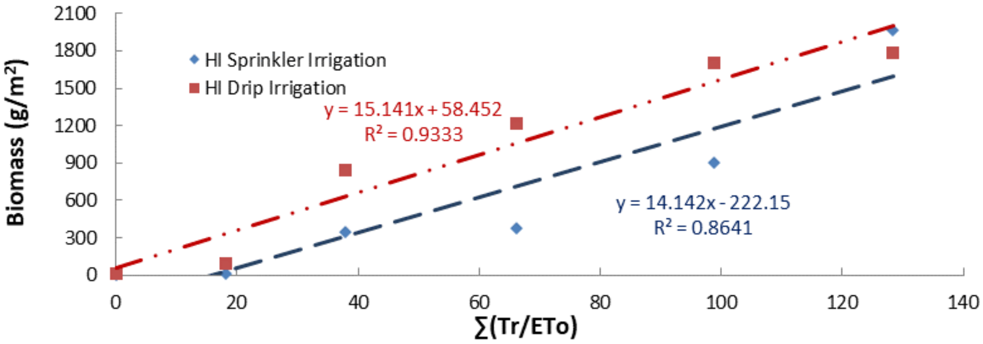

Figure 3. Determination of sugar beet crop water

Table 4. Statistical indicators for canopy cover and biomass for full irrigation.

Statistical Indicator	**Canopy Cover S 100**	**Biomass S 100**	**Canopy Cover D 100**	**Biomass D 100**
Pearson Correlation Coefficient (r)	0.99***	0.99***	0.98***	0.99***
Root means square error (RMSE) (ton/ha)	11.70*	1.30*	11.10*	1.45*
Normalized root mean square error CV(RMSE) %	23.80*	20.20*	20.50*	20.30*

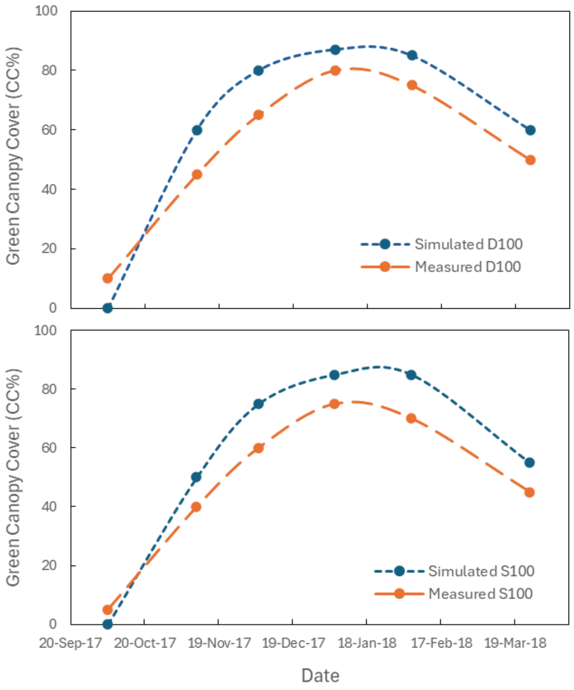

Figure 4. Measured and simulated green canopy cover (CC) under full irrigation.

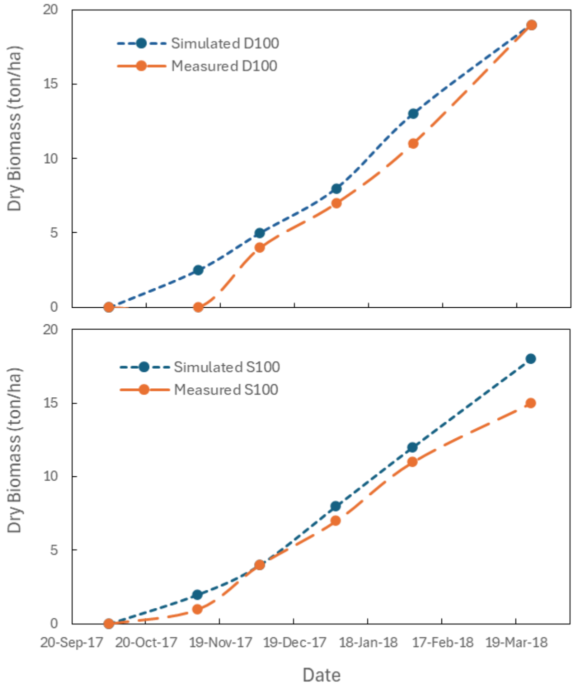

Figure 5. Measured and simulated dry biomass (B) under full irrigation

Dry Biomass (B) and Yield (Y)

The results of dry biomass (B) analysis for both irrigation systems are presented in Figure 5 under full irrigation requirement (100 % Etp). As shown, there was a little bit of difference During calibration, some characteristics of the measured crops were evaluated (plant height, rootstock, time to reach maximum green canopy cover, and physiological maturity).in the dry biomass between measured and simulated under surface drip irrigation system as the simulated dry biomass was greater than the measured, but there was no variation under solid-set sprinkler irrigation.

The maximum measured and simulated dry biomass yield for sugar beet was about 19.35 and 19.23 ton/ha, respectively, at harvest under surface drip irrigation, while it was about 14.56 and 17.33 ton/ ha under solid-set sprinkler irrigation. The dry yield response to applied water during the growing season is presented in Figure 6. The results obtained showed an increase in the dry yield with an increase in water applied under both irrigation systems.

When compared to the simulated green canopy cover, the deficit-irrigated treatments with 60% of crop potential evapotranspiration yielded lower values for green canopy cover. Because the crop's water requirements were not being met by the available water supply, the crop's demand for water increased as it grew, making the model's predictions less accurate. Nonetheless, the Aquacrop model's 80% treatment performed well in predicting crop growth, particularly in the middle and late seasons. The results of canopy cover model validation are acceptable according to the statistical indicators as shown in Table 5, but the modelling of 60% treatments was less satisfactory compared to 80% treatments, which showed better performance.

Simulated and measured dry biomass and yield comparison

The results of the comparison of simulated and measured dry biomass under both irrigations with water regimes (80% and 60% of crop potential evapotranspiration water requirements) are shown in Figure 8. The results showed variation between simulated and measured biomass under both irrigation systems; also, there was no variation between measured and simulated data under full irrigation as mentioned before, but under deficit irrigation (80% and 60% from Etp), especially under 60% treatment, the model showed over simulated dry biomass, Howell, 2001. Simulated and measured data showed that the dry yield of drip- irrigated sugar beet with 80% of crop potential evapotranspiration nearly matched with the yield of solid-set sprinkler- irrigated sugar beet with 100% was no variation between measured and simulated data under full and deficit irrigation for both irrigation systems.

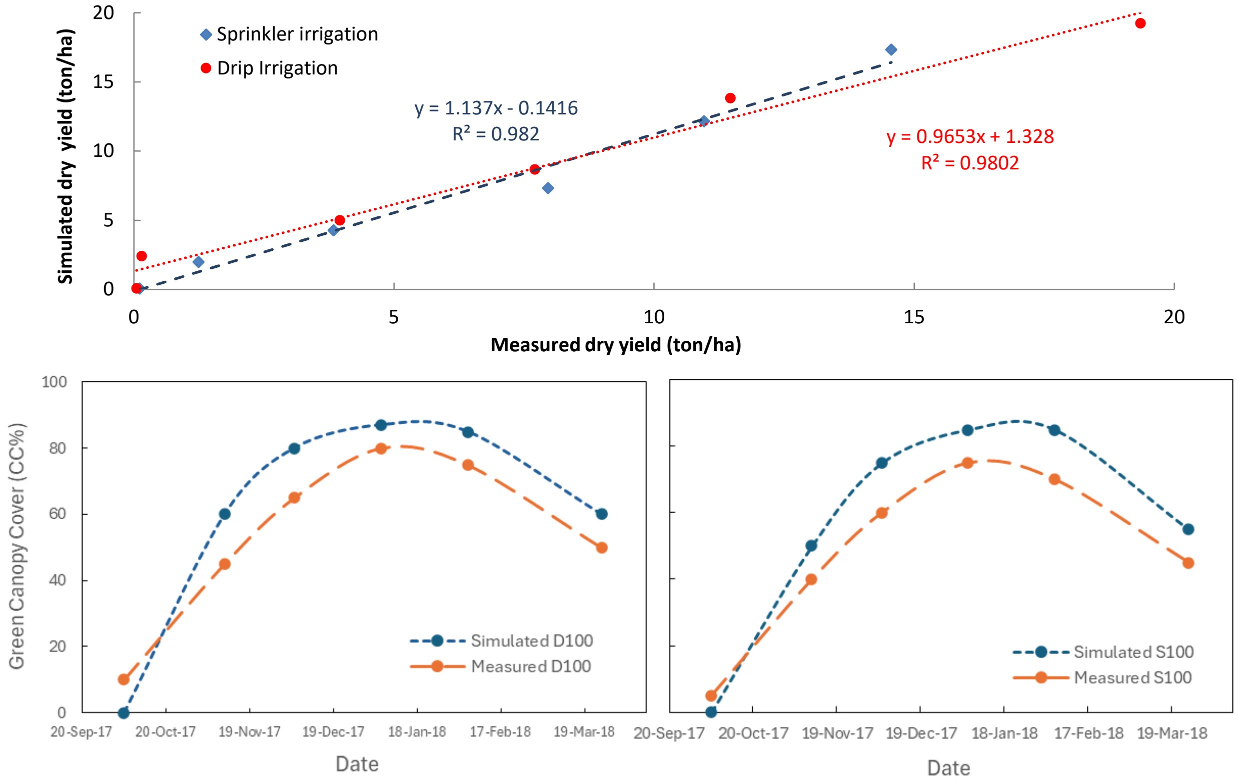

Figure 6. Measured and simulated dry yield under full irrigation

The statistical indicators for different water regimes (80% and 60%) are presented in Table 6. The results obtained from the model showed that the validation of Aquacrop is acceptable according to the statistical indicators for 80% treatment under both irrigation systems. The simulated dry biomass closely matched the real values, with Pearson Correlation Coefficients (r) of approximately 0.97 and 0.98 for solid-set sprinkler and surface drip irrigation, respectively. These coefficients indicate a highly substantial correlation with the other variables, Mansour *el al.,* (2019 a,b,c,d,e,f), Hellal et al., (2019), Mansour *et al.,* (2015 a, b, c, d), (2016a, b).

The modelling of 60% treatment was less satisfying. However, the Pearson Correlation Coefficient (r) was about 0.99 and 0.98 for sprinkler and surface drip irrigation, respectively, but the other indicators showed non-significance as the simulated dry biomass was higher than the measured under solid-set sprinkler irrigation with 60% and the opposite in the surface drip irrigation treatment. This may be attributed to the fact that 80% of treatment did not experience severe water stress to affect biomass accumulation. However, 60 % of treatment-experienced water stress throughout the growing season.

Also, the simulated crop water productivity for dry yield by the Aquacrop model was slightly higher than the measured values for all irrigation treatments, especially under deficit irrigation conditions and showed increases in crop water productivity with increasing water deficit. The maximum crop water productivity was obtained under surface drip irrigation, especially under 80% treatment r (11.02 kg/m^3), while productivity was less under solid-set sprinkler irrigation at 7.68, 6.89 and 7.44 under water regimes 100%, 80% and 60%, respectively, Mansour (2012), Mansour and Aljughaiman (2012), Mansour (2015a) and Mansour, (2015b).

Effect of water stress on sugar beet yield component

The findings demonstrated how a water deficit during the winter of 2017–2018 affected certain sugar beet characteristics and yield when surface drip and solid-set sprinkler irrigation systems were used. consisting of the amount of refined sugar produced, sucrose content, the average weight of the roots, and the proportion of impurities present. Increased water stress from 100% to 60% of the crop water requirement under both irrigation methods had a substantial impact on sugar beet productivity and white sugar output.

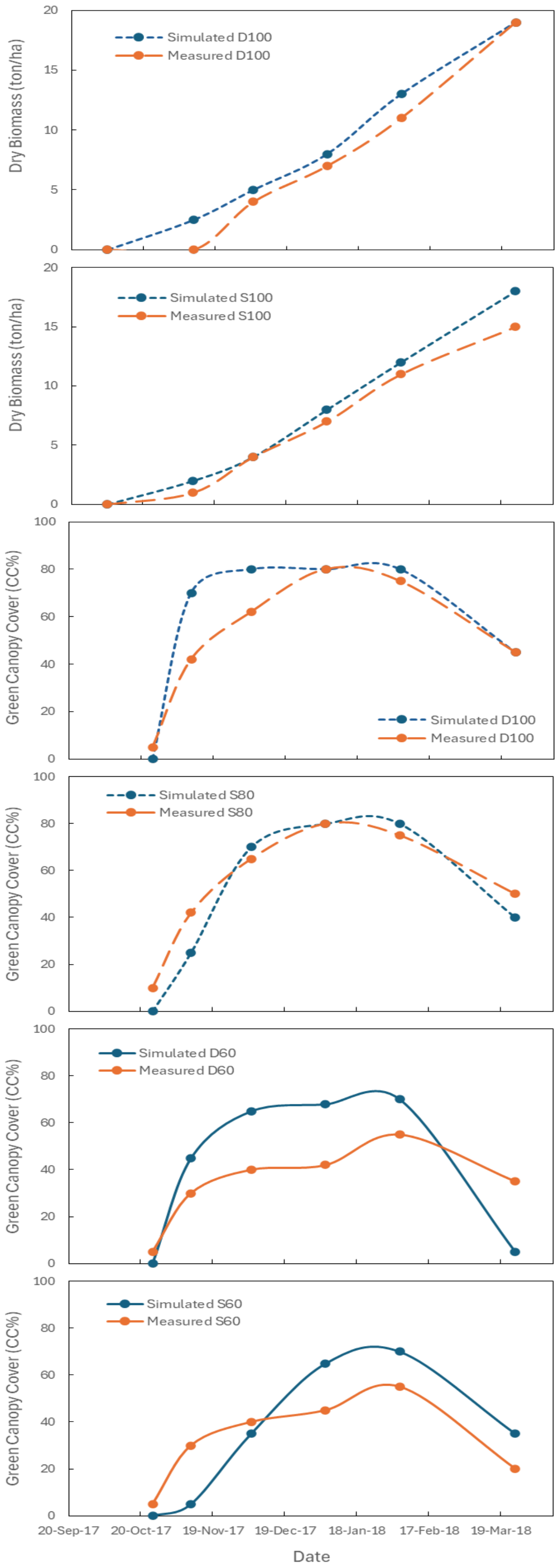

Figure 7. Measured and simulated green canopy cover with 80% and 60% regimes.

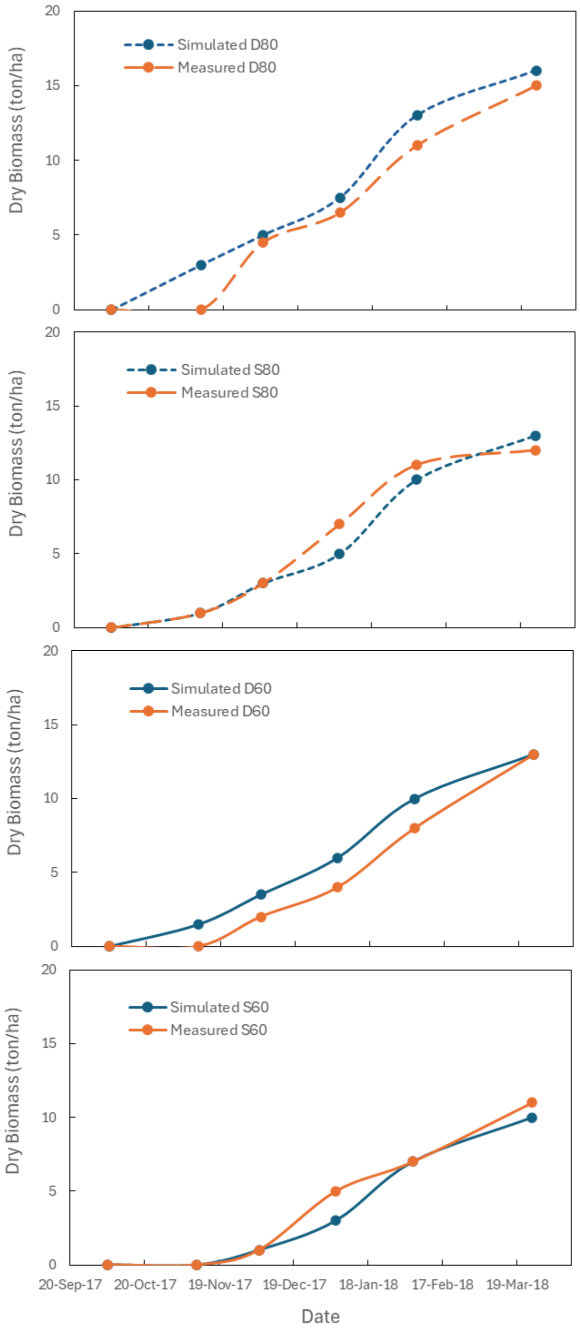

Figure 8. Measured and simulated dry biomass with 80% and 60% regimes.

Based on seasonally averaged data, the maximum root yield values (54.36 and 47.38 tons/ha) under surface drip and solid-set sprinkler irrigation, respectively, were obtained when 100% of the Etp was applied. Eighty percent of the sugar beet plants from Etp that were surface drip-irrigated showed the greatest percentages of purity (84.66%) and sucrose (19.90%). Furthermore, there was no discernible difference between crop Etp values of 60% and 80%.

Table 5. Statistical indicators for canopy cover under deficit irrigation

Statistical Indicator	Canopy Cover S 80	Canopy Cover S 60	Canopy Cover D 80	Canopy Cover D 60
Pearson Correlation Coefficient (r)	0.98***	0.86**	0.93***	0.80*
Root means square error (RMSE) (ton/ha)	9.80*	16.00***	12.20*	20.40**
Normalized root means square error CV(RMSE) %	18.10*	45.70***	22.60*	58.30**

Table 7. Cultivated area and productivity using the same water amount of surface drip and solid-set sprinkle full irrigation systems

	S100	S80	S60	D100	D80	D60
Water Applied amount (mm)	617					
Total area cultivated (ha)	1.00	1.25	1.76	10.25	11.43	10.79
Total White sugar yield (ton)	7.19	6.96	6.96	1.13	1.42	1.89

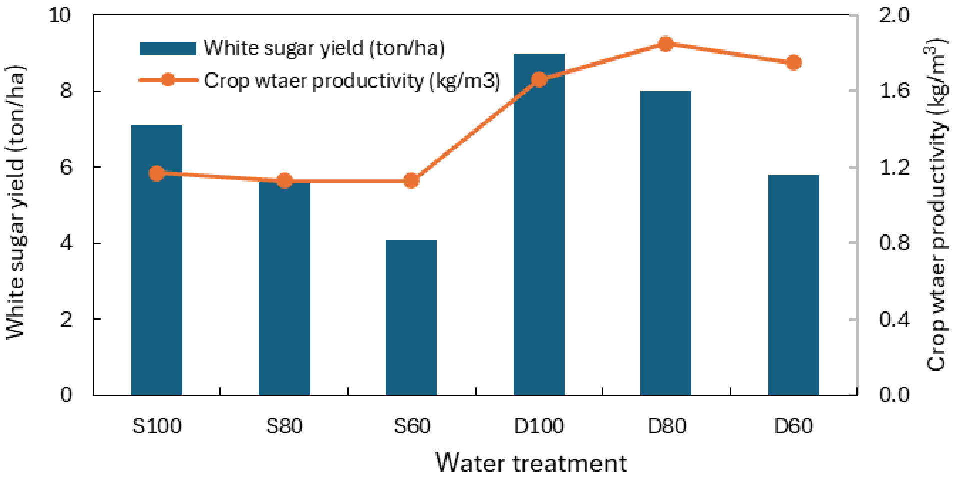

Figure 9. White sugar yield and crop water productivity under different irrigation systems regimes.

On the other hand, juice quality attribute values vary significantly between the three irrigation regimes under solid-set sprinkler irrigation. When comparing the yield of white sugar beet to all irrigation treatments, the highest crop water productivity was less than 80% of Etp, or 1.85 kg/m^3, as Figure 9 illustrates.

As the water deficit increased from 100% to 60% Etp, crop water productivity increased under both irrigation systems at a decreasing rate of water application. Furthermore, this indicates that there is a good chance of increasing the yield of white sugar by cultivating a larger area under solid-set sprinkle full irrigation (617 mm) with the same water application volume as indicated in Table 7. The reduction in white sugar yield under surface drip and solid-set sprinkler irrigation systems was 37% and 42 %, respectively, Mansour and El-Melhem, (2015) and Mansour and Aljughaiman, (2015).

CONCLUSIONS

When there is a water deficit, the calibrated Aquacrop model simulates sugar beet crop factors with good accuracy. The model is capable of accurately modeling sugar beet water productivity and crop output under various irrigation schedules and climate variations in the recently developed northern reclamation region of Egypt; nevertheless, this model becomes unsatisfactory for high water stress (intensive water stress). Thus, project managers, consultants, irrigation engineers, and farmers in the agriculture sector can use this model as a decision support tool to increase water productivity. To put it another way, this model can be used to predict how water management practices, such as deficit irrigation for other crops, and climate change scenarios affect yield and water unit productivity. Additionally, the yields of white sugar beet and roots obtained under surface drip irrigation systems, which were 80% and 8.05 tons/ha, respectively, of crop potential evapotranspiration, matched the yields of sugar beet planted under solid-set sprinkler irrigation, which was 100% of crop potential evapotranspiration, 37.39 tons/ha, and 7.19 tons/ha, respectively. This may was accomplished with a 30% water savings during this process. The findings demonstrate that increasing the amount of water applied from 60% to 100% significantly increased productivity and the output of white sugar. Additionally, the characteristics of sugar beets such as its sucrose content, purity, and percentage of extractable sugar rose as the water deficit increased.

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