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Response of Spring Wheat (*Triticum aestivum*) to Deficit Irrigation Management under the Semi-Arid Environment of Egypt: Field and Modeling Study

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Abstract: In many areas of the world, water shortages prevail and threaten food production. Deficit irrigation was commonly investigated in dry areas as a precious and sustainable production approach. Using the CropSyst model to simulate the effects of different deficit irrigation treatments could help draw conclusions and save time, effort, and money. Therefore, the aims of this research were (i) to calibrate and validate the CropSyst model for wheat under different sustained and phenological stage-based deficit irrigation treatments, (ii) to simulate the impacts of the latter treatments on limiting wheat yield reduction. Two field experiments were conducted in Nubaria (Egypt), representing an arid environment. They included seven irrigation treatments: (1) 100%, (2) 75%, or (3) 50% of crop evapotranspiration (ET_c) during the whole crop cycle; (4) 50% ET_c at tillering only, or (5) at booting only, or (6) at grain filling only, or (7) at both tillering and grain filling, with the replenishment of 100% ET_c to the treatments (4) to (7) in the remaining phenological stages. The results revealed that phenological stage-based deficit irrigation of wheat resulted in lower yield reduction compared to sustained deficit irrigation treatments, with a 6% yield reduction when 50% ET_c was applied at the booting stage. Wheat yield loss was reduced to 4 or 6% when 95 or 90% of ET_c were applied, respectively. The CropSyst model accurately simulated wheat grain and total dry matter under deficit irrigation with low RMSE value. In conclusion, the CropSyst model can be reliably used for evaluating the strategy of planned deficit irrigation management in terms of wheat production under the arid environment.

Keywords: CropSyst model; deficit irrigation; arid environment; wheat irrigation

1. Introduction

Freshwater resources are under pressure to meet the increasing food demand for the ever-increasing population. Globally, agriculture is the most consuming sector as irrigation uses about 70% of freshwater resources. Under water-stressed conditions, farmers cannot irrigate their cultivated areas with full crop water requirements. Under the latter circumstances, the growing plants suffer from water stress, negatively affecting growth and yield [1–3].

To reduce yield losses and use water more efficiently, the deficit irrigation can be practiced to irrigate a crop with less water than the total evapotranspiration [4–6]. There are several basic recommended strategies of deficit irrigation, which could minimize yield losses and save irrigation water at the same time. One of the strategy is sustained deficit irrigation, in which a reduced amount of irrigation is supplied during all the growing season [7]. The phenological stage-based deficit irrigation is a regulated deficit irrigation strategy [8], whose major principle is that plant's response to regulated deficit irrigation varies with the growth stage, and applying less water during non-critical stages causes no or low yield losses [9]. It was reported that a stage-based deficit irrigation approach could cause an insignificant negative impact on crop productivity [10].

In Egypt, irrigation land is the primary contributor to food production. Surface irrigation prevails in the Nile Delta and Valley, where it absorbs about 85% of Egypt's freshwater supplies [11]. For economical and managerial purposes, surface irrigation has been supplemented by sprinkling or drip in certain regions. Another common belief is that the only irrigation method that guarantees efficient water savings is drip irrigation, which is real; however irrigation systems must be well built and preferably run for drip irrigation. The production and conservation of water-saving equipment dedicated to crops, soil, water quality, and environmental conditions are necessary for sustainable agriculture. However, the productivity of surface irrigation is limited (about 60 percent), which means that the groundwater losses of this useful resource are high [12].

The reactions of crops to irrigation water rely on water application timetables. Farmers have already recognized this and have built sufficient expertise to irrigate their required land [13] based on the irrigation scheduling as a crucial decision. The system of irrigation involves how the optimal depth of the water is applied to the field. The crop development, its susceptibility to water stress, the ambient temperature, and the supply of water in the soil should be considered to decide when irrigation is to be applied or, in other words, the recurrence of irrigation. However, this frequency depends on the technique of irrigation, i.e., the water depths usually associated with the on-farm irrigation scheme. Thus, both method of irrigation and the scheduling of irrigation are interrelated.

Researchers have recently investigated new irrigation methods, structures, and techniques to increase water productivity (WP). One of the most promising ways to improve irrigation productivity is the implementation of regulated deficit irrigation strategies. Deficit irrigation is a way to optimize WP for higher yields per unit of irrigation water supplied [14]. In this regard, the introduction of deficit irrigation in Egypt may be a successful means of reducing Egypt's water shortage [15].

Wheat (*Triticum aestivum* L.) is an important crop in Egypt, characterized by sensitivity to water stress. There is a concern that the application of deficit irrigation to wheat might decrease the yield, though saving irrigation water, but Noreldin et al. [16] suggested that the application of deficit irrigation to wheat grown in sandy soil reduced the applied irrigation water by 25% and 20% under drip and sprinkler systems, respectively, and resulted in 20% and 18% yield losses, respectively. In Egypt, Abdrabbo et al. [17] indicated that saving 20% of the applied water to wheat grown in clay soil under drip irrigation resulted in 8% yield drop. Karrou et al. [18] revealed that the application of 78% of full irrigation to wheat grown under surface irrigation caused a 15% yield loss.

The use of calibrated and validated crop simulation models has many advantages in crop production. Quantitative analysis of “what if” scenarios of cropping systems, water, and fertilizer management as well as the impact of climate changes, can be carried out without the need for extensive field trials. Models can also be used in optimizing current management [19,20]. Van Keulen [21] stated that the use of crop simulation models could identify knowledge gaps and the most influential parameters of a system.

One of the most important crop simulation models is the CropSyst model [22], which simulates the crop growth and yield of a single crop or crop rotations and estimates the environmental impact (e.g., the effect of weather), soil, and management practices [23]. In the present study, the CropSyst model has been selected to study the effect of different

deficit irrigation treatments on wheat crop. Therefore, the objectives of this study were: (i) To calibrate and validate the CropSyst model for wheat under different water stress and phenological stage-based deficit irrigation treatments and (ii) to simulate the effects of sustained deficit irrigation treatments on wheat crop yield.

2. Materials and Methods

2.1. Experimental Procedures

Two field experiments were conducted during two successive growing seasons in 2010/11 and 2011/12 at the Nubaria Agricultural Research Station, North Tahrir, Egypt (30°54'21" N 29°57'24" E). The experimental area has an arid climate with cool winters and hot, dry summers. The data of average daily temperature and relative humidity, were obtained from the weather station located at the experimental area and are shown in Figure 1.

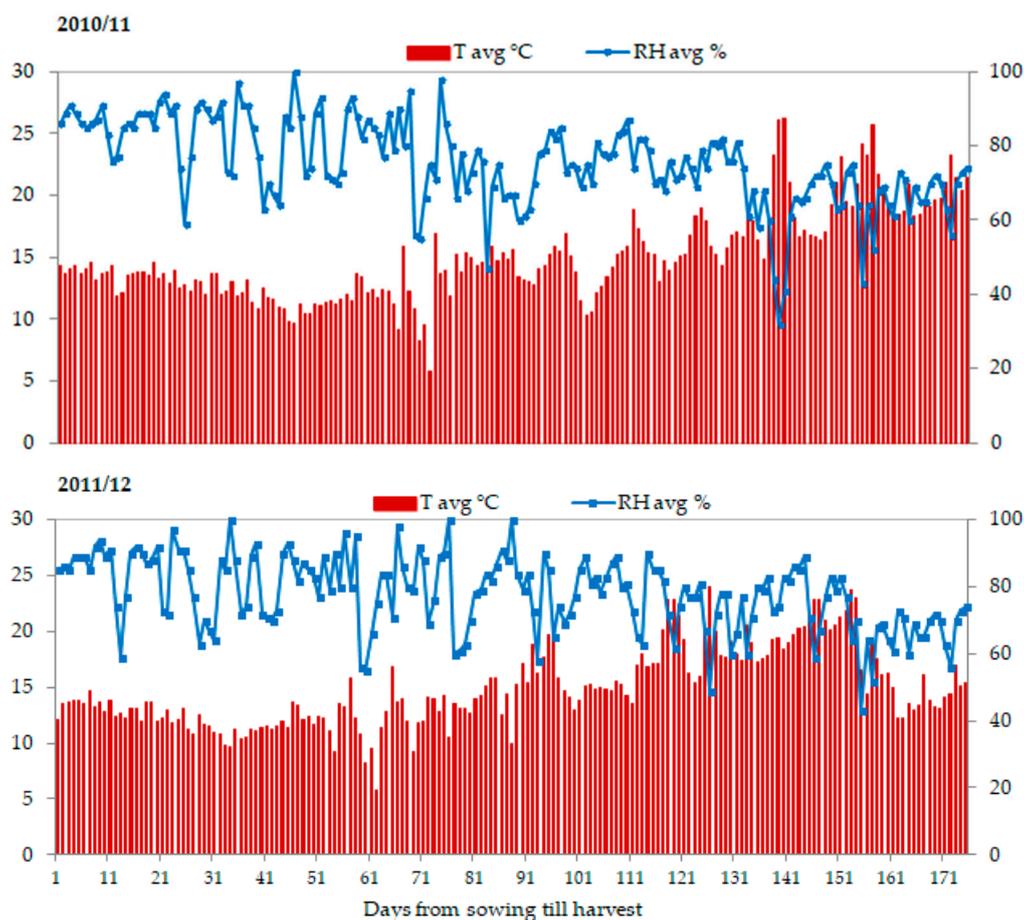


Figure 1. The data of average temperature, and relative humidity obtained from the weather station installed at the Nubaria Agricultural Research Station in seasons 2010/11 and 2011/12.

The soil of the experimental site is classified as sandy-loam soil. The experimental soil's physical and chemical properties are shown in Tables 1–3. The experimental field was plowed before planting, and a combined driller that facilitated the simultaneous application of fertilizer and seeds was used. The irrigation water was obtained from an irrigation channel near the experimental area, and its chemical characteristics are shown in Table 4.

Table 1. Main physical properties of soil at the experimental site.

Soil Depth (cm)	Bulk Density (Mg m ⁻³)	Hydraulic Conductivity (m s ⁻¹)	Particle Size (%)			Texture Class
			Sand	Silt	Clay	
0–15	1.35	5.4×10^{-6}	58.9	24.2	16.9	Sandy loam
15–30	1.37	4.9×10^{-6}	60.3	24.5	15.2	Sandy loam
30–45	1.45	5.8×10^{-6}	56.7	26.1	17.2	Sandy loam

Table 2. Chemical properties of soil at the experimental site.

Soil Depth (cm)	pH (1:2.5)	EC (dS m ⁻¹)	CEC (cmol kg ⁻¹)	CaCO ₃ (%)	OM (%)
0–15	8.5	3.86	14	25.9	0.12
15–30	8.3	4.89	20	24.9	0.24
30–45	8.2	5.37	17	26.7	0.26

Table 3. Concentration of cations and anions of soil at the experimental site.

Soil Depth (cm)	Soluble Cations (cmol m ⁻³)				Soluble Anions (cmol m ⁻³)			
	Ca	Mg	Na	K	CO ₃	HCO ₃	Cl	SO ₄
0–15	20.0	13.0	4.8	0.9	–	10.0	25.0	3.6
15–30	9.6	5.1	29.8	5.2	–	11.1	30.1	7.7
30–45	29.7	11.5	38.0	6.4	–	20.0	35.0	28.7

Table 4. Chemical characteristics of irrigation water used.

SAR%	Cations and Anions (meq L ⁻¹)								EC (dS m ⁻¹)	pH
	Anions				Cations					
	SO ₄ ²⁻	Cl ⁻	HCO ₃ ⁻	CO ₃ ²⁻	K ⁺	Na ⁺	Mg ²⁺	Ca ²⁺		
2.8	1.3	2.7	0.1	–	0.2	2.4	0.5	1.0	0.41	7.35

Wheat (*Triticum aestivum* L.) cultivar “Sakha 93” was sown on 29 November 2010 and 11 December 2011, for the two successive growing seasons and harvested on 22 May 2011 and 12 May 2012, respectively. Seventy kg ha⁻¹ of wheat seeds were sown, and the fertilizer applications were based on soil analysis recommendations. All plots received the same amount of fertilizers, i.e., 285 kg N ha⁻¹ as ammonium nitrate (33.5% N), 70 kg P₂O₅ ha⁻¹ as superphosphate (15.5% P₂O₅) and 115 kg K₂O ha⁻¹ as potassium sulfate (48% K₂O) during the growing season. All other agricultural practices for wheat crop production were carried out according to the recommendations of the Egypt Ministry of Agriculture and Land Reclamation.

The experimental layout was a randomized complete block design with four replicates that included seven surface irrigation treatments, namely: T1, 100% of crop evapotranspiration (ETc) throughout the growing season (control treatment); T2, 75% ETc throughout the growing season; T3, 50% ETc throughout the growing season (water stress treatment); T4, 50% ETc at tillering stage only + 100% ETc during the other growth stages; T5, 50% ETc at booting only + 100% ETc during the other growth stages; T6, 50% ETc at grain filling stage only + 100% ETc during the other growth stages; and T7, 50% ETc at tillering and grain filling stages only + 100% ETc during the other growth stages (phenological stage based deficit irrigation treatments).

2.2. Irrigation Water Amounts

Estimating crop evapotranspiration (ETc) or irrigation amounts under standard conditions was done as follows:

$$ETc = ETo \times Kc \quad (1)$$

where:

ETc = Crop evapotranspiration [mm day⁻¹]

ETo = Reference crop evapotranspiration [mm day⁻¹]

Kc = Crop coefficient

ETo was calculated using the Penman–Monteith equation [24]. The equation uses daily averages of the standard meteorological data of solar radiation (sunshine), air temperature (maximum and minimum), relative humidity, and wind speed calculated from daily measurements. The percentage of soil moisture content was measured gravimetrically. The value of the crop coefficient (Kc) of wheat was obtained according to Allen et al. [24].

The amount of irrigation water required was calculated according to the following equation:

$$AW = \frac{ETc}{Ea \times (1 - LR)} \quad (2)$$

where:

AW = applied irrigation water depth [mm day⁻¹].

Ea = application efficiency equals 60% for the surface irrigation system.

LR = leaching requirements equals 10% for surface irrigation system.

To determine water depletion from the root zone, soil moisture was measured gravimetrically a day before and a day after each irrigation as an average of three samples at each depth of 0–15, 15–30, 30–45, and 45–60 cm. The amount of irrigation water was measured by a flow meter connected to the irrigation pump. Bulk density, hydraulic conductivity, particle size distribution, and soil texture class values at the experimental site are presented in Table 1.

Water Productivity (WP) in kg ha⁻¹ m⁻³ was calculated by dividing grain yield (kg ha⁻¹) to the total applied irrigation water.

2.3. CropSyst Model

CropSyst (Cropping Systems) is a process-orientated simulation model [22], developed to study the effect of cropping system management on crop productivity. It has been designed to simulate the environmental impact, namely weather, soil characteristics, as well as crop characteristics, and cropping system management on the final crop yield [23]. To run the CropSyst model, five input data files are required: Simulation, location, soil, management, and crop files. The location file contains the weather data for each growing season. The management file contains all the field practices, such as irrigation, fertilizer, and weed control. The CropSyst User's Manual gives definitions, usage, and range of variation for all parameters required to run the model [23].

2.4. CropSyst Calibration

The model calibration was carried out using the field data of the first growing season. The required data were the date of each phenological stage of wheat, and growing degree days were calculated. Total leaf area per plant was determined using a leaf area meter (LiCOR 3100; Licor, Lincoln, NB, USA). Wheat leaf area index was measured for each growth stage. Grain yields were measured at harvest and the harvest index (HI) was calculated. Other unavailable parameter values were either taken from the CropSyst manual [23] or obtained from the literature. There are two main coefficients used in the calibration of the model, namely the aboveground biomass-transpiration coefficient (kPa kg·m⁻³) and photosynthesis efficiency (g·MJ⁻¹). These coefficients were slightly adjusted according to previous studies with this model.

2.5. CropSyst Validation

The field data obtained from the second growing season was used to validate the model. The calibration parameters, namely the aboveground biomass-transpiration coefficient (kPa kg m^{-3}) and photosynthesis efficiency (g MJ^{-1}) resulting from the calibration process, were used in validating the model. The predicted and measured values of grain yields were compared using the goodness of fit test between the measured and predicted data. The goodness of fit was done using percentages of difference between measured and predicted values of grain yields under each irrigation treatment, coefficient of determination (R^2), and Willmott index of agreement (*d-stat*). Both R^2 and *d-stat* take a value between 0 and 1.0, where the value of 1.0 means a perfect fit [25]. The root means square error (RMSE) was also calculated [26].

2.6. Simulation of Sustained Deficit Irrigation Conditions

In the CropSyst model, the effect of water shortage on the yield is expressed by an index, namely the water stress index. This index takes into account the effect of both water shortage and salinity stresses. It is used as an indicator of the plant's response to environmental conditions. Its numerical value ranges from 0 to 1.0, where 0 means no stress and 1.0 is maximum stress [22,23].

It is expected that the studied water stress treatments will cause high yield losses. Therefore, the effect of the application of sustained deficit irrigation during the whole season, namely 95, 90, and 85% of full irrigation requirement on wheat grain yield was simulated to lower yield losses and save a reasonable amount of irrigation water.

2.7. Statical Analysis

All data were subjected to analysis of variance for a randomized complete block design [27], after testing for the homogeneity of error variances using Levene test [28], and testing for normality distribution according to Shapiro and Wilk method [29]. Statistically significant differences between means were compared at $p \leq 0.05$ using Tukey's HSD (honestly significant difference) test. The statistical analysis was carried out using GenStat 17th Edition (VSN International Ltd., Hemel Hempstead, UK).

3. Results and Discussion

3.1. Wheat Yield Losses, Irrigation Water Saving and Water Productivity

Wheat yield losses and irrigation water saving percentages, consequent to applying the planned irrigation treatments, are shown in Table 5. The results indicate that reducing the irrigation amount by a certain percentage in the water stress irrigation treatments led to higher irrigation water saving but higher yield losses. Water-saving values were 20% and 40% averaged over the two growing seasons under T2 and T3 irrigation treatments, respectively; concurrently, wheat yield losses were 11% and 25% under T2 and T3 irrigation treatments, respectively, averaged over the two growing seasons. Similar results were obtained by Karrou et al. [18], who reduced the applied water to wheat grown under surface irrigation by 22%, thus obtaining a 15% yield reduction. Besides, Abdrabbo et al. [17] reported that reducing the applied water to wheat by 20% caused a 12% yield loss. El-Metwally et al. [30] indicated that a 7% drop of wheat grain yield could be attained by reducing the required amount of irrigation water by 25% under the sprinkler irrigation system.

Table 5. The percentage of reduction (PR%) in wheat grain yield (GY), irrigation water applied (IW), water productivity (WP), and percentage of irrigation water saving (PS%) as a result of the irrigation treatments application.

Treatment	First Growing Season					Second Growing Season				
	GY (ton ha ⁻¹)	PR (%)	IW (m ³ ha ⁻¹)	WP (kg m ⁻³)	PS (%)	GY (ton ha ⁻¹)	PR (%)	IW (m ³ ha ⁻¹)	WP (kg m ⁻³)	PS (%)
Control										
T1	5.21 ^{†a}	–	5791	0.899 ^d	–	6.76 ^a	–	6578	1.027 ^e	–
Water stress										
T2	4.61 ^c	12	4728	0.975 ^b	18	6.08 ^c	10	5184	1.172 ^c	21
T3	3.86 ^e	26	3662	1.053 ^a	37	5.04 ^e	25	3789	1.331 ^a	42
Stage-based										
T4	4.82 ^b	7	5007	0.963 ^b	14	6.36 ^b	6	5672	1.122 ^e	14
T5	4.88 ^b	6	5201	0.938 ^c	10	6.44 ^b	5	5698	1.131 ^e	13
T6	4.56 ^c	12	5035	0.905 ^d	13	6.09 ^c	10	5575	1.093 ^d	15
T7	4.32 ^d	17	4446	0.972 ^b	23	5.81 ^d	14	4669	1.243 ^b	29

[†] Mean values within the same column for each trait with the same lower-case letter are not significantly different according to Tukey's HSD (honestly significant difference) test at $p \leq 0.05$. T1, 100% evapotranspiration (ETc) throughout the growing season; T2, 75% ETc throughout the growing season; T3, 50% ETc throughout the growing season; T4, 50% ETc at tillering stage only + 100% ETc in the rest of stages; T5, 50% ETc at booting only + 100% ETc in the rest of stages; T6, 50% ETc at grain filling stage only + 100% ETc in the rest of stages; and T7, 50% ETc at tillering and grain filling stages only + 100% ETc in the rest of stages.

Under the application of phenological stage-based deficit irrigation treatments, the application of deficit irrigation as 50% of the required irrigation in a particular growth stage resulted in lower yield reduction than other treatments. The lowest wheat grain yield reduction was obtained when deficit irrigation was applied in one stage only. Grain yield losses were 6% and 5% in booting stage (T5), in the first and second growing season, respectively. Several researchers highlighted wheat sensitive growth stages to water stress, namely stem elongation [31], floral initiation, inflorescence development [32,33], and grain filling stage [31,33,34].

Water productivity (WP) calculated by dividing total grain yield (kg ha⁻¹) to total irrigation water applied (m³ ha⁻¹) differed depending on the treatments (Table 5). The lowest WP values were determined for control treatments (T1) in both years. WP increased by reducing irrigation water amount. Dry matter accumulation was increased by irrigation. WP of the wheat plants irrigated by T2 was higher by 8.3 and 14.1% in the first and second season, respectively, compared to control irrigation (T1). Under water stress, water was used more efficiently than regular irrigation. The higher values of WP observed under water stress treatment (T3) compared to regular irrigation (T1) were mainly due to less water applied for these treatments and the high obtained grain yield. These findings are in agreement with the results of other researchers [15,35]. Our study's results confirm the findings of other authors [15,35] who reported a decrease in WP with increasing the amount of irrigation water. Therefore, the results of the present research suggest that limited supplemental irrigation during a particular growth stage and/or growth season can significantly increase WP and wheat yield.

3.2. CropSyst Calibration

Table 6 shows the values of input parameters used in calibration process in the first growing season for each treatment. The measured versus predicted values of wheat grain and aboveground biomass under the studied irrigation treatments in the calibration experiment are shown in Table 7.

Table 6. The values of input parameters used in the calibration process in the first growing season for each treatment.

Input Parameter		Growing Degree Days	
Input parameter:			
Anthesis		950	Measured
Flowering		1000	
Grain filling		1080	
Physiological maturity		2100	
Calibration coefficients:			
Aboveground biomass-transpiration coefficient (kPa kg m ⁻³)			Calibrated
Photosynthesis efficiency (g MJ ⁻¹)			
Anthesis		HI	Measured
Treatments:			
Control			
T1	6.12 ^{†a}	0.38 ^{ab}	
Water stress			
T2	5.34 ^b	0.39 ^a	
T3	3.62 ^c	0.39 ^a	
Stage-based			
T4	5.22 ^b	0.38 ^{ab}	
T5	5.36 ^b	0.38 ^{ab}	
T6	5.47 ^b	0.38 ^{ab}	
T7	4.99 ^b	0.37 ^b	

[†] Mean values within the same column for each trait with the same lower-case letter are not significantly different according to Tukey's HSD (honestly significant difference) test at $p \leq 0.05$. T1, 100% ETc throughout the growing season; T2, 75% ETc throughout the growing season; T3, 50% ETc throughout the growing season; T4, 50% ETc at tillering stage only + 100% ETc in the rest of stages; T5, 50% ETc at booting only + 100% ETc in the rest of stages; T6, 50% ETc at grain filling stage only + 100% ETc in the rest of stages; and T7, 50% ETc at tillering and grain filling stages only + 100% ETc in the rest of stages.

Table 7. Measured versus predicted wheat grain and aboveground biomass, and percentage of the difference between measured and predicted values (PD%) under the studied irrigation treatments in the calibration experiment.

Treatment	Grain Yield (ton ha ⁻¹)			Aboveground Biomass (ton ha ⁻¹)		
	Measured	Predicted	PD (%)	Measured	Predicted	PD (%)
Control						
T1	5.21 ^{†a}	5.15	1.05	13.39 ^a	13.21	1.31
Water stress						
T2	4.61 ^c	4.59	0.50	12.00 ^c	12.07	-0.51
T3	3.86 ^e	3.84	0.44	10.48 ^e	10.37	1.05
Stage-based						
T4	4.82 ^b	4.79	0.68	12.86 ^b	12.94	-0.62
T5	4.88 ^b	4.84	0.70	12.96 ^b	12.75	1.61
T6	4.56 ^c	4.53	0.59	11.98 ^c	11.93	0.45
T7	4.32 ^d	4.30	0.46	11.63 ^d	11.63	-0.03
R ²		0.99			0.98	
d-stat		0.99			0.99	
RMSE		0.03			0.17	

[†] Mean values within the same column for each trait with the same lower-case letter are not significantly different according to Tukey's HSD (honestly significant difference) test at $p \leq 0.05$. T1, 100% ETc throughout the growing season; T2, 75% ETc throughout the growing season; T3, 50% ETc throughout the growing season; T4, 50% ETc at tillering stage only + 100% ETc in the rest of stages; T5, 50% ETc at booting only + 100% ETc in the rest of stages; T6, 50% ETc at grain filling stage only + 100% ETc in the rest of stages; and T7, 50% ETc at tillering and grain filling stages only + 100% ETc in the rest of stages.

The results suggest that the predicted values of grain and aboveground biomass were close to the measured values. The percentage difference between measured and predicted values was low. The results also showed that R² values were as high as 0.99 and 0.98 for grain and aboveground biomass, respectively. The value of d-stat was close to 1.0, i.e.,

0.99, and RMSE values were low, i.e., 0.30 and 0.17 ton a⁻¹ for grain and aboveground biomass, respectively. Similar results were obtained from CropSyst model for RMSE and *d-stat* values between measured and predicted yield in previous research carried out in clay soil [31], in sandy soil under sprinkler system [36], in clay soil under fresh and agricultural drainage water [37] and in sandy soil under sprinkler and drip systems [16]. Moreover, Benli et al. [38] and Singh et al. [39] stated that the CropSyst model prediction gave low RMSE values between the measured and the predicted values, which implied the accuracy of the model.

3.3. CropSyst Validation

The measured versus predicted wheat grain and aboveground biomass for the studied irrigation treatments in the validation experiment are shown in Table 8. The results indicated the capability of the CropSyst model to accurately simulate wheat grain and aboveground biomass. Although goodness of fit between measured and predicted in the calibration experiment was lower than its values in calibration experiments, it still reflects high accuracy. In the latter respect the values of R², namely 96%, and 94%, and *d-stat* values were 0.80 and 0.91 for wheat grain and aboveground biomass, respectively. Moreover, the low values of RMSE for wheat grain and aboveground biomass, i.e., 0.37 and 0.91 ton ha⁻¹, respectively, also showed the aforementioned accuracy. These results implied that the model could be used in simulating the effect of water deficiency on wheat. It was reported that the CropSyst model was appropriate in predicting growth and yield of wheat under different irrigation treatments, where the value of RMSE was 0.36 ton ha⁻¹ and the RMSE value between observed and predicted biomass was 1.27 ton ha⁻¹ [39]. Similar results were obtained with a low RMSE value and higher *d-stat* value [36,40,41].

Table 8. Measured versus predicted wheat grain and aboveground biomass, and percentage of difference (PD%) between measured and predicted values in the validation experiment.

Treatments	Grain Yield (ton ha ⁻¹)			Above Ground Biomass (ton ha ⁻¹)		
	Measured	Predicted	PD (%)	Measured	Predicted	PD (%)
Control						
T1	5.15 ^{†a}	4.82	6	13.21 ^a	12.36	6
Water stress						
T2	4.59 ^c	4.30	6	12.07 ^c	11.45	5
T3	3.84 ^e	3.65	5	10.37 ^e	10.99	6
Stage-based						
T4	4.79 ^b	4.57	5	12.94 ^b	12.51	3
T5	4.84 ^b	4.43	8	12.75 ^b	12.25	4
T6	4.53 ^c	4.38	3	11.93 ^c	11.45	4
T7	4.30 ^d	3.95	8	11.63 ^d	11.28	3
R ²		0.96			0.94	
<i>d-stat</i>		0.91			0.80	
RMSE		0.37			0.91	

[†] Mean values within the same column for each trait with the same lower-case letter are not significantly different according to Tukey's HSD (honestly significant difference) test at $p \leq 0.05$. T1, 100% ETc throughout the growing season; T2, 75% ETc throughout the growing season; T3, 50% ETc throughout the growing season; T4, 50% ETc at tillering stage only + 100% ETc in the rest of stages; T5, 50% ETc at booting only + 100% ETc in the rest of stages; T6, 50% ETc at grain filling stage only + 100% ETc in the rest of stages; and T7, 50% ETc at tillering and grain filling stages only + 100% ETc in the rest of stages.

3.4. Simulation of the Effect of Water Shortage

The simulated water stress index in each irrigation treatment is presented in Table 9. The table shows that under the application of 100% ETc (T1), there was no water stress, and the water stress index equaled 1.0. Under the application of 75% ETc (T2), the water stress index showed a water shortage in three periods during the growing season. A low water shortage and consequently low water stress index was recorded: From day 86 to 91 after sowing (below 0.3), which coincided with booting stage; during grain filling stage with

a higher water stress index (just below 0.7); and during late grain filling stage with very low water stress index. The shortage of water in the latter stage resulted in 11% yield loss averaged over the two growing seasons, as shown in Table 5.

Table 9 also shows that the application of 50% ETc throughout the growing season (T3) led to water stress during several crop cycle periods: twice during tillering, with a low water stress index (0.19) once during heading with a water stress index of 0.21; twice during booting with water stress indices of 0.20 and 0.49; and once during grain filling with high water stress index value of 0.72. The latter level of water stress caused a 25% yield loss averaged over the two growing seasons (Table 5).

Regarding the application of 50% ETc at tillering only (T4), water shortage was recorded during tillering with the stress index reaching a high value, namely 0.60, which resulted in a 7% yield loss as shown in Table 5. Application of 50% ETc at booting only (T5) led to the lowest value of yield loss, namely 6% as shown in Table 5, while the water stress index was 0.53. Furthermore, the application of 50% ETc at grain filling only (T6) resulted in two times of water stress, which sequentially corresponded to the water stress index of 0.65 and 0.25 during grain filling. In T7, two periods of water stress occurred under the application of 50% ETc at two phenological stages, i.e., at tillering (water stress index equal to 0.50) and grain filling (water stress index of 0.69) (Table 9). The associated yield loss reached 16% averaged over the two growing seasons, as shown in Table 5.

Table 9. Water stress index under the studied deficit irrigation treatments.

	Water Stress Index	Days after Planting	Duration	Stage
Control T1	1.0	No stress		
Water stress T2	0.29	85–91	6	Booting
	0.48	104–115	11	Early grain filling
	0.01	135–137	2	Late grain filling
T3	0.19	21–26	5	Tillering
	0.21	54–60	6	Tillering
	0.20	68–73	5	Booting
	0.49	87–93	6	Booting
	0.72	104–117	3	Grain filling
Stage-based T4	0.60	23–28	5	Tillering
T5	0.53	69–81	12	Booting
T6	0.65	97–107	10	Grain filling
	0.25	108–119	1	Grain filling
T7	0.50	23–28	5	Tillering
	0.69	97–116	19	Grain filling

T1, 100% ETc throughout the growing season; T2, 75% ETc throughout the growing season; T3, 50% ETc throughout the growing season; T4, 50% ETc at tillering stage only + 100% ETc during the other growth stages; T5, 50% ETc at booting only + 100% ETc during the other growth stages; T6, 50% ETc at grain filling stage only + 100% ETc during the other growth stages; and T7, 50% ETc at tillering and grain filling stages only + 100% ETc during the other growth stages.

3.5. Simulation of the Application of Sustained Deficit Irrigation Amounts

Although the above situation provides only a limited evaluation of the model, the model should be further tested as more data from more treatments in different locations and years become available. However, for this study, we found that the model worked sufficiently well to warrant the ascertaining of more irrigation water savings.

The measured versus predicted wheat grain yield under application of 85, 90, and 95% of ETc are shown in Table 10. Simulation of saving 15% of the applied irrigation water over the entire growing season showed that wheat yield could be reduced by 10% averaged over

the two growing seasons. Otherwise, the simulation of the effect of 10% and 5% saving of full irrigation resulted in grain yield reduction by 6% and 4% averaged over the two growing seasons, respectively (Table 10). The latter reductions in wheat grain yield were lower than losses obtained under T5, representing the lowest yield decrease, as shown in Table 5.

Table 10. Measured versus predicted wheat grain yield under application of 85, 90, and 95% of ETc.

Treatment	First Growing Season			Second Growing Season		
	Measured	Predicted	PD (%)	Measured	Predicted	PD (%)
85% ETc	5.21	4.71	10	6.76	6.15	9
90% ETc	5.21	4.89	6	6.76	6.42	5
95% ETc	5.21	4.94	5	6.76	6.51	4

PD%, Percentage of difference between measured and predicted values.

4. Conclusions and Perspectives

In this study, we tested the effects of deficit irrigation on different phenological stage-based on field cultivated wheat. The results showed that the water stress treatments of 75% and 50% ETc decreased wheat yield by 11% and 26%, respectively. The stage-based irrigation deficits resulted in lower wheat grain yield losses than the aforementioned water deficit treatments. The lowest yield loss of 6% with the concurrent 12% irrigation water saving was recorded when the 50% ETc replenishment was applied at the booting stage. In order to reduce wheat yield loss and increase irrigation water savings at the same time, we simulated the impact of the application of sustained deficit irrigation to save 15%, 10%, and 5% of the applied irrigation water and the correspondently mitigate yield drops. The simulated results showed that 15%, 10%, and 5% savings of the applied water could reduce wheat yield losses to 10%, 6%, and 4%, respectively. Subsequently, the application of sustained deficit irrigation is more suitable than the phenological stage-based model in yield loss decrease and irrigation water saving. Considering that the Egyptian farmers cannot afford high drops of wheat yield, we could recommend the application of either the phenological stage-based deficit irrigation as much as 50% ETc at the booting stage, or the sustained deficit irrigation of 90% ETc.

Previous studies on water management under climate change in Egypt projected that the cultivated crops' required irrigation water would increase in 2030 [42]. This rise is due to higher expected evapotranspiration [43,44]. Furthermore, it is expected that the share of Nile water assigned to agriculture will be reduced in the future in Egypt because of a high rate of population growth and climate variability that might reduce precipitation. Therefore, this study's results could help manage water more efficiently under climate change at national level. Under future water shortage, the studied model provides other options to irrigation water saving and the corresponding wheat yield drop, which can be used by the government to determine how to allocate the national water budget. This study could represent a basic knowledge for other studies focusing on different crops to determine the lowest yield loss under the application of deficit irrigation.

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