Jordan Journal of Agricultural Sciences, Volume **20**, No.**2** **2024**
DOI: https://doi.org/10.35516/jjas.v20i2.2335

Evaluating the Performance of the AquaCrop Model to Soil Salinity in Jordan Valley

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Received on 2/5/2022 and Accepted for Publication on 30/8/2023

ABSTRACT

The demand to apply a decision support system to simulate salinity and drought is increasing with time, particularly in arid and semi-arid regions like Jordan, where the threat of land degradation by salinization is of high concern. The main objective of this research was to evaluate the response of the AquaCrop model to soil salinity in Jordan Valley. Two experiments were conducted, one at the field and the other at the greenhouse. Three water salinity levels (S): S1 (control = 2 dS m−1), S2 (4 dS m−1), and S3 (8 dS m−1) with three irrigation amounts (R): R1 (control = 120%), R2 (100%), and R3 (70%) were used in the field. Four levels of saline water (S):S1 (control =0.65), (4) S2, (8) S3, and (10) dS m-1) S4 were used in the greenhouse. In both experiments, grain yield, and aboveground biomass were measured after harvesting. Soil salinity and pH were measured every three weeks during the growing season to monitor soil salinization. Results showed that the final field grain yield was good in calibration and validation, with a 0.96 agreement index (d). The efficiency factor (E) was 0.86 and 0.87 for calibration and validation, respectively, while the normalized root mean square error (NRMSE) was less than 4 %. Field biomass d-index of 0.87 and 0.71 and E of 0.65 and 0.45 for Calibration and Validation were found, respectively. In the greenhouse experiment, the results were less satisfactory. Grain yield showed d-index of 0.84 and 0.88 in calibration and validation, respectively, while biomass showed poor results. All statistical criteria used in this research indicated that the model can simulate grain yield and biomass properly in the field, however, biomass statistical results were less accurate. Overall it is recommended, to use AquaCrop for soil salinity management in Jordan Valley.

Keywords: AquaCrop, Salinity, Durum Wheat, Jordan Valley.

INTRODUCTION

In arid and semiarid regions, the impact of climate change and global warming in the last decades has led to considerable retardation in land and water sectors. Jordan is a country in the Middle East with a 90% arid climate Decreasing inflow of water from neighboring countries, increasing population dramatically because of refugees, hot dry weather in summer, and flocculated low rainfall in winter are some of the reasons for water scarcity and land degradation because of salinization, which is defined as the accumulation of salts in the soil to a level that affects the agricultural productivity, lowers its economic

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value, causes environmental damage, and threatens food security (Machado and Serralheiro., 2017).

The Jordan Valley is considered as Jordan's most fertile region, with its exclusive advantage of early agricultural production. Nevertheless, in recent decades, the salinization rate has been on the rise due to the region's high evaporative conditions and low annual precipitation, which result in fewer natural floods to leach salts. This issue is exacerbated by the fact that a majority of farms in the Jordan Valley lack a proper drainage system (Miyamoto *et al.*, 2005). More studies are needed to help farmers and decision-makers in the agricultural sector improve agricultural management practices and maintain a relatively sufficient crop yield in areas of water and salinity stresses. Adopting new technologies and changing established cropping patterns represent a risk not many farmers in the region can afford, although crop sensitivity to soil salinity may make some cropping systems unfeasible. Appropriate crop models offer farmers and decision-makers a low-risk method to do so. Crop models are also able to explore the possible effects of changes in environmental conditions on crop growth, and to run simulations in the long and short term for better investigations (Jones *et al.*, 2017).

AquaCrop (the crop water productivity (FAO) model) is a friendly user agro-hydrological model developed by the Food and Agriculture Organization (FAO) of the United Nations (Raes *et al.*, 2009). It simulates crop yield response to water and is particularly suited to address conditions where water is a key limiting factor in crop production. Moreover, the biomass weight is simulated directly from transpiration and water availability. The input parameters have easy physical interpretation compared to other crop models, and have shown successful validation and high performance when applied in many regions for multiple crop types across a wide range of environmental and agronomic settings (Foster *et al.*, 2017). Soil water balance in AquaCrop is relatively a critical component, the water content changes by the amount of precipitation, irrigation, capillary rise runoff, evaporation, transpiration, and deep percolation. The root zone is considered as a reservoir where the model divides the soil profile into compartments (the default is 12) with a thickness of ΔS. The one-dimensional root water uptake and water flow can be determined by a finite difference technique that is written in terms of the dependent variable θ (soil water content). It is assumed that rainfall has no dissolved salts, and so the accumulation of salts in the soil profile highly depends on the quality and quantity of irrigation water, frequency of irrigations, evaporation and transpiration, and soil characteristics.

Soil salinity stress is simulated with a soil salinity stress coefficient (Kssalt). The salinity stress indicator in AquaCrop is the average electrical conductivity of saturated soil paste extract (ECe) from the root zone. The upper and lower threshold for ECe is crop-specific. Soil salinity stress results in smaller canopy cover (CC) and a closure of the stomata that causes a direct reduction in transpiration. In Aquacrop, a reduction in biomass production occurs with a decrease in the rate of expansion of canopy cover as a result of soil water stress. Consequently, stomatal closure, early canopy senescence, and reduction in pollination are sensitive factors when simulating drought in AquaCrop (Raes *et al.*, 2009). The model translates the limited amount of daily water uptake as a reduction in actual transpiration (Castaneda-Vera *et al.*, 2015).

Under the conditions of a very hot summer and warm winter with low rainfall in Jordan Valley, the need to use a robust crop model such as AquaCrop is essential for enhancing farm and field management in marginal lands of high drought and salinity stresses. The main objective of this research is to evaluate the performance of the AquaCrop model in saline soils in Jordan Valley.

Methodology

Study area and the experimental design

The experiment was conducted in Jordan Valley for one year starting from January 2018. Two experiments were conducted using the same local variety of durum wheat (Um Qais), one in the field and the other in a greenhouse. In the field, the experimental area was divided into four blocks, each block combines the two factors: salinity and drought in a factorial design. Three plots represented the three irrigation levels in each block: R1 (120%), R2 (100%), and R3 (70%). While the three subplots consisted of three water salinity levels (S): S1 (2 dS m−1), S2 (4 dS m−1) and S3 (8 dS m−1). The total is nine treatments (S1R1, S1R2, S1R3, S2R1, S2R2, S2R3, S3R1, S3R2 and S3R3) in each block. Irrigation water amounts (R) were estimated using readily available water (RAW), the term refers to the soil moisture level that lies between field capacity (FC) and a specified refill point, facilitating ideal growth conditions by enabling plants to freely absorb water. The greenhouse experiment was carried out using four levels of water salinity: S1 (control =0.65 dS m-1), S2 (4 dS m-1), S3 (8 dS m-1) and S4 (10 dS m-1). All salinity treatments in the greenhouse were irrigated with 100% RAW. Final grain yield and aboveground biomass (Biomass) were measured at final harvest as being the parameters used in this research. Further details on the experimental procedures can be found in Hamdi *et al*. 2019.

Input data

Weather data

Daily maximum and minimum air temperature (ºC), daily reference evapotranspiration (mm), and daily rainfall (mm) are the minimum requirements for weather data in AquaCrop. The seasonal rainfall at the field was 77 mm. The average seasonal maximum temperature was (1.6 ºC) degrees higher in the greenhouse (24.8 ºC) than in the field (23.1 ºC), while the average seasonal minimum temperature was less in the greenhouse (8.4 ºC) than in the field (13.7 ºC) with about five degrees. DeirAlla weather station was used for weather data in the field experiment, it is located around 10 km far from the study area in Damea (Jordan University farm).

Daily reference evapotranspiration was calculated using the Penman-Monteith equation (Allen et al., 1998). Daily solar radiation was also recorded for the two experiments, the average seasonal solar radiation in the field was 12.1 MJ m-2 day-1, while in the greenhouse was 13.6 MJ m-2 day-1. A micro weather station was established in the greenhouse to record the daily weather data. More details about the weather data in the two experiments can be found in Hamdi et al. 2019.

Soil and Crop Management Data

The measured soil data were: Soil water content (θ) at saturation, field capacity (upper limit), permanent wilting point (lower limit), and bulk density. The soil type is Entisol with a fine loamy sand texture. The same soil was used in both experiments (field and greenhouse), and the measured soil physical parameters are shown in (Table 1). Measured soil physical parameters were inserted in the model for the two experiments.

Table 1: The measured soil physical parameters for the two experiments used as input soil data.

Soil Physical Properties	
Clay (%)	16 ± 0.48
Sand (%)	73 ± 0.65
Silt (%)	11 ± 0.33
Upper Limit (cm^3 cm^{-3})	0.186 ± 0.01
Lower Limit (cm^3 cm^{-3}) (Θ)	0.09 ± 0.01
Saturated Water Content(cm^3 cm^{-3})	0.38 ± 0.02
Bulk Density (g cm^{-3})	1.58 ± 0.11

Calibration and Validation

The calibration was conducted using the control non-saline treatments in the field experiment (S1R1) and the greenhouse experiment (S1). The model was used to calculate crop yield and biomass, based on crop growth parameters, which were either measured and taken from literature or estimated while conducting calibration using trial and error to get the closest point between measured and simulated output (yield and biomass). The validation was conducted using other saline treatments in the field and greenhouse experiments.

Measured parameters were: The soil physical parameters (Table 1), harvest index (HI), number of plants per unit area, ECe threshold, and the duration of plant phenological stages. While estimated parameters were: soil fertility, maximum canopy cover, and days to maximum rooting depth. A summary of the parameters determined after calibration for both experiments is shown in Table 2.

Table 2: AquaCrop parameters after calibration for field and greenhouse experiments**.**

Parameter		Field experiment	Greenhouse experiment
No. of plants		200 plants m^{-2}	28 plants m^{-2}
Canopy size----seedling		5 cm^2 $plant^{-1}$	5 cm^2 $plant^{-1}$
Emergence		4 days	5 days
Maximum canopy		40 days	38 days
Maximum canopy cover		80 %	80 %
Maximum effective rooting depth		0.8 m	0.4 m
Days to maximum rooting depth		40 days	38 days
Days to flowering		52 days	50 days
Flowering Duration		12 days	12 days
Maturity		94 days	98 days
Water productivity		17 g m^{-2}	17 g m^{-2}
Harvest Index (control)		35 %	34 %
Soil fertility		0.9	0.8
ECe Thresholds	**Lower**	4 dS m^{-1}	4 dS m^{-1}
	Upper	14 dS m^{-1}	14 dS m^{-1}
Base temperature		5 ºC	5 ºC
Upper temperature		35 ºC	35 ºC

After calibrating the model, validation was conducted using saline treatments in field and greenhouse experiments to test the accuracy of the model in simulating grain yield and biomass.

Results

The simulation of AquaCrop to water use (transpiration) for both experiments showed an obvious difference among salinity treatments in water use. In the field, the transpiration rate (mm/day) of the most water and salinity-stressed treatment (S3R3) was much lower than the control (Fig.1a). The average water use difference between the control (S1R1) and the most stressed treatment (S3R3) was nearly 0.45 mm. In the greenhouse, the water use difference among treatments was highly noticeable. (Fig.1 b).

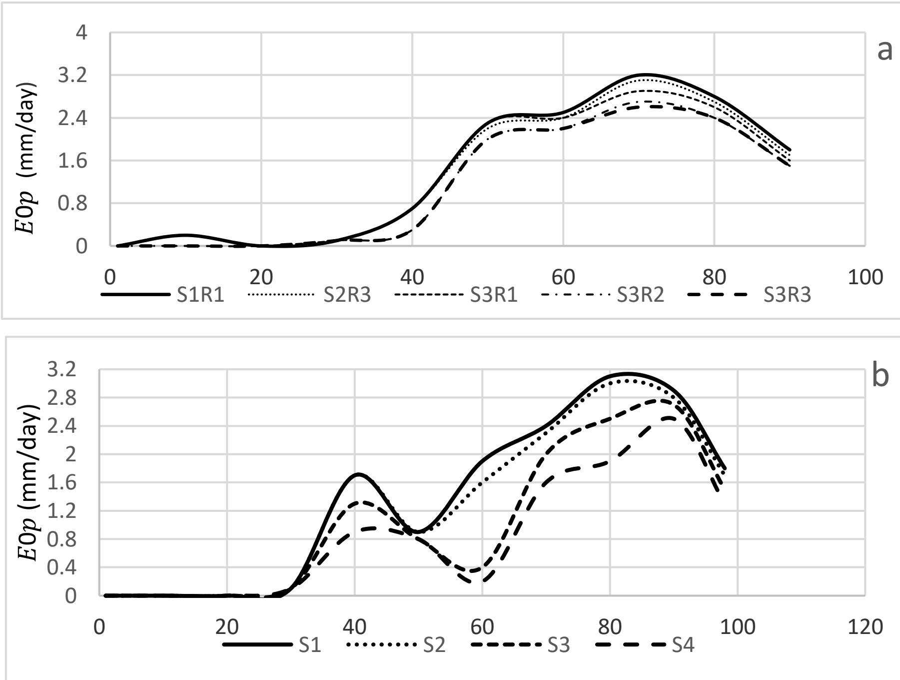

Figure 1: Simulated data for daily transpiration (mm/day) using AquaCrop model. Daily simulated transpiration (mm) in field experiment (a). Daily simulated transpiration (mm) in greenhouse (b).

AquaCrop simulated the final grain yield with an agreement index (d) of 0.96 in calibration (C) and validation (V) of the field experiment. The relative efficiency (E) was also good and almost the same in calibration and validation with 0.86 and 0.87, respectively. The normalized root mean square error (NRMSE) has recorded low values of 3.80 and 2.74%, in C and V, respectively, as a result, based on statistical measures AquaCrop model has shown a very good simulation to grain yield even under dry and saline soil in the field. Biomass estimation was of a 0.87 and 0.71 d-index in C and V, respectively at the field. The E was a little satisfactory with 0.65 in C, while in V was lower by 0.6. The NRMSE showed more satisfactory results for biomass in the field experiment with a value of less than 4% in the field experiment for calibration and validation treatments (Table 3).

Table 3: Performance evaluation of the AquaCrop model using the calibration (C) and validation (V) data sets of the field experiment**.**

Variable of interest	**Model version**		**No**	**Obs. Mean**	**Sim. Mean**	**NRMSE (%)**	**MAE**	**E**	**d**
Final grain yield (kg/ha)									
	AquaCrop	C	6	3062	3031	3.80	93.00	0.86	0.96
	AquaCrop	V	3	3059	3074	2.74	78.67	0.87	0.96

Aboveground biomass(kg/ha)									
	AquaCrop	C	6	9245	9129	3.95	286.50	0.65	0.87
	AquaCrop	V	3	9305	9304	2.77	216.33	0.49	0.71

In a greenhouse experiment, the d index for grain yield was 0.84 and 0.88 for C and V, respectively. The E was 0.55 for C, while V was less by 0.2. The NRMSE was close in C and V with an average of 7.74 %. However, biomass results were poor in a greenhouse with 0.33 and 0.61 in C and V, respectively. The E was below zero which indicates that the average of simulated results was far from the average of observed data in both C and V (Table 4).

Table 4: Analysis of the performance of AquaCrop in greenhouse experiment using the calibration (C) and validation (V) data sets.

Variable of interest	Model Version		No	Obs. Mean	Sim. Mean	NRMSE (%)	MAE	E	d
Final grain yield (kg/ha)									
	AquaCrop	C	2	1298	1378	7.74	79.5	0.55	0.84
	AquaCrop	V	2	990	1065	7.73	75.5	0.53	0.88
Aboveground biomass (kg/ha)									
	AquaCrop	C	2	3850	4770	24.1	920	-18	0.33
	AquaCrop	V	2	3607	4012	11.5	405	-1.94	0.61

Discussion

The trend of daily transpiration of AquaCrop indicates that the model is sensitive to water and salinity stresses, as it simulates the lowest transpiration rates of the most stressed treatments in the field and greenhouse successfully. The best simulating results for both experiments are grain yield which reaches 0.96 d-index in field and greenhouse experiment. AquaCrop shows a better simulation in the field than the greenhouse, this can be attributed to the use of a low number of treatments for C and V of the greenhouse which would lower the accuracy of the results obtained by statistical analysis. In addition, obtaining moderate values of soil electrical conductivity (ECe) in the field compared to high salinity levels obtained in the greenhouse, especially for S3 and S4 treatments with average ECe levels higher than 10 dS m−1 at the middle of the growing season, thus the possible ion toxicity might affect the final results in the greenhouse. However, the poor performance in the greenhouse experiment could also contribute to the decline in the model performance as soil salinity increases, this result is supported by (Ebrahim *et al.*, 2015, and Sandhu and Irmak, 2019).

The simulation of grain yield and aboveground biomass in the field is fairly accurate similar to previous research in arid regions (Kumar *et al.*, 2014, Tan *et al.*, 2018). The aboveground biomass is less satisfactory unlike previous research (Kumar *et al.*, 2014, Tan *et al.*, 2018), this can be explained based on the approach used to calculate the biomass in AquaCrop, which depends on a coefficient for water use efficiency (WUE). Many other models use radiation use efficiency (RUE) instead, or a combination of the two (WUE and RUE) to calculate the biomass (Castaneda-Vera *et al.*, 2015).

Because of the unique climate conditions in Jordan Valley with a relatively high solar radiation intensity during the year, Aqua Crop may not be sensitive in simulating biomass in such conditions, where biomass could be affected by RUE more than WUE (Castaneda-Vera *et al.*, 2015).

Conclusions

Two experiments, one at the field and the other at the greenhouse, were carried out to test the performance of AquaCrop in simulating the yield and biomass of wheat under water and salinity stresses in Jordan Valley. AquaCrop simulates grain yield and biomass fairly well in the field experiment in Jordan Valley. However, biomass simulation results are less satisfactory than the grain yield in the field experiment. In the greenhouse experiment, the grain yield has fairly good results for grain yield, while biomass simulation is poor. It can be concluded that the AquaCrop model is a valuable tool for farm irrigation water management in Jordan Valley under different levels of irrigation water and salinity to simulate crop yield.

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تقييم أداء نموذج AquaCrop لملوحة التربة في وادي الأردن

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تاريخ استلام البحث: 2022/5/2 وتاريخ قبوله: 2023/8/30

ملخص

يتزايد الطلب على تطبيق نظام دعم القرار لمحاكاة الملوحة والجفاف مع مرور الوقت، لا سيما في المناطق القاحلة وشبه القاحلة مثل الأردن، حيث يشكل خطر تدهور الأراضي بسبب التملح مصدر قلق كبير. الهدف الرئيسي من هذا البحث هو تقييم استجابة نموذج AquaCrop لملوحة التربة في وادي الأردن. تم إجراء تجربتين، واحدة في الحقل والأخرى في الدفيئة. ثلاثة مستويات لملوحة المياه (S) :S1 ((التحكم = 2 dS m−1)، S2 (4 dS m−1)، وS3 (8 dS m−1) مع ثلاث كميات للري (R) :R1 التحكم = 120 (%)،(% R2 (100، R3 (70%)وتم استخدامها في الميدان. بينما تم استخدام أربعة مستويات من الماء المالح): (S) التحكم = S10.65 ،(4) S2، S3(8)، و) S4 10 (dS m−1 في البيت المحمي. في كلتا التجربتين، تم قياس محصول الحبوب والكتلة الحيوية الموجودة فوق الأرض بعد الحصاد. تم قياس ملوحة التربة ودرجة الحموضة كل ثلاثة أسابيع خلال موسم النمو لرصد ملوحة التربة. أظهرت النتائج أن المحصول النهائي للحبوب الحقلية كان جيداً في المعايرة والتحقق، بمعامل اتفاق 0.96 (د). وكان عامل الكفاءة (E) 0.86 و0.87 للمعايرة والتحقق من الصحة، على التوالي، في حين كان جذر متوسط مربع الخطأ (NRMSE) أقل من 4٪. تم العثور على مؤشر d للكتلة الحيوية الميدانية بقيمة 0.87 و0.71 وE بقيمة 0.65 و0.45 للمعايرة والتحقق من الصحة، على التوالي. وفي تجربة الدفيئة، كانت النتائج أقل إرضاءً. أظهر إنتاج الحبوب مؤشر d قدره 0.84 و0.88 في المعايرة والتحقق من الصحة، على التوالي، في حين أظهرت الكتلة الحيوية نتائج ضعيفة. أشارت جميع المعايير الإحصائية المستخدمة في هذا البحث إلى أن النموذج يمكنه محاكاة محصول الحبوب والكتلة الحيوية بشكل صحيح في الحقل، إلا أن النتائج الإحصائية للكتلة الحيوية كانت أقل دقة. بشكل عام، يوصى باستخدام AquaCrop لإدارة ملوحة التربة في وادي الأردن.

الكلمات الدالة: أكوا كروب، الملوحة، القمح القاسي، وادي الأردن

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