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Research Paper

Parameterization of the AquaCrop model for simulating table grapes growth and water productivity in an arid region of Mexico

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ABSTRACT

Currently, the AquaCrop model has been widely tested for many fruit/grain crops; root and tuber crops; leafy vegetables, or forage crops, but is restricted to annual herbaceous species, while deciduous crops have received less if no attention. In this context, this study aims to test for the first time the ability of the AquaCrop model to simulate canopy cover (CC), actual evapotranspiration (ETa), total soil water content (TWC), biomass (B) and fruit yield (FY) of table grapes vineyards (Vitis vinifera L., cvs. Perlette and Superior) at the Costa de Hermosillo, Sonora in Northwest Mexico. Observed weather and soil physical parameters, with measured crop parameters from an experiment conducted during 2005 were used to develop climate, soil and crop input files for AquaCrop and for calibrating the model. While collected data during the 2006 growing season were used to validate the model. The model adequately simulated CC, ETa and TWC during 2005 and 2006. The Root Mean Square Error (RMSE) between observed and measured CC, ETa and TWC were 5.18%, 0.46 mm/day and 10.11 mm during 2005, and 8.82%, 0.84 mm/day and 9.1 mm during 2006, respectively. The good accuracy of simulations of CC, ETa and TWC by the model have been confirmed by additional statistical parameters like the coefficient of determination (R^2), The Mean Bias Error (MBE), the Willmott's index of agreement (d) and the Nash–Sutcliffe Efficiency (NSE).For the B and FY simulations, the results showed that the model correctly reproduced the B and FY with NRMSE value of 8.8%. The estimated average value of FY (14.56 t/ha) for both seasons are in the range of the potential yield (14–18 t/ha) of table grapes in the irrigated Costa de Hermosillo in northwest Mexico.After the validation of the AquaCrop model, it was used to evaluate the irrigation scheduling by the farmer as well as to assess the water productivity computed as the ratio of crop production to crop water use. The results showed that, the recommended irrigation by the model was about 547 mm and 509 mm, which it is about half of that applied by the farmer (1006 mm and 929 mm) during 2005 and 2006, respectively. This large difference, which represents approximately 54% and 57% of the irrigation supply, is lost through deep percolation and could be saved without vegetation suffering from water stress while maintaining the same yield. The high loss of water by percolation affects significantly the water productivity (WP), which decreases from 3.22 to 1.74 kg/m^3 if we consider the transpiration (WP_{Tr}), and the sum of ETa and Percolation (WP_{ETa+Pr}) for WP computations, respectively. Consequently, the AquaCrop model can be used as an operational tool by decision makers and growers to improve irrigation management. This is of crucial importance in arid and semi-arid regions where water is becoming increasingly scarce.

1. Introduction

Optimizing water in agriculture is essential over arid and semi-arid regions in order to preserve water resources, which are already scarce due to climate change and human activities related mainly with agriculture that accounts for approximately 70% of the total water used (Cosgrove and Rijsberman, 2000).

In these regions, water scarcity is one of the main factors limiting agricultural development, and threatening food security. The impact of water scarcity is amplified by inefficient irrigation practices, since irri-

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gation consumes more than 85% of the available water in these regions (Chehbouni et al., 2007).

In the Northwest region of Mexico, table grapes is the main agricultural crop, and accounts for about 25% of all agricultural exports and therefore is an important source of income as well as rural employment (Rodríguez et al., 2010). In this region, water storage (small dams or ground water) provides a reliable irrigation water supply. However, the amount of available water has gradually decreased due to the impact of climate change combined with the overexploitation of aquifers (Rangel-Medina et al., 2004). Consequently, agriculture in this region might be in jeopardy if no efficient irrigation system is implemented. This can be achieved by applying useful tools for scheduling the amount and timing of irrigation.

In this context, the AquaCrop tool developed by the United Nation's Food and Agricultural Organization, can be used for determining crop water needs and schedule irrigation on an operational basis. This approach is often preferred for operational applications since it combines simplicity and robustness. Additionally, AquaCrop requires relatively few input data and the reported results are satisfactory (Hsiao et al., 2009; Raes et al., 2009; Heng et al., 2009).

As stated above, all previous studies that used AquaCrop have been focused on annual herbaceous species such as: wheat (e.g. Andarzian et al., 2011; Toumi et al.,), maize (Paredes et al., 2014; Akumaga et al., 2017), rice (Maniruzzaman et al., 2015); soybeans (Paredes et al., 2015; Adeboye et al., 2017); sorghum (Araya et al., 2016) and cotton (Farahani et al., 2009). As far as to our knowledge, very limited or no studies on the application of AquaCrop model for deciduous crops (e.g. table grapes, Apricot, etc.) have yet been performed. Although this type of crops, is characterized by a canopy cover development similar to annual crops, some difficulties for the parameterization of canopy cover (CC) can be encountered mainly at the beginning of season since the deciduous crops are not sown every season but remain planted for several years. This results with some difficulties in the determination of some parameters used for CC estimation, mainly the time from sowing to emergence. After a dormancy period when the growth and the development of vines stop temporarily, the start of the vegetative cycle begins with the appearance of the first green leaves through the bud scales, which is called ''budbreak'' (Williams and Ayars, 2005; Rodríguez et al., 2010; Er-Raki et al., 2013; Vanino et al., 2015). Based on this observation, the sowing date was replaced by budbreak for simulation of CC in AquaCrop for table grapes, and the emergence was replaced with the full budbreak that corresponds to about 10% of CC, because the growth of table grapes is generally slow at the beginning of the season.

The main objective of this work, is to test for the first time the ability of the AquaCrop model to simulate canopy cover (CC), actual evapotranspiration (ETa), total soil water content (TWC), biomass (B) and fruit yield (FY) of table grapes (Vitis vinifera L., cvs. Perlette and Superior) in the arid region of Costa de Hermosillo, Sonora in Northwest Mexico. The performance of the AquaCrop model has been evaluated based on field data collected during two consecutive growing seasons (2005 for calibration and 2006 for validation). The drip irrigation planning practiced by the farmer has been also assessed through evaluating the water use efficiency and crop productivity.

2. Materials and methods

2.1. Study and data description

The research was carried out in Costa de Hermosillo, located in the lower part of the Sonora river watershed in northwest Mexico. The area is characterized as arid climate with an average annual temperature of 22 °C, with occasional extremes temperature below 0.0 °C in winter and over 45.0 °C in summer, and 200 mm of annual rainfall, with the rainy season from July to September.

Two plots of table grapes vineyards were conducted in years 2005 (Vitis vinifera L., cvs. Perlette: 111, 348 W; 28.929 N; 96 m a.s.l) and 2006 (Vitis vinifera L., cvs. Superior: 111, 343 W; 28.928N; 96 m a.s.l) with more than 10 ha each of them. The vines were planted in rows with 3.8 m spacing, 1.0 m apart for the Perlette vineyard and 1.8 m apart for the Superior vineyard. A ''Y'' trellis system was used in both Perlette and Superior vineyards. The soils have high sand and low clay contents (64% of sand, 22% of clay, and 14% of silt). The crop was maintained in well-watered conditions by drip irrigation, with high application of fertilizers (Rodríguez et al., 2010; Er-Raki et al., 2013).

Following the guidelines provided for the AquaCrop users (Hsiao et al., 2012), the main in situ data needed for parameterization, calibration and validation of AquaCrop are generally related to the main components of the soil–plant–atmosphere continuum. These components include CC, ETa, soil moisture at different depth, biomass (B) and grain or fruit yield (FY), which are the main output of AquaCrop model.

Table 1
List of Measurements and Instruments for the automatic weather station and Eddy covariance system installed over table grapes at the Costa de Hermosillo, Sonora river watershed in northwest Mexico.

Measurement	Instrument used	Height/depth	Target parameter as input /output of AquaCrop
Incoming solar radiation	Radiometer CM6 (Kipp and Zonen, Netherlands)	4 m	ET_0 : input
Air temperature (Ta) and humidity (HR)	HMP45C Vaisala	6 m	ET0 : input
Wind speed and direction	anemometer model 034B (Met One, USA)	6.1 m	ET0 : input
Rainfall	TE525mm tipping bucket automatic rain gauge (Campbell Inc., USA).	2 m	Input
Net radiation (Rn)	Net radiometer (Kipp and Zonen, Netherlands)	5 m	ET_0 : input
U, V and W wind vectors speed to measure the sensible heat (H)	three-axis ultrasonic anemometer, (CSAT3, Campbell Scientific Ltd.)	6.1 m	ET_a: output
concentration of water vapor to measure latent heat flux (LE)	Hygrometer KH20 (Campbell Scientific Ltd.)	6.1 m	ETa: output
Soil heat flux (G)	heat flux plates (HTF3), REBS	-1 cm	ETa: output
Canopy Cover (CC)	1 m^2 white plate (shaded area)	Beneath the grapes	CC: output
Soil moisture content	a split tube sampler	– 10, – 20, – 30, – 40, – 50, – 60, – 80, – 90, – 100, – 110, – 120	TWC: output
Biomass (B)	Based on the weight measurements of canes, leaves, litter and fruit		B: output
Fruit Yield (FY)	Estimated by the farmer based on the bunches measurements	–	FY: output

Table 1 illustrates the list of the measurements and instruments used in this study. More details about the study site and different measurements were presented in Rodríguez et al. (2010) and Er-Raki et al. (2013).

Daily meteorological air temperature, relative humidity, rainfall, reference evapotranspiration (ET_0) and the irrigation amount given by the farmers during each of the studied growing seasons (2005 and 2006) are presented in Fig. 1. The seasonal air temperature in two seasons is similar with a maximum and minimum air of about 40 °C and 4 °C, respectively. The peak air temperature occurred during July, while the low values was during February–March period.

Regarding the reference evapotranspiration (ET_0) which is the main input component in the AquaCrop model, the temporal pattern of ET_0 for both seasons is typically of arid continental climates, with an average accumulated annual ET_0 of 1800 mm. The lowest values of ET_0 occurred during the winter and autumn (2 mm/day) and the highest values occurred in the end of spring and summer season (around 9 mm/day). Concerning the irrigation scheduling by the farmers, as shown in Fig. 1, the irrigation frequency was almost every day with an average daily amount about 6 mm, without taking into account neither the rainfall events nor the crop water demand. The soil water content was measured weekly using a split tube down to 120 cm depth at 10 cm intervals (Rodríguez et al., 2010). Then, total water content (TWC) in the root zone layer (0–120 cm) was computed by using linear weighting, and was used for comparison with the estimated TWC by the AquaCrop model (Raes et al., 2012). Soil samples taken at each layer allowed us to determine the different parameters needed for the soil file for the AquaCrop model (Table 2). The soil texture classes, field capacity (FC), wilting point (WP), saturation and saturated hydraulic conductivity were determined at the Soil Survey Laboratory of the Colegio de Posgraduados (http://www.colpos.mx). Soil texture was obtained by the Bouyoucos hydrometer method, while FC and WP were measured using the pressure membrane apparatus at − 30 kPa and − 1.5 MPa, respectively. Additionally, the measurements of the canopy cover (CC) over each field were collected on the shaded area beneath the grapes by using 1 m^2 white plate, divided into 100 small squares of 100 cm^2 each. These measurements were performed around noon, generally between 12:00 and 12:30 p.m, every week on sunny days according to Williams and Ayars (2005) and Er-Raki et al. (2013).

In addition, direct measurements of ETa were performed by an eddy covariance system that measured latent (LE) and sensible (H) heat fluxes, similar to that described in Rodríguez et al. (2010) and Er-Raki et al. (2013). An eddy covariance (EC) system was installed on a tower at 6 m above ground level at a position that allowed a fetch of about 400 m. The eddy covariance system used, consisted of commercially available instrumentation: a 3D sonic anemometer (CSAT3, Campbell Scientific Ltd.), which measured the fluctuations in the wind velocity components and temperature, and a KH20 (Campbell Scientific Ltd.) that measured concentration of water vapor. Raw data were sampled at a rate of 20 Hz and were recorded using CR5000 data loggers (Campbell Scientific Ltd.). The half-hourly values of fluxes were later calculated off-line after performing coordinate rotation, correcting the sonic temperature for the lateral velocity and the humidity effects, making frequency integration, and including the mean vertical velocity according to Webb et al. (1980), Schotanus et al. (1983) and Wilczak et al. (2001). Two heat flux plates (one between the rows and the other underneath the vines) were installed to measure the soil heat flux (G). The calculation of actual evapotranspiration ETa (mm) at a daily time scale was obtained by summation of the half hourly values. Finally, the biomass (B) and fruit yield (FY) are measured based on counting the number of canes per plant, leaves, litter and fruit harvest. During the annual pruning in winter, 10 plants were randomly selected and all canes of the growing season were counted and weighted. During the development cycle of the vine, baskets were placed under the vine to collect the litter. Selective pruning to remove leaves and fruits were collected manually per plant and weighted. The yield estimation was carried out by collecting the fruits during the harvest, taking the bunches from six boxes of 8.2 kg. The statistical information of the producers association was used in relation to the number of boxes per year for each variety. The total annual biomass is computed as the sum of canes, leaves, litter and fruits masses. Based on those measurements, the total biomass (fruit yield) are about 32.89 (17.60) t/ha and 27.75 (14.5) t/ha during 2005 and 2006, respectively. The fruit yield (FY) for two cultivars are inside the range of what is produced (14–18 t/ha) in Costa de Hermosillo, northwest Mexico, following the statistical data

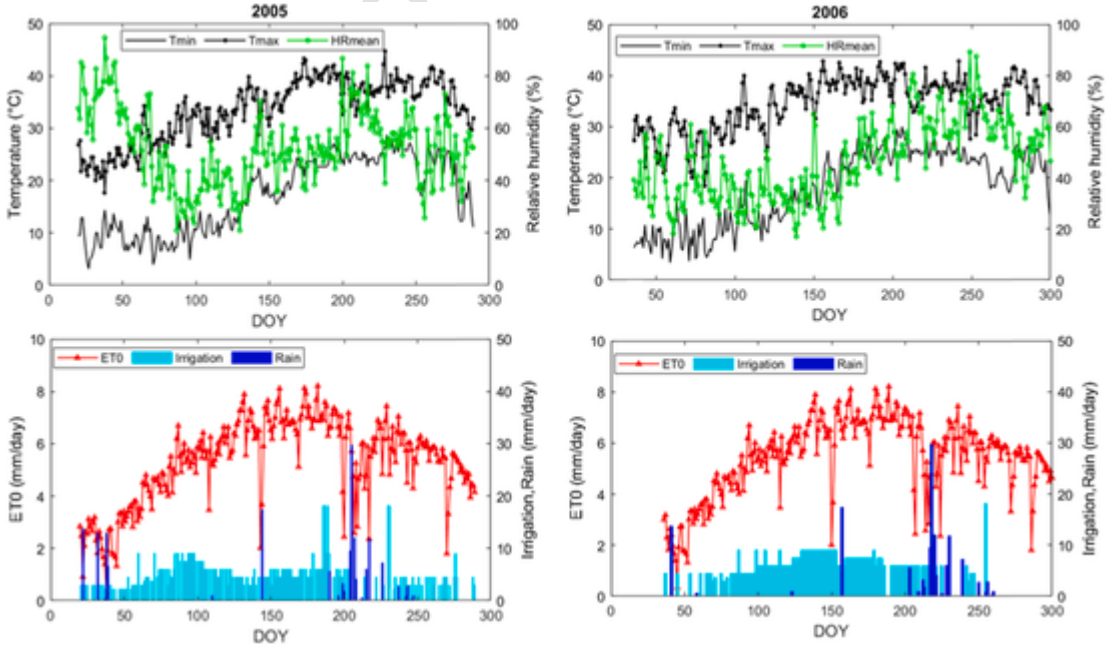

Fig. 1. Daily evolution of meteorological data during 2005 and 2006 cropping seasons. ET0: reference evapotranspiration, Tmin and Tmax are the minimum and the maximum of daily air temperature and HRmean is the average daily relative humidity. Rainfall and irrigation amounts are also shown.

Table 2
Soil hydraulic properties of experimental fields.

Soil hydraulic properties	Depth (cm)			
	0–30	30–60	60–90	90–120
Field capacity FC (m^3/m^3)	0.14	0.15	0.18	0.19
Wilting point WP (m^3/m^3)	0.06	0.07	0.08	0.08
Saturation SAT (m^3/m^3)	0.30	0.32	0.43	0.41
Saturated hydraulic conductivity, K_{sat} (mm/day)	350	340	325	320

provided by the Farmers Association of Northern Sonora and by the Economic Services of the Agriculture Agency in the irrigated Costa de Hermosillo of northwest Mexico (SAGARPHA, 2018). The grapes yield production depends mainly on the irrigation water supply and fertilization (Li et al., 2020).

2.2. Description of the AquaCrop model

AquaCrop (http://www.fao.org/nr/water/aquacrop.html) is a software system developed by the Land and Water Division of FAO in order to simulate the yield response to water by increasing water efficiency practices in agricultural production (Araya et al., 2010). The AquaCrop model relates the soil-plant-atmosphere components through the water balance (Araya et al., 2010). The main input file for the simulation are: climate data (minimum and maximum air temperature, ETo, rainfall and CO2), crop data (time to emergence, maximum canopy cover, start of senescence, maturity), soil data (field capacity, permanent wilting points, saturated hydraulic conductivity), management data (irrigation, field management practices) and initial soil water conditions (Steduto et al., 2012). Some of them were used from the reference manual for AquaCrop as default (Raes et al., 2012).

AquaCrop uses canopy ground cover (CC) instead of leaf area index (LAI) as the basis to calculate separately transpiration (Tr) and soil evaporation (Es) (Araya et al., 2010). Through its leaf expansion growth, ageing, stomata control of transpiration, canopy development and senescence (Steduto et al., 2009; Araya et al., 2010), CC determines the amount of water transpired (Tr), which in turns determines the amount of biomass produced (B) and the final yield (Y) as the product B and harvest index (HI). A further detailed description of the AquaCrop model with additional fundamental concepts, and different equations are available in Raes et al. (2009, 2012), Hsiao et al. (2009) and Steduto et al. (2009).

2.3. Parameterization, calibration and validation of the AquaCrop model

In this study, AquaCrop V6.1 was used. Various parameters that need to be calibrated are those produced as the main output of the model: CC, ETa, TWC, B and FY. Those parameters are grouped into two classes: conservative and non-conservative. The conservative parameters do not change with time, location, management or cultivar (Raes et al., 2012). While the non-conservative parameters depend on environmental conditions and management practices.

As table grapes are not available in the data base of AquaCrop model, a crop file has been created by specifying the crop as fruit crops. The main difference between table grapes and the existing crops (e.g. wheat, maize, sorghum, other.) is the beginning of season (mainly the sowing and the emergence dates) because table grapes are not sown every season but are planted for several years. However, the development of its CC is similar to the annual crops through the season. Then, for AquaCrop simulation, the sowing date is replaced by budbreak date, which corresponds to the appearance of the first green leaves through the bud scales, and the emergence is replaced with the full budbreak that corresponds to about 10% of CC because the growth of table grapes is generally slow at the beginning of season (https://www.grapesfromcalifornia.com/annual-grapevine-cycle/).

Table 3 represents the main conservative and non-conservative parameters used for the calibration and the validation of the AquaCrop model for table grapes during 2005 and 2006 growing seasons, respectively. A good simulation of the CC is very important in AquaCrop because it influences transpiration, which has effects on the final biomass and yield of the crop. The calibrated parameters for good estimation of CC are: initial canopy cover (CC_0), maximum canopy cover (CCx), canopy growth coefficient (CGC), canopy decline coefficient (CDC) and the values of cumulative growing degree days (CGDD) in each development stages (budbreak to full budbreak, budbreak to maximum CC, budbreak to start senescence and budbreak to maturity). The water stress parameters and the curve shapes were also adjusted to accurately estimate the canopy cover (Table 3).

Concerning the actual evapotranspiration (ETa), two main parameters should be adjusted in order to produce a good estimates of ETa: the maximum crop transpiration coefficient ($Kc_{Tr,x}$) for calculation of plant transpiration and the maximum soil evaporation (K_{ex}) for soil evaporation. Finally, the reference harvest index (HI_0) and the normalized crop water productivity (WP*), were calibrated for table grapes in order to reproduce correctly the actual B and FY. The adjusted of the main conservative and non-conservative parameters (Table 3) will be discussed and analyzed in Section 3, when the performance of AquaCrop for estimating CC, ETa, TWC biomass and FY is presented.

Table 3
Main input parameters used for the calibration and the validation of the AquaCrop model for table grapes during 2005 and 2006 growing seasons.

Parameters	Value	
	Calibration stage	Validation stage
	2005	2006
Conservative		
Base temperature (°C)	10	10
Upper temperature (°C)	35	35
Initial canopy cover, CC_0 (%)	6.4	6.4
Canopy growth coefficient, CGC (%/GDD)	0.0054	0.0054
Canopy decline coefficient, CDC (%/GDD)	0.0014	0.0014
Maximum coefficient for transpiration, $Kc_{Tr,x}$	0.6	0,6
Maximum coefficient for soil evaporation, K_{ex}	0.23	0.23
Upper threshold for canopy expansion, $P_{exp,upper}$	0.3	0.3
Lower threshold for canopy expansion, $P_{exp,lower}$	0.8	0.8
Leaf expansion stress coefficient curve shape	5.5	5.5
Upper threshold for stomatal closure, $P_{sto,upper}$	0.5	0.5
Stomata stress coefficient curve shape	3	3
Canopy senescence stress coefficient, $P_{sen,upper}$	0.85	0.85
Senescence stress coefficient curve shape	3	3
Reference harvest index, HI_0 (%)	55	55
Normalized crop Water productivity, WP*(g/m^2)	35	35
Non conservative		
Time from budbreak to full budbreak, days (CGDD)	10 (58)	20 (130)
Time from budbreak to maximum CC, days (CGDD)	113(952)	123 (1120)
Time from budbreak to start senescence, days (CGDD)	141(1560)	170 (1941)
Time from budbreak to maturity, days (CGDD)	253 (3450)	265 (3681)
Maximum canopy cover, CCx (%)	63	65
Maximum effective rooting depth, Zx (m)	1.2	1.2

Finally, the different output of AquaCrop model were used to calculate the water productivity (WP) as the ratio of FY and water consumption (Molden, 1997). Three different ways referring to amount of water consumption were chosen to calculate different forms of WP according to Molden et al. (2001): WP_{Tr} referred to transpiration (Tr), WP_{ETa} to evapotranspiration (ETa), WP_{ETa+Pr} to the sum of evapotranspiration and percolation (Pr).

2.4. Model evaluation

To evaluate the performance of AquaCrop for simulating CC, ETa, TWC, several statistical parameters were used in this study: (1) Coefficient of Determination (R^2) which expresses the degree to which the measured and simulated variables are linearly related. (2) The mean bias error (MBE) and the mean absolute error (MAE), which indicates the percent of the average deviation of the simulated values from the measured ones (Zacharias et al., 1996). (3) the Root Mean Square Error (RMSE), which measures the discrepancy of simulated values around observed ones (Jacovides and Kontoyiannis, 1995). (4) The normalized root mean square error (NRMSE) expresses the relative difference between the model and measured data. (5) The Nash-Sutcliffe efficiency (NSE), is a normalized statistic that determines the relative magnitude of the residual variance compared to the measured data variance (Nash and Sutcliffe, 1970). (6) Willmott's index of agreement (d), which is a standardized measure of the degree of model simulation error which varies between 0 and 1 (Willmott, 1981), with higher index values indicating that the simulated data have better agreement with the observations.

$$NRMSE = \frac{1}{\bar{O}}\sqrt{\frac{\sum_{i=1}^{n}(S_i - O_i)^2}{n}} \times 100$$

$$RMSE = \frac{1}{n}\sqrt{\sum_{i=1}^{n}(S_i - O_i)^2}$$

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(S_i - O_i)$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|S_i - O_i|$$

$$d = 1 - \left[\frac{\sum_{i=1}^{n}(S_i - O_i)^2}{\sum_{i=1}^{n}\left(|S_i - \bar{O}| + |O_i - \bar{O}|\right)^2}\right]$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}(S_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}$$

where O_i measured data, S_i simulated data, $\bar{O}$ average of simulated data and n number of data.

3. Results and discussions

The evaluation of the AquaCrop model was based on the performance simulation of CC, ETa, TWC biomass and FY. Then, the model has been used for assessment of the irrigation planning practiced by the farmer through evaluating the water use efficiency and productivity.

3.1. AquaCrop model calibration

As mentioned in the previous section, the main parameters that need to be calibrated are those related with the main output of AquaCrop: CC, ETa, TWC biomass and FY.

For canopy cover (CC) which is considered as a crucial feature of AquaCrop, the key parameters affecting the development of CC are: CC_0, CDC, CGC, and CGDD in each crop development stages. Those parameters were adjusted using the data collected over the table grapes during the 2005 season. The best values of CC_0, CDC, CGC that give a good estimates of CC are 6.4%, 0.0014 and 0.0054 (%/GDD). Other parameters ($P_{exp,upper}$, $P_{exp,lower}$, $P_{sen,upper}$ and $P_{sto,upper}$) which affect the CC development have been also adjusted and their values being 0.3, 0.8, 0.85 and 0.5, respectively (see Table 3). In addition to these adjusted parameters, the values of CGDD in each crop development stages were determined based on the base temperature (T_{base}) and the upper temperature (T_{upper}), which are equal to 10 and 35 °C, respectively according to Williams and Ayars (2005).

For crop evapotranspiration (ETa) simulations by AquaCrop, two main parameters (maximum coefficient for transpiration, $Kc_{Tr,x}$ and maximum coefficient for soil evaporation, K_{ex}), that affect plant transpiration and soil evaporation are calibrated. The obtained values of K_{ex} and $Kc_{Tr,x}$ were 0.23 and 0.6, respectively. The value 0.23 of K_{ex} was expected because the majority of the soil surface is shaded with the trees and not fully wetted due to the drip irrigation system. For $Kc_{Tr,x}$, as CCx did not reached 100% for table grapes (see Table 3), AquaCrop model adjusted the value of $Kc_{Tr,x}$ based on the observed values of ETa during 2005. The obtained value of $Kc_{Tr,x}$ is in agreement with other works (e.g. Er-Raki et al., 2013; Rodríguez et al., 2010; Campos et al. 2010; Vanino et al., 2015), where they found near by the values derived from in situ measurements or from different vegetation indices. For a good simulation of biomass and fruit yield (FY), the HI_0 and WP* are adjusted and are equal to HI_0 = 55% and WP* = 35 g/m^2 (Table 3), respectively.

Fig. 2 and Table 4 show the simulation results for table grapes using the calibration data set (2005) for CC, ETa and TWC. It can be seen that the AquaCrop model correctly simulates the canopy cover (CC) development of table grapes (Fig. 2-a). The RMSE, MBE, d and R^2 are 5.18%, 2.61%, 0.98 and 0.96, respectively. Additional statistical results presented in Table 4, confirm the accurate estimate CC by the model. The accurate parameterization of the CC curve has a direct effect on the estimation of ETa (Fig. 2-b). The goodness of fit indicators relative to the comparison between measured and simulated ETa is given in Table 4. The corresponding R^2, slope and d are close to 1 with low values of RMSE (0.46 mm/day) and MBE (−0.04 mm).

The AquaCrop model was also used for evaluating the soil water content of the total profile (0–120 cm) for table grapes during 2005, and the results are shown in Fig. 2-c. Daily patterns of simulated and measured TWC are similar and respond well to water supply (irrigation and rainfall). In addition, the simulated and the measured soil water content remained above field capacity (FC) for most of time, which means that excess water can percolate to deep soil layers. One can note that the model tends to underestimate TWC for high TWC (>FC), but the opposite happens when the soil moisture is below FC. Although some discrepancies, the AquaCrop model gives acceptable results in estimating TWC, which was confirmed by different statistical values (Table 4). For example, The NRMSE and the index of agreement (d) between simulated and measured TWC are 5.66% and 0.67.

3.2. Validation of the AquaCrop model

After an accurate calibration of the model during 2005, data collected during 2006 season were used for the validation of AquaCrop, considering the same parameters derived in the calibration procedure. Fig. 3 and Table 4 show the measured and simulated results for the validated data sets for CC, ETa and TWC.

One can note that, the beginning of 2006 season is delayed compared to 2005 season, which can be related to climatic conditions and grapes varieties. In fact, there was a post-dormancy period named the "quiescence" period (Sarvas, 1974) during which buds remain dormant due to adverse environmental conditions, mainly due to higher

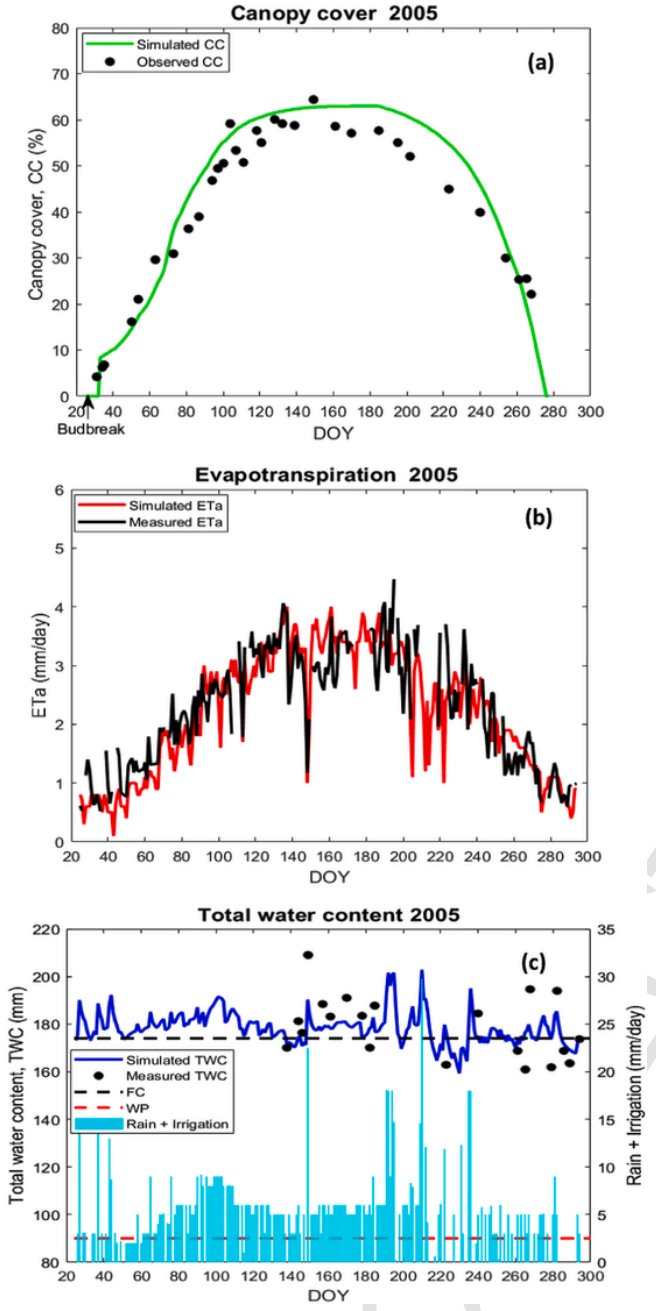

Fig. 2. Comparison between measured and simulated canopy cover (CC), actual evapotranspiration (ETa) and Total water content (TWC) for table grapes during 2005 (calibration stage).

air temperature and lower relative humidity for our study site (see Fig. 1).

It can be seen that, the AquaCrop model correctly simulates CC (Fig. 3-a), which was confirmed by different statistical values provided in Table 4.. It is also important to note that, the simulated CC was close to the observed values from budbreak to maximum CC (Fig. 3-a). However, one notices a slight overestimation of CC by the model, because the model do not include the possibility of make changes, like canes pruning to reduce the CC and grape transpiration during the maximum atmospheric demand especially where there is a net decrease in CC during the maximum crop stage (DOY160 to DOY 200). This discrepancy is related to the decrease in leaf area, resulting from the mechanical pruning and training of the grapes, which are two of the most important aspects for quality grape production (Campos et al., 2010; Er-Raki et al., 2013). Despite this slight mismatching related to the pruning and training systems, which are not taken into account by the model, the overall results in estimating CC for table grapes are satisfactory. Globally, the obtained results are in agreement with the previous results testing AquaCrop for annual herbaceous species such as wheat (Andarzian et al., 2011; Toumi et al.,), maize (Paredes et al., 2014; Akumaga et al., 2017), soybeans (Paredes et al., 2015; Adeboye et al., 2017); sorghum (Araya et al., 2016).

Regarding the validation of the model for ETa simulations (Fig. 3-b and Table 4), statistical parameters displayed in this table show that the model correctly estimates ETa, but with less accurate estimations if we compare with the obtained results for 2005. For example, the RMSE and R^2 were equal to 0.84 mm/day and 0.66 while during the previous year they were equal to 0.46 mm/day and 0.8 (see Table 4 for other statistical parameters). This may be due that $Kc_{Tr,x}$ is calibrated for a set data of ETa not exceeding 4 mm/day as the case for 2005 season. Thus, a clear underestimation of ETa is observed during 2006 at higher values of evapotranspiration (> 4 mm/day). This is expected because the evapotranspiration during 2006 (cv. Superior) is generally greater than that for cv. Perlette (2005). This is because the Superior variety develops more leaves, which can be superimposed leading to CC saturation, and then underestimating ETa while the Leaf area index (LAI) and vegetation transpiration were still increasing as measured by eddy covariance system. The same observations have been reported by Er-Raki et al. (2013), in the same study site when applying the relationship between crop coefficient (Kc) and the Normalized difference vegetation index (NDVI) for determining evapotranspiration, and found the underestimation of ETa due to the NDVI saturations. In the same context of misrepresenting of $Kc_{Tr,x}$ which is linked to transpiration and directly influenced ETa. In line with this, Sandhu and Irmak (2019) and Paredes et al. (2014) highlighted that the high dependency of $Kc_{Tr,x}$ on the CC curve can affect the simulated transpiration and then ETa, and they suggested to revise this large dependency in order to improve the ETa estimates by the AquaCrop model.

Another factor may partially explain, the difference between measured and simulated ETa for high values of ETa is the presence of the understory between the trees, which can increase the measured ETa by

Table 4
Statistical analysis between the measured and the simulated canopy cover (CC), actual evapotranspiration (ETa) and total water content (TWC) of Table grapes during 2005(calibration) and 2006 (validation) agricultural seasons.

Variables	Season	R^2	Slope	d	NSE	NRMSE (%)	RMSE	MBE	MAE
CC (%)	2005	0.96	1.11	0.98	0.91	12.52	5.18	2.61	4.64
	2006	0.90	1.07	0.93	0.69	21.23	8.82	6.62	6.91
ETa (mm/day)	2005	0.80	0.95	0.94	0.77	20.65	0.46	-0.04	0.37
	2006	0.66	0.61	0.87	0.61	31.27	0.84	-0.26	0.63
TWC (mm)	2005	0.55	0.28	0.67	0.38	5.66	10.11	-2.52	8.77
	2006	0.73	0.70	0.91	0.73	5.17	9.11	-0.69	7.40

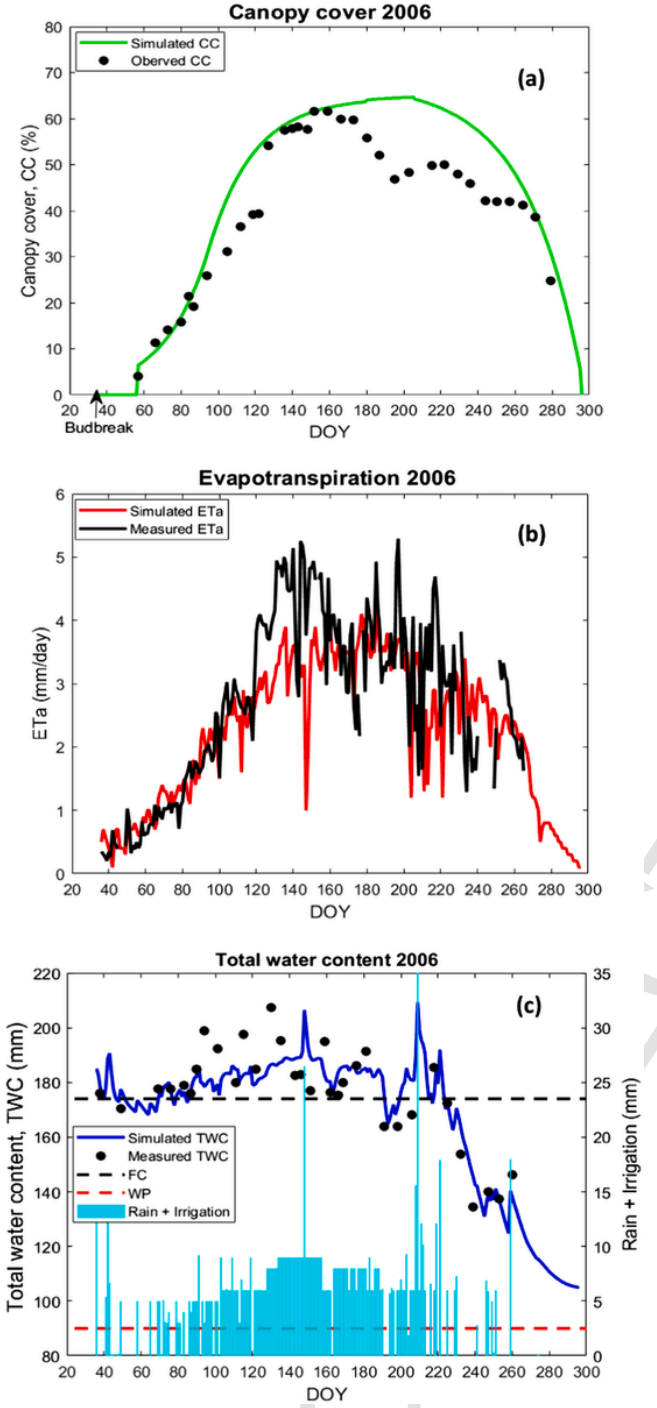

Fig. 3. Comparison between Measured and simulated canopy cover (CC), actual evapotranspiration (ETa) and Total water content (TWC) for table grapes during 2006 (validation stage).

eddy covariance. This is possible because the irrigation amount (477 mm) supplied from DOY 120 to DOY 180 during 2006 was higher than that supplied (269 mm) during 2005 for the same period.

Without exception, the obtained results showed a good reliability of the AquaCrop model for estimating ETa for table grapes in a semi-arid region. The results are in concordance with other methods applied for table grapes such as Kc- NDVI relationship (Er-Raki et al., 2013) used in the same study area in Mexico and FAO-56 model (Campos et al., 2010) in the province of Albacete, Spain, and in the Apulia region, Italy (Vanino et al., 2015).

Concerning the validation of AquaCrop predictions of TWC, Fig. 3-c shows the comparison between the observed and the simulated TWC for table grapes during 2006 season. The model adequately simulated the water dynamics of TWC, and responds well to water supply (irrigation and rainfall). The performances of the model for estimating TWC are better during 2006 than during 2005 (see statistical parameters in Table 4). The simulated as well as the measured soil water content remained above field capacity (FC) for most of the time, particularly from DOY 70 to DOY 180, which can lead to water losses through percolation. Also, both simulated and measured TWC are significantly higher than the wilting point (WP), which indicates that the plant does not suffer from water stress due to high frequency scheduling of irrigation by the farmer (see Fig. 1). It can be also noted that, the model tends to underestimate TWC when the soil moisture is above FC, while the TWC has been overestimated by the model when the soil moisture is below FC. Similar observations have been previously reported in several studies testing AquaCrop under different irrigation regimes (e.g. Farahani et al., 2009; Hussein et al., 2011; Mkhabela and Bullock, 2012; Iqbala et al., 2014; Toumi et al.,; Kale Celik et al., 2018; Adeboye et al., 2019).

Despite some slight discrepancy between the measured and simulated TWC, the AquaCrop model gives acceptable results in estimating TWC, which was confirmed by different statistical values (Table 4). For example, The RMSE, d and R^2 between simulated and measured TWC were 9.11 mm, 0.91 and 0.73, respectively. In general, the performances of AquaCrop in simulating TWC in this study are better than the previous studies using the same model. For example, Andarzian et al. (2011) and Toumi et al. applied the AquaCrop model for simulating TWC for winter wheat, and considered that the model accurately simulates TWC with a RMSE equal to 18 mm, 22 mm and 49,4 mm, respectively. On the other hand, Paredes et al. (2014) and Sandhu and Irmak (2019) reported a very low performance of the model in simulating TWC for maize when using default parameters. Sandhu and Irmak (2019) found high values of RMSE which ranged from 43.4 to 108 mm in 2011 and from 21 to 84 mm in 2012. Paredes et al. (2014) reported that the RMSE between measured and simulated TWC ranged from 16 to 36 mm. Based on their finding, they suggested the need for additional adjustments in model parameters.

Finally, the simulated biomass (B) and fruit yields (FY) of table grapes by the model are correctly reproduced (Fig. 4). The R^2 and NRMSE between estimated and measured B and FY for two growing seasons are 0.98% and 8.8%. The estimated average value (14.56 t/ha)

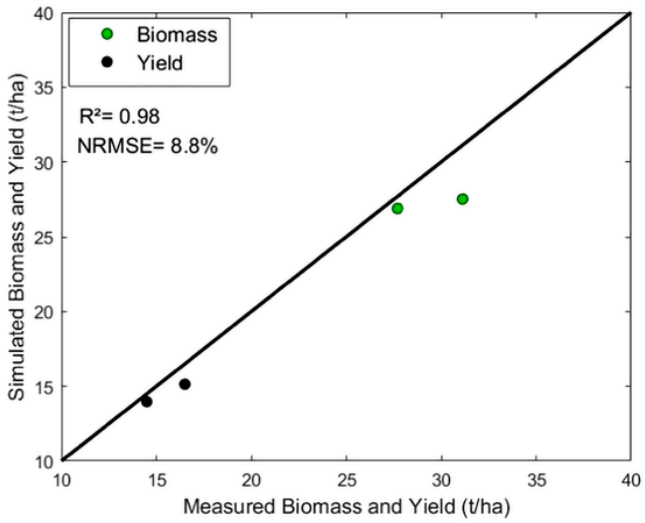

Fig. 4. Comparison between simulated and measured total biomass and fruit yield for table grapes during 2005 and 2006 seasons.

during two seasons are inside the range of what is produced (14–18 t/ha) in Costa de Hermosillo, northwest Mexico, following the statistical data provided by the Farmers Association of Northern Sonora. The good estimates of the yield confirms that the values of HI_0 and WP* have been correctly adjusted, which equal to 55% and 35 g/m^2 respectively (Table 3). These values are in agreement with other studies performed over table grapes (e.g. FAO, 2019; Li et al., 2020).

After an accurate calibration and validation of the AquaCrop model for estimating CC, ETa, TWC biomass and FY, it is of interest to apply this model for evaluating the irrigation planning practiced by the farmer over the study sites as well as to assess the water use efficiency and productivity.

3.3. Assessment of irrigation efficiency and crop water productivity

In this section, we use the AquaCrop model for evaluating the irrigation planning practiced by the farmer over the study sites. For this purpose, we analyze if the plant suffers from the water stress due to inadequate distribution of irrigation or there is some excessive irrigation that creates the water losses through percolation.

Fig. 5-a, b present the simulated water stress coefficient (Ks = ETa/ETc) and percolation losses during 2005 and 2006 seasons by using the amount and frequency of irrigation used by the farmer. According to those figures, as expected the vegetation does not suffer from water stress (Ks = 1) throughout both seasons because the farmer usually applies an excessive high frequency irrigation (about 6 mm per day) and the soil water content is frequently above field capacity as shown in Figs. 2-c and 3-c. This can result in a significant loss of water by percolation with a daily maximum of about 10 mm for 2005 and 15 mm for 2006, which coincides with the rainfall and irrigations events. When using the AquaCrop model simulations in order to avoid both water stress and deep percolation (Fig. 5c, d), the model recommends less water for irrigation and no percolation losses are recorded except during the heavy rainfall events.

For more quantitative analysis of the obtained results, the seasonal main components of water balance (evapotranspiration, transpiration and percolation) and the fruit yield (FY), simulated by the AquaCrop model using two irrigation scheduling systems (practiced by the farmer and the recommended by the model) are regrouped in Table 5. In addition, we calculate the crop water productivity (WP) for two irrigation regimes (see Table 5), in order to evaluate the water use efficiency and productivity. According to this table, the recommended irrigation by the model was about 547 mm and 509 mm, which it is about half of that given by the farmer (1006 mm and 929 mm) during 2005 and 2006, respectively. This large difference, which represents approximately 54% and 57% of the irrigation supply, is lost through deep percolation, which could be saved without vegetation suffering from water stress. The high percolation losses are not surprising due to inadequate use of the drip technique by the farmer. The same observations have been reported by Nassah et al. (2018), when applying the water balance method for evaluating the deep percolation losses of drip irrigated citrus crops in a semi-arid area of Morocco, and they found that about 45% of the water supply lost through deep percolation is due to the excessive irrigation.

Regarding the crop water needs (evapotranspiration or transpiration), it is similar for both irrigations treatments, which confirms that the additional amount of irrigation lost by percolation is not necessary and is not used by the plant either. The simulated average seasonal ETa are about 615 mm and 563 mm for 2005 and 2006, respectively, which are not significantly different for both years. Our results are similar to

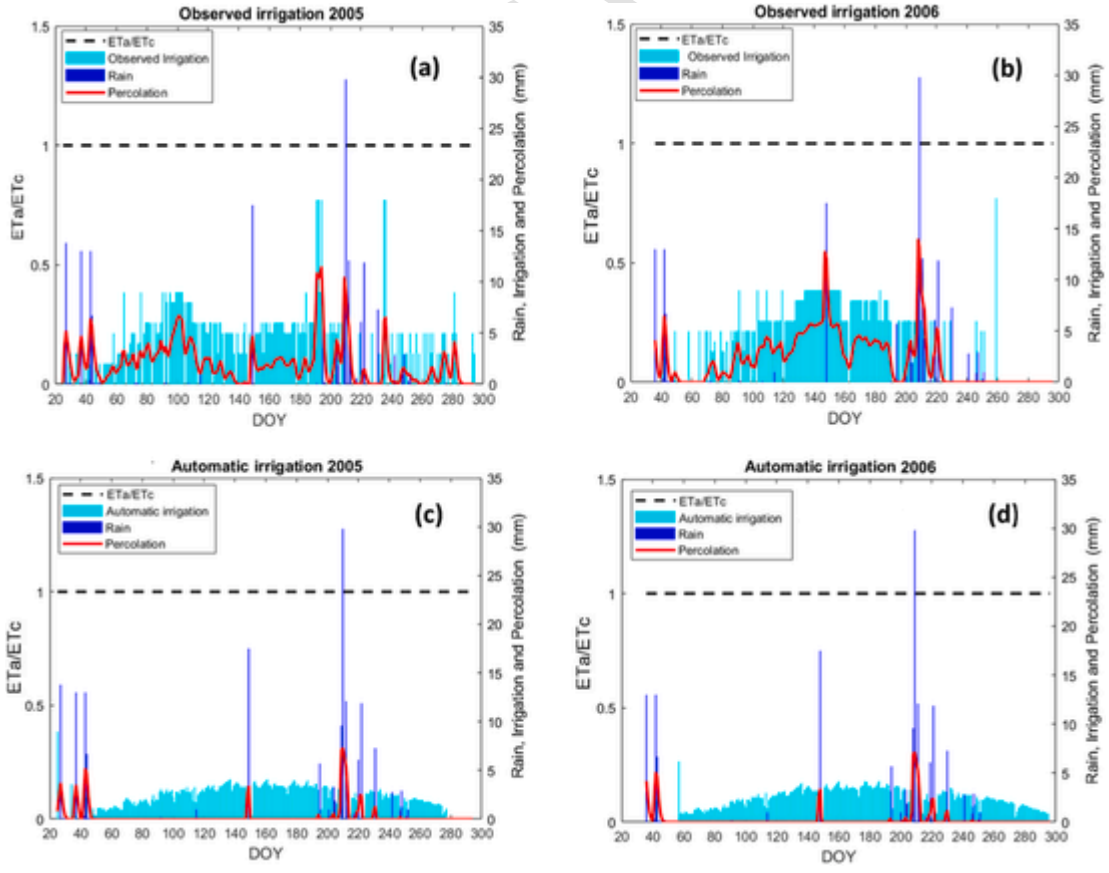

Fig. 5. Estimated daily water stress coefficient (ETa/ETc) and deep percolation of table grapes during 2005 and 2006 seasons with amount and frequency of irrigation given by the farmer (figures a, b) and recommended by the AquaCrop model (figures c, d). Rainfall and irrigation amounts are also shown.

Table 5
Simulated seasonal actual evapotranspiration (ETa), actual transpiration (Tr), percolation (Pr), Fruit Yield (FY) and water productivity (WP) of table grapes by using the practiced irrigation by the farmer and the recommended by the AquaCrop model.

		Irrigation (mm)	Rainfall (mm)	Eta (mm)	Tr (mm)	Percolation, Pr (mm)	FY (t/Ha)	WP (kg/m^3)		
								WP_{ETa}	WP_{Tr}	WP_{ET+Pr}
2005	**Observed irrigation**	1006	168.50	612.00	463.20	544.40	15.14	2.47	3.27	1.31
	automatic irrigation	547.30	168.50	621.60	463.20	78.40	15.14	2.44	3.27	2.16
2006	**Observed irrigation**	929	154.40	560.30	440.70	537.50	13.98	2.50	3.17	1.27
	automatic irrigation	509.70	154.40	566.20	440.70	68.60	13.98	2.47	3.17	2.20

WP_{ET} = FY/ETa, WP_{Tr} = FY/Tr, WP_{ET+Pr} = FY/ETa + Pr

those reported in some other studies working on table grapes. For example, Er-Raki et al. (2013) found about 660 mm for ETc by using the relationship between crop coefficient and NDVI for the same study site. Jairmain et al. (2007) used the water balance method for table grapes in South Africa, and they reported the values of ETc ranged from 519 to 827 mm depending on the length of growing season. Zúñiga-Espinoza et al. (2015) studied the seasonal variation of table grapes in the Aconcagua Valley in Chile, and they found that ETc varied from 674 to 799 between 2007/08–2010/11 seasons. Similar results were also obtained by Williams et al. (2003) and Williams and Ayars (2005) in California for a mature Thompson seedless grapevines, by Campos et al. (2010) and Vanino et al. (2015) for Vineyards.

As stated above, the recommended irrigations by the AquaCrop model could save about half of the water supplied, avoiding percolation losses. The question addressed after this, is to know if this reduction in irrigation water can affect the crop production and water productivity (WP). In this case, the comparison between the simulated fruit yields with both irrigation scenarios, was performed (Table 5) and the results showed that both fruit yields are similar and being 15.14 t/ha in 2005 and 13.98 t/ha in 2006. This is expected, because the plant uses the same crop water need (ETa or Tr) for both irrigation scenarios. Some differences in the yield between two seasons, could be attributed to the differences in some environmental conditions and agricultural practices (irrigation water, fertilization, soil management, or other) in each season, but can be basically explained by the difference in water supply (rainfall + irrigation) which is greater in 2005 by about 90 mm.

Regarding crop water productivity (WP), as shown in Table 5, the values of WP_{ET} and WP_{Tr} were found to be almost similar for both irrigation scenarios, while WP_{ET+Pr} varies from irrigation scenario to another and from 2005 to 2006 season. It was equal to 1.31 and 1.27 kg/m^3 for observed irrigation and 2.16 and 2.20 kg/m^3 for recommended irrigation by Aquacrop, during 2005 and 2006, respectively. It is clear that by using the recommended irrigation by Aquacrop, WP_{ET+Pr} greatly improved by about 60%. If we compare three WPs, as expected, the best one is WP_{Tr} followed by WP_{ET} and then WP_{ET+Pr}, with an average value of 3.22, 2.47 and 1.74 kg/m^3, respectively (Table 5). Although drip irrigation is practiced, the inevitable loss of water due to soil evaporation, decreases water productivity from WP_T to WP_{ET}, and high water losses by percolation due to the excessive irrigation, decreases more and more water productivity. The obtained values of WP_{Tr} and WP_{ET} of table grapes are comparable to the previous results reported by Klaasse et al. (2007) in South Africa and Teixeira et al. (2007) in Brazil.

4. Conclusion

This study aims to test for the first time, the ability of the AquaCrop model to simulate canopy cover (CC), actual evapotranspiration (ETa), total soil water content (TWC) biomass (B) and fruit yield (FY) in table grapes (Vitis vinifera L., cvs. Perlette and Superior) in the semi-arid region of Northwest Mexico. The performance of the model simulations was based on field data collected during two consecutive growing seasons: 2005 for calibration and 2006 for validation. The irrigation planning practiced by the farmer has been also assessed through evaluating the water use efficiency and crop productivity.

Simulation results showed that the model adequately simulated CC, ETa and TWC for both seasons 2005 and 2006. The RMSE values between observed and measured CC, ETa and TWC were 5.18%, 0.46 mm/day and 10.11 mm for 2005, and 8.82%, 0.84 mm/day and 9.1 mm for 2006, respectively. Other goodness of fit indicators such as (d) which is close to 1, indicating that the simulated CC, ETa and TWC have better agreement with the observations. Some discrepancies in estimating ETa and TWC have been observed, which already noted by many authors (e.g. Sandhu and Irmak, 2019), when they proposed that the AquaCrop model should be improved in terms of parameterization of crop senescence stress coefficients, in order to enhance the simulation of soil water content, which affects ETa. In the same context, the high dependency of $Kc_{Tr,x}$ on the CC curve, can affect the simulated transpiration and then ETa, as reported before by Sandhu and Irmak (2019) and Paredes et al. (2014), where they suggested to revise this strong dependency in order to improve the ETa estimates by the AquaCrop model.

For the biomass (B) and fruit yield (FY) simulations, the results showed that the model correctly reproduced the B and FY with low NRMSE value (8.8%). The estimated average value (14.56 t/ha) for both seasons are in the range of the potential yield (14–18 t/ha) for table grapes in the irrigated Costa de Hermosillo of northwest Mexico.

After accurate calibration and validation of the AquaCrop model, we used this model to evaluate the irrigation scheduling design used by the farmer. The results showed that, the recommended irrigation by the model was about 547 mm and 509 mm, which it is about half of that given by the farmer (1006 mm and 929 mm) during 2005 and 2006, respectively. This large difference, which represents approximately 54% and 57% of the irrigation supply, is lost through deep percolation and could be saved without vegetation suffering from water stress, and thus maintaining the same yield. This high loss of water by percolation, affects significantly water savings and crop water productivity (WP) which is about 1.74 kg/m^3. If we considered transpiration (WP_{Tr}) and evapotranspiration (WP_{ETa}) losses for WP calculations, without taking into account percolation loses, WP clearly improved and equal to 3.22 kg/m^3 for WP_{Tr} and 2.47 kg/m^3 for WP_{ETa}. This difference between

WP_{Tr} and WP_{ETa}, which is about 24% is linked to soil evaporation losses, although drip irrigation is practiced. Consequently, the AquaCrop model could be used as a potentially useful tool for planning irrigation schedules for increasing crop water productivity.

Finally, further calibration and validation of the AquaCrop for table grapes in other climate conditions and in other geographic regions is needed to improve the parameterization of the AquaCrop model for table grapes growth. However, the results reported in this study provide an initial foundation for further research aimed at adapting the model for table grapes and for other deciduous crops (e.g. apricot, peach,..), which can bring an added value for enriching the model database.

Uncited references

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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