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Using AquaCrop Model to simulate irrigation water use efficiency of potato crop under semi-arid conditions of Central Tunisia

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Abstract. In Tunisia, water scarcity forces producers to face stress conditions. In this study, AquaCrop was used to reproduce the dynamic of water contents, vegetative growth, yield production and water use efficiency under a non-stressed and water stressed treatments. Calibration procedure aimed to use in maximum default parameters of AquaCrop. Since, the paper presented only the parameters that have to be adjusted to obtain similar results of field measurements. Root mean squared error, RMSE, values were always lower than 0.04 $cm^3.cm^{-3}$ for water contents lower than 0.06 for vegetation cover estimation. Moreover, results from Nasch Coefficient, E, were almost equal to one. RMSE and E justified that the model was well assessed to predict the soil water contents and vegetation development under the study area. However, the model presented a greater performance in the case of full irrigation strategy. When evaluating different values of water productivity, it was showed that a *WP* of 32 $g.m^{-2}$ produced the lowest estimation error. Regarding yield productions, statistical indictors, computed for a water productivity value of 32 $g.m^{-2}$ show in general RMSE values lower than 0.4 t/ha. In addition, E was closer to one for the non stressed treatment, T1. For irrigation water use efficiency, it was depicted that the model underestimated field IWUE. Moreover, the discrepancy between simulated and estimated irrigation water use efficiency rose for treatment T2, implying that the model calibration should be improved, especially for stressed conditions. The model, after being calibrated, could be used for simulating the response of the crop to different irrigation management aiming to optimize water use efficiency.

Keywords: Canopy development; Production; Water productivity; AquaCrop.

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Introduction

In Tunisia, water resources are in a continuous decrease. Farmers are usually obliged to face situations of deficit irrigation allocation (DI). Although, DI has not been experimented under the semi-arid Tunisian conditions. In Tunisia, potato crop with more than 50 varieties, represents the second main crop, with a total surface of 27,000 ha (7% of irrigated lands) and a total production of 360,000 t per year (Chehaibi et al., 2013). Several researchers consider that is difficult to manage deficit irrigation for potato crop because of the rapid effect of water stress (Wright and Stark, 1990; Shock et al., 1993; Eldredge et al., 1996). In that context, model simulations after calibration and validation, could be a powerful tool for testing the impact of different deficit irrigation strategies on final yield (Droogers and Hunink, 2012).

The FAO AquaCrop model allows investigating the effect of a biotic stress on final crop yield (Farahani et al., 2009). Several researchers have found satisfactory results with AquaCrop when simulating the effect of different soil humidity on plant growth and production for many crops like sunflower, beans, winter wheat and tomato (Kaysha et al., 2009). According to Farahani et al. (2009), AquaCrop is a simple model combining robustness and accuracy. Moreover, the model does not recommend numerous input parameters compared to other growth crop models. Since, model calibration does not require skilled researchers, especially with the existing set of default parameters by Hsiao et al. (2009). These conservative parameters overcome the influence of geographical site and crop cultivar (Steduto et al., 2009). Some researchers suggested even to not adjust these parameters since their modulation is dependent on the stress function. Actually, potato is between the most water demanding crops compared to arboreal or cereal. So that, the possibility to manage irrigation based on field measurement and site calibrated model could have a strong impact on increasing local productions.

Objective of the paper was to use a previously calibrated and validated model based on canopy cover and water contents for the simulation of yield production and irrigation water use efficiency under different irrigation management.

Material and methods

Description of the study area and irrigation management

Field Experiments were conducted at the High Agronomic Institute of Chott Meriem, Sousse, Tunisia (longitude 10.5632° W; latitude 35.9191° N, altitude 19.0 m a.s.l.), under a semi-arid climate, with hot and dry summer and mild-rainy winter seasons. Potato tuber seeds of the same potato cultivar (*Solanum tuberosum* L., cv. Safran), were planted on January, 15th and on January, 22nd, respectively, in 2014 and 2015. Distance along the row was equal to 0.40 m and 0.80 m between the rows, in an experimental plot, 25 m length and 7 m wide. The experimental plot was divided in two subplots (treatments T1, T2) receiving similar seasonal management and different irrigation doses. Each treatment was composed by five rows. Sixty potatoes crop were planted per row. In particular, treatments T1 was maintained under full irrigation management by supplying the volumes corresponding to the maximum crop evapotranspiration estimated between consecutive watering, whereas treatments T2 (deficit irrigation) received approximately the half of volumes provided in T1. Volumetric counters (precision 0.1 dm^3) allowed checking the total volume provided in the plots, during each watering. For all season, irrigation consisted on two treatments replicated five times, arranged in a complete split plot block design.

Maximum evapotranspiration

Agroclimatic data were acquired from a climate station located at 300 m far from the experimental site in 2014 and inside the experimental field in 2015. The station provided hourly records of solar radiation, precipitation, maximum and minimum temperature and relative humidity. From hourly records, daily maximum and minimum values of temperature and humidity were obtained. Similarly, daily radiation and precipitation were accumulated. From these records, reference evapotranspiration (ETo) was computed using the Penman-Monteith equation.

Soil water retension curves, irrigation management and water contents

Preliminarily, in laboratory the soil proprieties (saturated water content, water content at field capacity and water content at permanent welting point) were determined on soil samples, 8.0 cm diameter and 5.0 cm height collected in the field at depths 0.15, 0.30 and 0.45 m. The water column technique performed in Buckner funnels (Dane and Hopmans, 2002), equipped with porous plates with air entry point h= -200 hPa was used for matric potentials ranging between 0 hPa (saturation) and about -150 hPa, whereas the pressiometric method using the Richard apparatus (Dane and Hopmans, 2002) was applied for soil matric potential of 330, 1,000, 3,300 and 15,000 hPa. Saturated soil hydraulic conductivity was determined by the constant head permeameter on undisturbed soil samples 8.0 cm diameter and 5.0 cm height. Spatial and temporal variability of soil water content around a single emitter, was daily monitored with a Trime TDR probe (IMKO Micromodultechnik GmbH) having a precision of ±0.03 cm^3/cm^3 (Douh, 2012). In each plot, soil water content was regularly measured at 15 cm, 30 cm and 40 cm depths and distance 0 cm and 15 cm and 30 cm from the emitter.

Plant measurements

Crop agronomic parameters mainly leaf area index, rooting depth and yield productions, were measured different plants from randomly chosen locations of each subplot, and from six plant every 8 days in 2014. In particular, after cleaning the root, they were measured and leaves were detached and their surface areas were measured with the planimetric technique implemented in the Skye Leaf version 2 software (Skye Instruments Ltd.). Leaf areas were then divided by total ground area by a plant. Thereafter, and approximately from the starting of tuber formation, around DAP 40, tubers of plants used for the determination of LAI and root depths, were collected and weighed. In 2014, sampling was less intensive, and agronomic parameters were measured every ten days. Leaf area index was converted to CC using the following formula (Heng et al., 2009):

$$\mathrm{CC} = 1.005[1 - \exp(-0.6\mathrm{LAI})]^{1.2} \qquad (1)$$

At the end of the growth season, irrigation water use efficiency (IWUE) was calculated as the ratio between the final crop yield (Y) and the irrigation water supplied by the following formula:

$$\mathrm{IWUE} = \frac{\mathrm{Y}}{\mathrm{I}} \qquad (2)$$

Statistical analysis for model evaluation

Table 2. Summary of statistical parameters used for model evaluation.

Statistical index	Formula	Indications
Root Mean Square Error	$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(X_{sim,i} - X_{obs,i})^2}{N}}$	Error expresed in the same units of the considered variable
Mean Bias Error	$MBE = \frac{1}{N}\sum_{i=1}^{N}(X_{sim,i} - X_{obs,i})$	Average over- or under-prediction
Nash-Sutcliffe efficiency index	$E = 1 - \frac{\sum_{i=1}^{N}(X_{sim,i} - X_{obs,i})^2}{\sum_{i=1}^{N}(X_{obs,i} - \overline{X_{obs}})^2}$	E = 1 (Perfect agreement); 0 < E < 1 (model suitable to reproduce measured data); E < 0 (unacceptable performance)

Results and discussion

Table 2 shows the parameters used for the characterization of the soil profile for treatment T1 and T2 during the experimental years of 2014 and 2015.

Table 2. Soil properties used to represent the soil profile in AquaCrop for T1 and T2 during the experimental year of 2014 and 2015.

Horizon	Texture	Depth	ϴs [cm^3.cm^{-3}]	ϴcc [cm^3.cm^{-3}]	ϴpfp [cm^3.cm^{-3}]	Ks [cm.h^{-1}]
1	Sandy loam	0-15	0.40	0.28	0.10	11.00
2	Sandy loam	15-30	0.39	0.28	0.10	6.40
3	Sandy loam	30-40	0.40	0.28	0.10	3.80

In this study, several iterations were investigated for testing the possible application of parameters of Hsiao et al. (2009). Results showed satisfactory results for wide number of these parameters. In fact, Table 3 shows the only canopy growth parameters that were modified to reproduce field measurements. The sensitivity of plant to soil water stress were chosen as 'moderately tolerant to water stress', including the soil water stress coefficient for canopy expansion, stomatal closure, and canopy senescence.

Table 3. Coefficients for crop growth development used by AquaCrop, the regression lines (B: slope; A: intercept) and the determination coefficient R^2 for the relationship between observed and simulated values in 2015.

	CC_0	CC_x	CGC	CDC	A	B	R^2
T1	0.4	89	0.4	19	0.979	0.783	0.992
T2	0. 3	60	0.19	8	0.952	0.254	0.987

CC_0: Initial canopy cover; CC_x: maximal canopy cover; CGC: development rate of canopy cover; CDC: daily coefficient decline

In order to reproduce final *Y* for the environmental condition of the study area, different values of water productivities *WP* were tested. Subsequently, a relationship between observed and estimated *Y* for the examined *WP* was depicted, as shown in Figure 3.

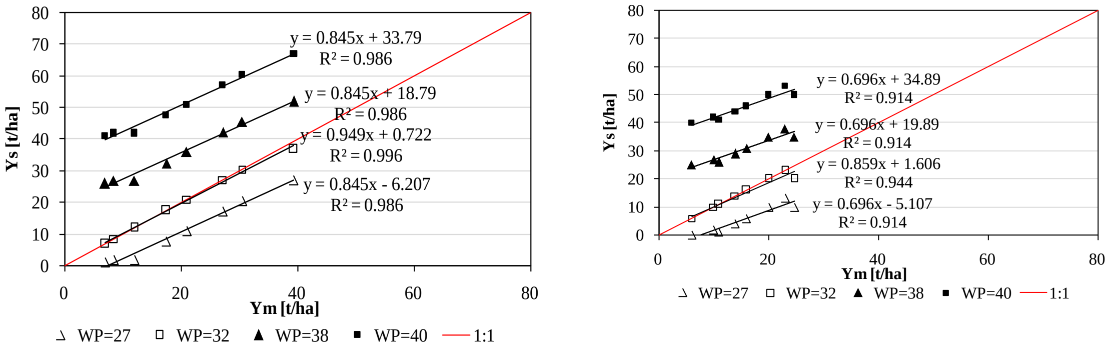

Figure 3. Relationship between simulated and measured yield productions, Ys and Ym, for the different investigated water productivities during the calibration.

Statistical analysis computed during the calibration process for water contents, canopy develpement and yield production are summarized on Table 4.

Table 4. Statistical indices of simulated water contents, canopy cover development and simulated yield for the calibration dataset.

	N	**RMSE**	**E**
	Water contents		
T1	347	0.02	0.03
T2	347	0.71	0.62
	Canopy cover development		
T1	16	3.84	0.98
T2	16	5.54	0.95
	Yield production		
T1	8	2.05	0.97
T2	8	3.08	0.80

In 2014, potato crop was planted on the same field of 2015 and was used as a control test for evaluating the calibration of the AquaCrop software. Sampling was less intensive since vegetation cover was determined from a single plant at nine dates during the growth cycle. The different statistical indicators computed during the validation are presented on Table 5.

Table 5. Statistical indices of simulated water contents, canopy cover development and simulated yield for the validation dataset.

	N	RMSE	E
	Water contents		
T1	347	0.03	0.04
T2	347	0.75	0.51
	Canopy cover development		
T1	8	5.86	0.96
T2	8	7.90	0.86
	Yield production		
T1	8	2.38	0.95
T2	8	1.4	0.95

Figure 4 shows irrigation water use efficiencies for Treatments T1 and T2 during the experimental seasons of 2014 and 2015.

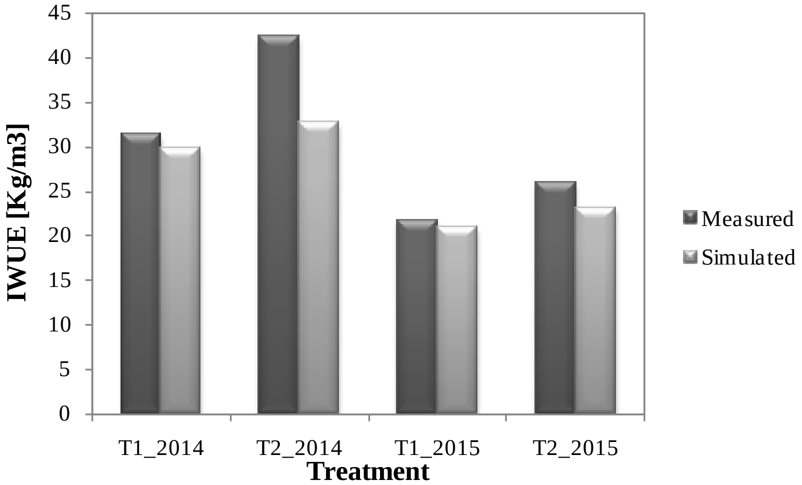

Figure 4. Irrigation water use efficiences for Treatments T1 and T2 during the experimental seasons of 2014 and 2015.

Discussion

To assess the performance of the model in reproducing field conditions of the soil plant atmosphere system, statistical indexes for mean squared error, RMSE and Nasch coefficient were calculated.

Table 5 showed that RMSE values were always lower than 0.04 $cm^3.cm^{-3}$, suggesting the goodness of fit between average moisture content in the 40 cm soil layer. This result was also confirmed with the Nash coefficient (Katerji Et al., 2013).

Moreover, when analyzing results from statistical indicators of canopy cover predictions presented on Table 5, it is noticed that RMSE were higher in T2 than in T1, and was in general lower than 6%. Results from E were almost equal to one, showing that the model is well assessed to predict the vegetation development under the study area. However, the model presented a greater performance in the case of full irrigation strategy.

Moreover, Water productivity is a key factor in simulating yield production from any crops. When evaluating different values of water productivity, the adjustment function between observed and estimated productions showed in all cases a correlation coefficient greater than 0.9. However, with a *WP* = 38 $g.m^{-2}$ or 40 $g.m^{-2}$, an overestimation was well denoted. However, for a *WP* of 27 $g.m^{-2}$, final productions were remarkably underestimated. In conclusion, a *WP* of 32 $g.m^{-2}$ produced the lowest estimation error. Kayschap et al. (2002) reported that potato crop is classified between the characteristic values of species C3 and C4, which corresponds to water productivity between 20 and 30 $g.m^2$, respectively. Regarding yield productions, statistical indictors, computed for a *WP* value of 32 $g.m^{-2}$ shows in general RMSE values lower than 0.4 t/ha. In addition, E was closer to one for the non stressed treatment, T1. This results confirms that the model is well calibrated to reproduce the productive function. Moreover, performance of the model declines in a condition of water stress. In 2014, the potato crop was planted on the same field of 2015 and was used as a control test for evaluating the calibration of the AquaCrop software. Sampling was less intensive since vegetation cover was determined from a single plant at nine dates during the growth cycle. In 2014, AquaCrop was unable to reproduce the punctual dynamic of soil water content. However, simulated average values were considered acceptable.

The presence of grape of air between soil and measurement tube, observed especially during that season, could justify this inability. The analysis of statistical indicators for water contents, canopy cover and yield production confirmed the previous results of ability of the model to simulate water movement through the soil plant atmosphere system obtained in 2015. Additional calculation for mean bias error showed negative values for all the component. When it is the case of IWUE, the model underestimated field IWUE (Figure 4). Many other researches underlined the mismatch of simulated IWUE. Moreover, the discrepancy between simulated and estimated IWUE rose for treatment T2, implying that the model calibration should be improved, especially for stressed conditions. Likewise, Evett and Todorovic (2009) suggested that AquaCrop could be reliable in simulating WUE only under non-deficit irrigation and tended to misestimate WUE under conditions of deficit irrigation. Furthermore, Katerji et al. (2013) concluded even that AquaCrop's performance in simulating IWUE is not satisfactory in cases of severe water stress. Figure 4 shows that in general, the higher values of IWUE were associated to deficit irrigation, even if the high efficiencies connected to the water restricted regimes were counterbalanced by reduced yield and quality. El Mokh et al. (2014), based on experiments carried out in Southern Tunisia found similar results. However, if from one side limiting irrigation depth determines a certain increase of IWUE, from the other side produces a reduction of crop yield, with unavoidable effects on the farmer's gross revenues. For this reason, in order to identify irrigation scheduling strategies, it is necessary to monitor the climatic variables from one side, but also to make economic analysis aimed to compare the costs associated to irrigation with the benefits corresponding to the higher productions. In agreement with El Mock et al. (2004), full irrigation strategies could be recommended for irrigation of potato crop under the semi-arid climate of Tunisia, even if the possibility to reduce water supply can be envisaged when water availability is limited, but with the awareness to accept shortage of production.

Conclusion

In this study, performance of AquaCrop for simulating field conditions of water content, vegetation cover, yield production and irrigation water use efficiency was performed. RMSE values were always lower than 0.04 $cm^3.cm^{-3}$ for water contents lower than 0.06 for vegetation cover estimation. Moreover, Results from E were almost equal to one. These latter results justified that the model was well assessed to predict the soil water contents and vegetation development under the study area. However, the model presented a greater performance in the case of full irrigation strategy. When evaluating different values of water productivity, the adjustment function between observed and estimated productions showed in all cases a correlation coefficient greater than 0.9. However, with a *WP* = 38 $g.m^{-2}$ or 40 $g.m^{-2}$, an overestimation was well denoted. However, for a *WP* of 27 $g.m^{-2}$, final productions were remarkably underestimated. In conclusion, a *WP* of 32 $g.m^{-2}$ produced the lowest estimation error. Regarding yield productions, statistical indictors, computed for a *WP* value of 32 $g.m^{-2}$ shows in general RMSE values lower than 0.4 t/ha. In addition, E was closer to one for the non stressed treatment, T1. For irrigation water use efficiency, it was revealed that the model underestimated field IWUE. Moreover, the discrepancy between simulated and estimated IWUE rose for treatment T2, implying that the model calibration should be improved, especially for stressed conditions.

Conflict of interest

The authors declare that there is no conflict of interest.

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