Performance of Aquacrop to simulate variability of vegetative growth under deficit and non deficit irrigation

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ABSTRACT

In this study, Aquacrop was calibrated to estimate effects of different irrigation management on canopy cover development and water contents under the semi-arid condition of Tunisia. Calibration procedure aimed to define the parameters to be changed from the default values set on Aquacrop. Results from the calibration process showed that to reproduce dynamic of field canopy growth function, it was necessary to calibrate initial canopy cover, maximal canopy cover, development rate of canopy cover and the daily coefficient decline. Soil function was set according to measurement of water contents of field capacity, wilting point and saturated hydraulic conductivity. Results showed that the model was able to simulate canopy cover (CC) and water contents (θv) RMSE lower than 6% for canopy development and then 0.03 cm³.cm⁻³ for water contents. However, values of E were close to 1 for both parameters. Being assessed, this model could be used to study effects of different irrigation strategies on dynamic of vegetative growth and water contents from full and deficit irrigation.

1. Introduction

Water is essential for plant growth. It is a crucial factor for many physiological processes. Furthermore, water enters on the constitution of plant cells and tissues, with about 90% of its total fresh weight. However, water contributes only with 1% on the metabolic process; the rest is dedicated for transpiration. Therefore, water stress may lead to a complete, partial, reversible or irreversible inhibition of one or more physiological process such as transpiration, photosynthesis, cell enlargement and enzymatic activities (Barrs, 1968). Potatoes are characterized by a superficial root system and a quite high sensitivity for water stress more than other horticultural crops like tomatoes corn and sugar-beet (Fulton, 1970). Boyer (1970) studied the effect of the decrease of leaf water potential on leaf enlargement and metabolic rates on three crops: corn, sowbean and sunflower and found that threshold for the inhibition of leaf potential were
almost the same for the three plants. Moreover, Boyer (1970) found that leaves enlargement were severely stopped even before photosynthesis and respiration. Moreover, he found that the impact of stress on cell enlargement is irreversible, and leaves enlargement rate did not return to the rate of unstressed plant after been rewatered. Gandar and Tanner (1976) found that at a water potential of about -3 bars, potato starts to reduce leaf cell elongation, which completely ceases at a water potential of -5 bars. Therefore, a water stress conducted on a period of vegetative growth will lead to a reduction of leaf area. Since this will retard or prevent a good soil coverage during tuber bulking phase. Moreover, according to Moorby and Milthorpe 1975, it is important that new leaves are formed during this period to reduce the net assimilation of the old leaves, leading to a higher daily production rate. It is also shown that leaf area reduction occurred even before the reduction of photosynthesis or plant transpiration. Therefore, when testing different irrigation strategies, it is crucial to know the effect of these strategies on vegetative growth, in order to prevent possible irreversible drastic effects on crop development. In that context, agroclimatic models could play a major role in predicting the response of plant growth to different irrigation strategies without the need of time consuming field experiments. Farahani et al. (2009) considered that Aquacrop among the simplest models joining robustness to accuracy. Moreover, the models recommend few number of input parameters compared to other growth crop models. Therefore, model calibration does not require skilled researchers, especially with the existing set of default parameters by Hsiao et al. (2009). These default parameters are not affected by geographical site and crop cultivar (Steduto et al., 2009). Both Heng et al. (2009) and Hsiao et al. (2009) suggested that Aquacrop is able to simulate crop development and productions under non stressed conditions. However, Katerji et al., 2013 suggested model performance decreases in case of environmental stress conditions. In Tunisia, potato crop with more than 50 varieties occupies a surface of 27,000 ha (7% of irrigated lands) and produce about 360,000 tons per year (Chehaibi et al., 2013). The objective of this paper is to calibrate Aquacrop based on measurements of growth parameters and to test the performance of this calibration to predict canopy growth as response to deficit and non deficit irrigation strategies.

2. Material and methods

2.1. Description of the study area

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.). The climate of the study area is classified as semi-arid, with hot and dry summer and mild-rainy winter seasons. In 2014 and 2015, tuber seeds of the same potatoes cultivar (Solanum Tuberosum L., cv. Safran), were planted on January, 15th and on January, 22nd, respectively, at distance of 0.40 m along the row 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) subjected to similar seasonal management, except for irrigation doses. In particular, treatments T1 was received full irrigation doses corresponding to the maximum crop evapotranspiration and treatments T2 (deficit irrigation) received half of volumes provided in the treatment. Total volumes were checked according to readings before and after irrigation on volumetric counters (precision 0.1 dm3) installed on each treatment. Drip emitters, spaced 0.40 m, discharged a flow rate of 3.5 l/h at nominal pressure of 100 kPa. Reference evapotranspiration (ETo) was computed in accord to the Penman-Monteith equation (Allen et al., 1998). Preliminarily, Soil characterization was carried out to determine water contents corresponding to saturated, field capacity and wilting point. Thereafter, Saturated soil hydraulic conductivity was experimentally determined by the constant head permeameter. Spatial and temporal variability of soil water content around a single
emitter, was 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 45 cm depths.

2.2. Monitoring agronomic crop parameters

In order to monitor the dynamic of root length and leaf area during the seasonal growth cycle, in 2014 and 2015 three different plants were collected from random locations of each sub-plot, respectively at DAP 24, 78 and 109 and DAP 29, 83 and 113. Each plant was used to measure the main root parameters and leaf area. For these same plant samples, all leaves of each plant were detached. The planimetric technique, implemented in the Skye Leaf v2 software (Skye Instruments Ltd.), was applied to measure the area of each plant leaf. The method is based on the proportionality between the individual leaf area and the number of area units covered by the

**Figure 1.** Map of the experimental field with the four treatments (T1, T2, T3 and T4) investigated in 2014 and 2015.

**Figure 2.** Individual small leaves on the field view of Skye Leaf v2 software.
same leaf placed in a horizontal plane (Jonckheere et al., 2004). The software was connected to a standard flatbed scanner allowing to capture the images to be elaborated. After disposing one or more leaves on the scanner the acquisition resolution was fixed by considering that higher resolutions need longer time analysis. Large leaves were analyzed individually, whereas small leaves were analyzed jointly depending on the scanner’s surface dimensions, as illustrated in figure 2.13. Then, it was necessary to select the scaling factor for image calibration and to fix a threshold function to train the software on which part of the image had to be analyzed. All these steps were automatically run and the results, in terms of leaf area, were shown in the lower left side of the window. Leaf area index was finally estimated by dividing the total leaf area by the surface occupied by a single plant.

Finally, leaf area index was converted to CC using the following formula (Heng et al., 2009):

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

2.3. Model input parameters

Aquacrop is a crop model that uses the water balance equation to reproduce dynamic of water and the linked physiological process in soil plant atmosphere continuum. The model is articulated on sub files allowing introducing data retrieved from field conditions. 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. Daily maximum and minimum values of temperature and humidity were the computed and introduced into the Weather files together with the default values of daily concentration of carbon dioxide Atmospheric CO concentration. According to the soil profile of the experimental site, the parameterization of soil component was assessed using basic characteristics such as saturated volumetric water content, water content at field capacity and at permanent wilting point, saturated hydraulic conductivity of the different soil profile depths. Groundwater table was greatly deeper than the effective root zone. Since, the action of capillary rise was neglected in the simulation. Initial water contents required for the initial conditions file were determined according to the first measurement. Irrigation files included irrigation depths and its time of application. Crop component consisted on a set of introduced or conservative parameters, mainly articulated on crop parameters, phonology, development and water stress.

The performance of Aquacrop for simulating canopy growth was assessed taking into account canopy development and water contents. Conditions of no fertility and salinity stress were considered. Hence, simulations were restricted to investigate on the effect of two irrigation depths on the previously mentioned parameters. As sampling was more intensive in 2015, data from this year was used for Aquacrop calibration. However, data from 2014 was considered during the validation. Firstly, the calibration started with a comparison between simulated and measured canopy cover $CC$ and water content $\theta_v$ for full irrigation treatment. Finally, the performance of this calibration was tested for deficit irrigation.

The performance of Aquacrop model was evaluated by considering the Mean Bias Error (MBE), the Root Mean Square Error (RMSE), and the Nash-Sutcliffe model efficiency index (E) (Nash and Sutcliffe, 1970; Willmott, 1980), evaluated as:

$$MBE = \frac{1}{N} \sum_{0}^{N} (X_{\text{sim},i} - X_{\text{obs},i})$$

$$RMSE = \frac{1}{N} \sqrt{\sum_{0}^{N} (X_{\text{sim},i} - X_{\text{obs},i})^2}$$

$$RMSE = 1 - \frac{\sum_{0}^{N} (X_{\text{sim},i} - X_{\text{obs},i})^2}{(X_{\text{sim},i} - X_{\text{obs},i})^2}$$

where $X_{\text{sim},i}$ and $X_{\text{obs},i}$ are the simulated and observed values of any considered variable at the time $i$ and $N$ the number of measured data.
3. Results

3.1. Agroclimatic characterization

For treatments T1 and T2, table summarizes the number of precipitation and irrigation events, the cumulated seasonal precipitation, irrigation, reference evapotranspiration ET0, for treatments T1, T2 in 2014 and 2015. As can be observed from that table, Cumulative value of precipitation and reference evapotranspiration resulted lower in 2014. Moreover, the number of raining days was more important during that year (40 in 2014 compared to 21 in 2015). Therefore, irrigation events were more frequent in 2015 and the cumulated height of irrigation resulted more important.

3.2. Model simulations

3.2.1. Canopy growth

One interesting aspect of Aquacrop model is the possible use of a set of conservative parameters that do not affect results even under different time and field management. Hence, they are not site specific or not related to a certain cultivars (Raies et al., 2012). Simulations showed satisfactory results for wide number of these parameters. In fact, table 3 shows the only canopy growth parameters that were calibrated in order to obtain results comparable to measured ones. Since the aim of the model calibration was to test values that can work adequately under all conditions, the proposed values were maintained for use in predicting crop development as they worked well in non-stressed and moderately stressed conditions.

According to the table 2, full irrigations doses favored higher values of vegetation cover during the full development stage. In particular, a full irrigation dose promotes greater soil water availability, inducing a greater growth rate for treatment T1. These results are in agreement with the experimental results of Munns and Pearson (1974).

Figure 3. a and figure 3. b show simulated CC during the growth season of 2015 (continuous line) as compared with measured value (dots), respectively for treatment T1 and T2. In general, it is shown from figure 3a,b that the observed CC functions are accurately simulated with the model. Therefore, the slope of the regression line between the two variables was very close to 1, while the intercept was almost equal to 0, as shown in Figures 3. c and 3.d. The correlation coefficients R² for both treatments resulted almost close to 1, indicating a good fitness between measured and simulated values. Montaya et al. (2016) has also confirmed that the model was able to simulate CC function of potato crop under different irrigation management with a correlation coefficient greater than 0.9. In addition, the comparison between CC development for treatments T1 and T2 showed that values of vegetation cover were significantly higher (p <0.5) for treatment receiving full irrigation doses. Results by Beletse et al. (2013) suggested that model predicts vegetation cover as well as for stressed and non stressed treatments. Furthermore, unstressed crops gave higher maximum CC compared to stressed treatments. The correlation coefficients between measured and predicted vegetation cover (R²) values were 0.92.

Moreover, when analyzing results from statistical indicators presented in table 3, 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.

Figure 4 illustrates Aquacrop's ability to simulate CC during the 2014 growing season, following the same calibration of 2015 and changing only the climate data sets. From the analysis of this figure, it is shown the ability of the model to reproduce the temporal evolution of the CC during the experimental season of 2014.

These results were confirmed with the statistical indicators presented on table 4. However, simulated CC were in general underestimated. In addition, it is
**Table 1.** Number of precipitation events, N.P, and irrigation watering, N.I, of cumulated seasonal precipitation, P, irrigation, I, reference evapotranspiration ET0 for treatments T1, T2 in 2014 and 2015.

<table>
<thead>
<tr>
<th>Year</th>
<th>N.P</th>
<th>N.I</th>
<th>P</th>
<th>I</th>
<th>ET0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[-]</td>
<td>[-]</td>
<td>[mm]</td>
<td>[mm]</td>
<td>[mm]</td>
</tr>
<tr>
<td>2014</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1</td>
<td>40.0</td>
<td>8.0</td>
<td>108.6</td>
<td>124.4</td>
<td>198.0</td>
</tr>
<tr>
<td>T2</td>
<td>40.0</td>
<td>8.0</td>
<td>108.6</td>
<td>61.1</td>
<td>198.0</td>
</tr>
<tr>
<td>2015</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1</td>
<td>21.0</td>
<td>14.0</td>
<td>73.6</td>
<td>181.9</td>
<td>280.0</td>
</tr>
<tr>
<td>T2</td>
<td>21.0</td>
<td>14.0</td>
<td>73.6</td>
<td>94.5</td>
<td>280.0</td>
</tr>
</tbody>
</table>

**Table 2.** Coefficients for crop growth development used by Aquacrop, the regression lines (B : slope ; A : intercept) and the determination coefficient R2 for the relationship between observed and simulated values in 2015.

<table>
<thead>
<tr>
<th>CC0</th>
<th>CCx</th>
<th>CGC</th>
<th>CDC</th>
<th>A</th>
<th>B</th>
<th>R2</th>
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</thead>
<tbody>
<tr>
<td>T1</td>
<td>0.4</td>
<td>89</td>
<td>0.4</td>
<td>19</td>
<td>0.979</td>
<td>0.783</td>
</tr>
<tr>
<td>T2</td>
<td>0.3</td>
<td>60</td>
<td>0.19</td>
<td>8</td>
<td>0.952</td>
<td>0.254</td>
</tr>
</tbody>
</table>

CC0: *Initial canopy cover*; CCx: *maximal canopy cover*; CGC: *development rate of canopy cover*; CDC: *daily coefficient decline*

**Figure 3.** Comparison between measured (black dots) and simulated (solid line) canopy cover, CC, in treatments T1(a) and T2 (b) during the experimental year of 2015. Regression lines between simulated and measured CC for T1 (c) and T2 (d) are also shown.
also remarkable from this figure that the slope of the decline phase of vegetation cover was less pronounced than the one observed in 2015. This can be retrieved to the climatic demand, which was higher in 2015 than in 2014. Furthermore, it is also shown that differences between observed and simulated CC was more accentuated under treatment showing water stress condition. The difference between observed and simulated CC and even the positive interaction between this difference and the stress level to which the plant was subject, have been reported for potatoes crop (De casa et al., 2013).

3.2.2. Soil water contents

![Table 3](image)

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>RMSE</th>
<th>E</th>
</tr>
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<tbody>
<tr>
<td>T1</td>
<td>16</td>
<td>3.84</td>
<td>0.98</td>
</tr>
<tr>
<td>T2</td>
<td>16</td>
<td>5.54</td>
<td>0.95</td>
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</table>

![Table 4](image)

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>RMSE</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>8</td>
<td>5.86</td>
<td>0.96</td>
</tr>
<tr>
<td>T2</td>
<td>8</td>
<td>7.90</td>
<td>0.86</td>
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</tbody>
</table>

![Table 5](image)

<table>
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<tr>
<th>Horizon</th>
<th>Texture</th>
<th>Depth</th>
<th>Θs  [cm$^3$.cm$^{-3}$]</th>
<th>Θcc [cm$^3$.cm$^{-3}$]</th>
<th>Θpfp [cm$^3$.cm$^{-3}$]</th>
<th>Ks [cm.h$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sandy loam</td>
<td>0-15</td>
<td>0.40</td>
<td>0.28</td>
<td>0.10</td>
<td>11.00</td>
</tr>
<tr>
<td>2</td>
<td>Sandy loam</td>
<td>15-30</td>
<td>0.39</td>
<td>0.28</td>
<td>0.10</td>
<td>6.40</td>
</tr>
<tr>
<td>3</td>
<td>Sandy loam</td>
<td>30-40</td>
<td>0.40</td>
<td>0.28</td>
<td>0.10</td>
<td>3.80</td>
</tr>
</tbody>
</table>

**Figure 4.** Comparison between measured (black dots) and simulated (solid line) canopy cover, CC, in treatments T1 and T2 during the experimental year of 2014.
Table 5 presents Soil properties used to represent the soil profile in Aquacrop for T1 and T2 during the experimental year of 2014 and 2015.

Figure 5 presents the statistical values of the mean square error, MBE, the square root of the error, RMSE and the Nash-Sutcliffe coefficient, E, obtained on the basis of the observed and measured values of water contents. Values of MBE, were negative, showing that model underestimated soil water contents. As shown on the figure, the RMSE values were always lower than 0.02 cm$^3$.cm$^{-3}$, suggesting that simulated water were similar to the measured ones in the 40 cm soil layer. The calibration of the soil functions was also tested during 2014 and 2015. As it was with vegetation cover, statistical indices showed the model simulated better the full irrigated treatment. However, despite this underestimation, statistical indicators (Figure 5) showed that RMSE were close to 0 and E close to one for both treatments, which confirm the performance of the model to simulate water contents for non deficit (T1) and deficit treatment (T2). When evaluating Aquacrop's ability for soil water content simulation, Bello and Walker (2016) suggested that the model ability is acceptable but considerable improvement should be investigated. Furthermore, difference between estimated and measured soil water content could be justified by an appropriate estimation of evapotranspiration. In fact, the combination of soil evaporation and crop transpiration, leads to discourse about accuracy. Katerji et al. (2013) noted that AquaCrop typically simulated low values of Evapotranspiration and emphasize the drought effect. In the same direction, Farahani et al. (2009) concluded that the model estimation of soil evaporation still arguable since it resulted almost similar under different water application. This last result could be accentuated when is not possible to introduce the exact depth of the drip line.

4. Conclusion

In this study, Aquacrop was calibrated to estimate variability of canopy cover development and water contents for two irrigations strategies under the semiarid condition of Tunisia. During the calibration procedure, several iterations were
investigated to test the possibility to use the conservative parameters proposed by Aquacrop. Therefore, the paper discussed the parameters that were modified from default values of Aquacrop to obtain the discussed results. Findings showed that the model was able to simulate canopy cover (CC) and water contents (θv) under deficit and full irrigation. Statistical indicators for root mean square error (RMSE), Mean Bias Error (MBE), Nasch coefficient (E) and coefficient of determination (R²) for CC underlined that model performance was better under non-stressed plots. However, in general, values of RMSE were lower than 6% for canopy development and than 0.03 cm³.cm⁻¹ for water contents. For both parameters, values of E were close to 1. Once assessed, this model could be used to study effects of different irrigation strategies on dynamic of vegetative growth and water contents corresponding to different irrigation scheduling and to avoid the fact real drastic effect of field production.

References


