Agricultural Water Management 163 (2016) 219–235

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Performance assessment of AquaCrop model for estimating evapotranspiration, soil water content and grain yield of winter wheat in Tensift Al Haouz (Morocco): Application to irrigation management

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ARTICLE INFO

Article history:
Received 9 August 2014
Received in revised form 1 September 2015
Accepted 10 September 2015
Available online 6 October 2015

Keywords:
Crop water requirement
Agronomic model
Model calibration
Model validation
Irrigation scheduling
Winter wheat

ABSTRACT

Crop growth simulation models have become important tools to assess and develop deficit irrigation strategies especially in arid and semi-arid regions. In this study, we tested the ability of the FAO developed AquaCrop model (V 4.0) to simulate canopy cover (CC), actual evapotranspiration (ET_{cact}), total soil water content (TWC) and grain yield (GY) for winter wheat under flood irrigation in the semi-arid region of Tensift Al Haouz, Marrakech (center of Morocco). The simulation was performed at a daily time step, using thermal units, i.e., growing degree days (GDDs) during two successive growing seasons: 2002/2003 and 2003/2004. Firstly, the calibration of the model was performed on three fields during 2002/2003 cropping season. Various parameters affecting CC, ET_{cact}, TWC and GY have been calibrated based on the comparison between measurements and the results of simulations. Afterward, the validation was done on six fields during the 2003/2004 cropping season. The results showed that the model simulates reasonably well CC, ET_{cact}, TWC and GY over two growing seasons. The average values of the Mean Bias Error (MBE) between observed and measured CC, ET_{cact}, TWC and GY were −4.6%, −0.23 mm/day, 17.56 mm and 0.05 t/ha for the calibration fields, and 7.89%, −0.01 mm/day, 0.5 mm and 0.06 t/ha for the validation fields, respectively. Additional statistical parameters like the root mean square error (RMSE) and the Nash–Sutcliffe efficiency (NSE) showed also that the model gives acceptable estimates of CC, ET_{cact}, TWC and GY.

After accurate calibration and validation of the AquaCrop model, it was used for irrigation scheduling based on the threshold of the root zone water depletion ($D_{r,threshold}$) over two fields with contrasted sowing dates. The various simulations (irrigation scenarios) showed that early sowing is more adequate than late sowing in saving water and obtaining adequate grain yield. It has been also shown that the value 0.6 of $D_{r,\,threshold}$ can be used as an appropriate threshold of water depletion to improve the wheat irrigation management. Consequently, the AquaCrop model can be considered as a potentially useful tool for planning irrigation schedules on an operational basis in the arid and semi-arid regions.

1. Introduction

In arid and semi-arid regions, climate change coupled with demographic growth will profoundly affect the availability and quality of water resources (Funk and Brown, 2009). This can lead to a serious water crisis. Undoubtedly, the agriculture sector in these regions is the most affected. Indeed, the water and agricultural sector are tightly coupled. Irrigated agriculture which represents a major contribution to food security is the largest consumer of water. On average, it accounts for approximately 80–90% of total available water with an efficiency which does not exceed 50% (Plan Bleu, 2009). Therefore, the great challenge for the coming decades will be to increase food production with less water in order to meet global food security.

In Morocco, cereals represent the main agricultural crop, accounting for about 65% of all agricultural lands, among which common wheat constitutes 54% (MADRPM, 2010). Thereof, about half of cereal production is concentrated in the favourable and

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http://dx.doi.org/10.1016/j.agwat.2015.09.007
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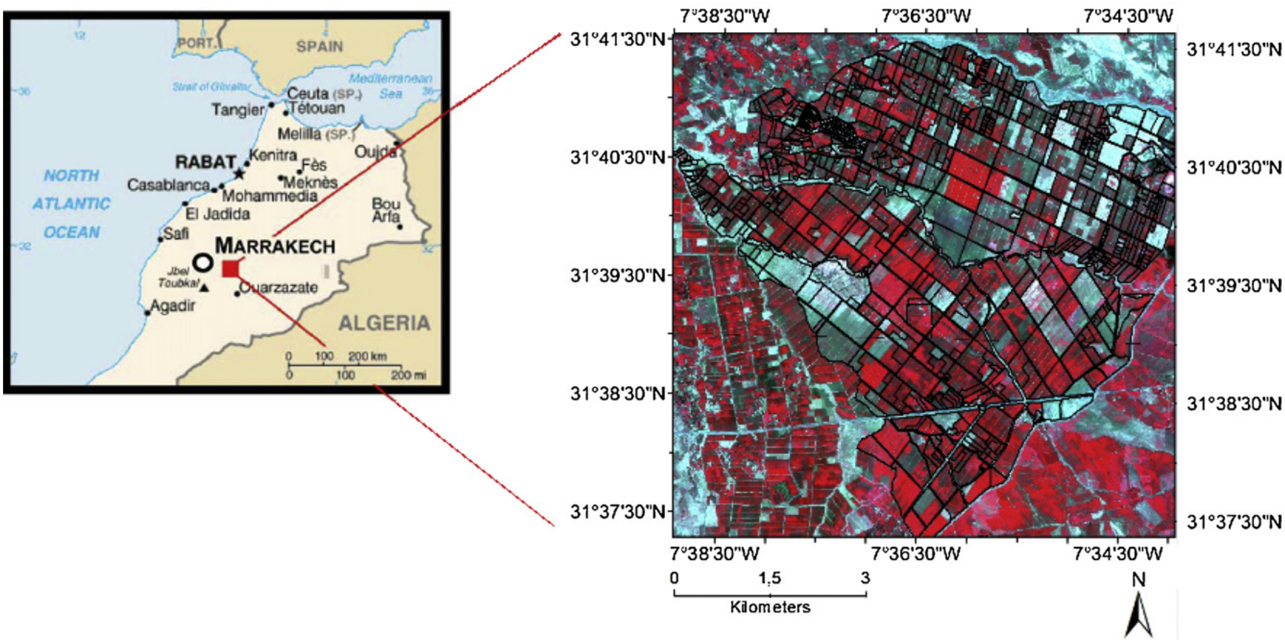

Fig. 1. Location of the experiment sites: on the left, the general map of Morocco highlights the Marrakech city (blank circle) and the experimental site (blank square); on the right, the whole irrigated zone R3 is delineated on a Quickbird image.

intermediate zones, the rest occurs mostly in less favourable (arid and semi-arid) zones, with an average annual rainfall of below 300 mm (Karrou, 2003). In the Haouz plain (central of Morocco) which is classified as a semi-arid region (Driouech et al., 2010), water availability is a major limitation for cereal production. Therefore, irrigation is of crucial importance in this region in order to avoid water stress and thus to get a maximized crop yield. Water storage (dam or ground water), provides a reliable irrigation water supply in this region. However, this quantity of water has gradually decreased recently due to the impact of climate change and more importantly to the use of inefficient irrigation practices (MADRPM, 2007). Indeed, the actual capacity of the dam is decreased by 50% and the ground water level decreased by about 1 m every year (Abourida, 2007). Consequently, agriculture in this region might be in jeopardy if no judicious irrigation scheduling based on solid science is implemented. This can be plausible by answering two basic questions: when to irrigate the crops and how much water should be applied during sensitive growth stages?

Modelling can be a useful tool to asses and develop promising irrigation scheduling strategies under limited available water for increasing crop water productivity (Blum, 2009; Geerts and Raes, 2009; Pereira et al., 2009). Models allow a combined assessment of different factors affecting yield such as weather conditions, soil conditions and crop management scenarios in order to derive optimal irrigation quantities for different scenarios (Pereira et al., 2002; Liu et al., 2007). In this regard, substantial advances have been made recently in improving crop models to simulate yield response to water such as STICS (Brisson et al., 2003; Hadria et al., 2007), CERES-maize (Jones and Ritchie, 1986), WOFOST (Diepen Van, 1989) and CropSyst (Stoeckle et al., 2003). This type of models are used mostly by scientists, and advanced users in highly commercial farming. However, it is also important to recognize that these models are quite sophisticated; require advanced modeling skills for their calibration and subsequent operation, and require large number of model input parameters not easily available for the diverse range of crops and sites around the world (Abedinpour et al., 2012). Some of these variables are much more familiar to scientists than to end users (e.g., leaf area index or leaf water potential). Consequently these types of models are rarely used by the water user associations, consulting engineers, irrigation and farm managers, planners and economists. In this context, the Water Unit at the FAO (Food and Agriculture Organization) has developed a model named AquaCrop (Raes et al., 2009a; Steduto et al., 2009) resulting from the revision of the FAO Irrigation and Drainage paper no. 33—yield response to water (Doorenbos and Kassam, 1979). This model which simulates yield response to water of several herbaceous crops is a user-friendly and practitioner oriented type of model, because it attempts to balance accuracy, simplicity, and robustness. It uses a relatively small number of explicit and mostly-intuitive parameters and input variables requiring simple methods for their determination. AquaCrop model has been parameterized and tested on several crops such as sunflower (Todorovic et al., 2009), cotton (Farahani et al., 2009; Garcia-Vila et al., 2009; Hussein et al., 2011), maize (Hsiao et al., 2009; Heng et al., 2009), quinoa (Geerts et al., 2010), sugar beet (Stricevic et al., 2011), and wheat (Andarzian et al., 2011; Mkhabela and Bullock, 2012; Singh et al., 2013) under different environment conditions. Most of these investigations have reported that the model simulates accurately the crop biomass (B) and grain yield (GY), actual evapotranspiration (ET_{cact}), canopy cover (CC) as well as soil water content dynamics under full irrigation and fertility conditions. However, the performance of AquaCrop has some limitations in estimating ET_{cact} and soil moisture when there is a severe stress condition as shown by Katerji et al. (2013) and Heng et al. (2009). Farahani et al. (2009) also showed that AquaCrop tended to underestimate the ET_{cact} measurements of cotton under different water regimes. As far as we know such a study on the testing of AquaCrop on Moroccan conditions has never been performed before.

In this context, the objective of this paper is two-fold: (1) to calibrate and validate the AquaCrop model for estimating canopy cover (CC), actual evapotranspiration (ET_{cact}), total soil water content (TWC) and grain yield (GY) on flood-irrigated wheat fields located at the Haouz plain (Centre of Morocco); and (2) to apply the model for simulating the effects of different irrigation scenarios on grain yield.

Table 1
Sowing and irrigations dates for the calibration and validation fields.

	Field	Sowing date	Irrigation dates[b]					
			1st irrig	2nd irrig	3rd irrig	4th irrig	5th irrig	6th irrig
Calibration fields	C1	17-December-02	28-January-03 (DAS[a] 43)	22-February-03 (DAS 68)	10-April-03 (DAS 115)			
	C2	11-January-03	1-February-03 (DAS 22)	21-February-03 (DAS 42)	14-March-03 (DAS 63)	24-March-03 (DAS 73)	7-April-03 (DAS 87)	24-April-03 (DAS 104)
	C3	14-January-03	04-February-03 (DAS 22)	20-March-03 (DAS 66)	13-April-03 (DAS 90)	21-April-03 (DAS 98)		
Validation fields	V1	21-November-03	20-January-04 (DAS 61)	23-February-04 (DAS 95)	1-April-04 (DAS 133)			
	V2	21-November-03	16-January-04 (DAS 57)	17-February-04 (DAS 89)	28-March-04 (DAS 129)			
	V3	15-December-03	20-January-04 (DAS 37)	15-February-04 (DAS 63)	17-March-04 (DAS 94)			
	V4	19-December-03	18-January-04 (DAS 31)	24-February-04 (DAS 68)	21-April-04 (DAS 125)			
	V5	20-December-03	16-January-04 (DAS 28)	16-February-04 (DAS 59)	26-March-04 (DAS 98)			
	V6	24-December-03	26-January-04 (DAS 34)	21-February-04 (DAS 60)	27-March-04 (DAS 95)			

[a] DAS: day after sowing.
[b] Calibration and validation fields were periodically irrigated by applying 30 mm and 60 mm in each irrigation event, respectively.

2. Materials and methods

2.1. Site description

The experiment took place in the irrigated zone R3, located 40 km East of Marrakech city (centre of Morocco) (Fig. 1), during both 2002/2003 and 2003/2004 cropping seasons. This region is characterized by a semi-arid Mediterranean climate. The atmosphere is very dry, with an average relative humidity of 56% (Duchemin et al., 2006; Er-Raki et al., 2007). The annual average evaporation demand is very high (around 1600 mm/year) according to reference evapotranspiration ET_o (Allen et al., 1998), greatly exceeding the annual rainfall ranging from 190 to 250 mm/year (Er-Raki et al., 2010a). Most of the precipitation falls during winter and spring, from the beginning of November until the end of April (Duchemin et al., 2006; Er-Raki et al., 2007).

The R3 region covers about 2800 ha and is almost flat (slope less than 1%), with deep soil of xerosol type and a fine, clay to loamy texture (Duchemin et al., 2006). It is managed by the ORMVAH (Office Regional de Mise en Valeur Agricole du Haouz) since 1999. The main crop grown in the region is the durum variety wheat (Karim) due to its adaptation to semi-arid conditions. This variety which has relatively short life cycle is generally sown between mid-November and mid-January, depending on climatic conditions and the start of the rainfall season. The ORMVAH manages the distribution of water starting from December to May through concrete canals that carry water from the main canal to the irrigated units. The latter are watered by using the flood irrigation method which is widely practiced by the majority of the farmers in this district. The frequency and the amount of each irrigation event are predetermined according to the dam water level at the beginning of the cropping season without any consideration for the actual surface soil moisture status and atmospheric demand. More details about the study site were presented in Duchemin et al. (2006), Er-Raki et al. (2007) and Hadria et al. (2007).

2.2. Field experiments

AquaCrop model was calibrated using data from three fields and was validated on six ones, conducted during 2002/2003 and 2003/004 cropping season, respectively. The calibration fields are denoted C1–C3, whereas the validation ones are labeled (V1–V6) (Fig. 2). All fields were cropped with durum wheat variety (Karim). They did not require any vernalization and they were harvested at the end of May. The soil is homogeneous characterized by the clay loamy texture (47% of clay, 33% of loam and 20% of sandy) with the same soil pre-plowing for all fields. The values of field capacity (Fc), permanent wilting point (PWP), saturation (Sat) and hydraulic conductivity (K_{sat}) were 0.32, 0.17, 0.45 m^3/m^3 and 100 mm/day, respectively. The K_{sat} value used here was the default value for clay loam soils. A typical value of 9 mm of readily evaporable water (REW) for a clay loam soil (FAO-56, Table 19, Allen et al., 1998) was used for the soil evaporation calculations. For the curve number (CN), a default value of 75 was used for the same type of soil. The groundwater table in the region is facing enormous pressure with an over-exploitation (about 0.5–1.5 m decrease level by year) (Abourida, 2007). This results in very deep ground water (more than 50 m), and so no interaction between surface water and ground water is considered in the AquaCrop simulations.

The studied fields differ in the sowing date, irrigation timing and water amounts applied. Table 1 summarizes the sowing and the irrigation dates of all studied fields. The fields were periodically irrigated by applying 30 mm during 2002/2003 and 60 mm during 2003/2004 growing seasons in each irrigation event. The seeding rate, plant density and the amount of fertilization for each field are displayed in Table 2. Fertilization depended upon the economical

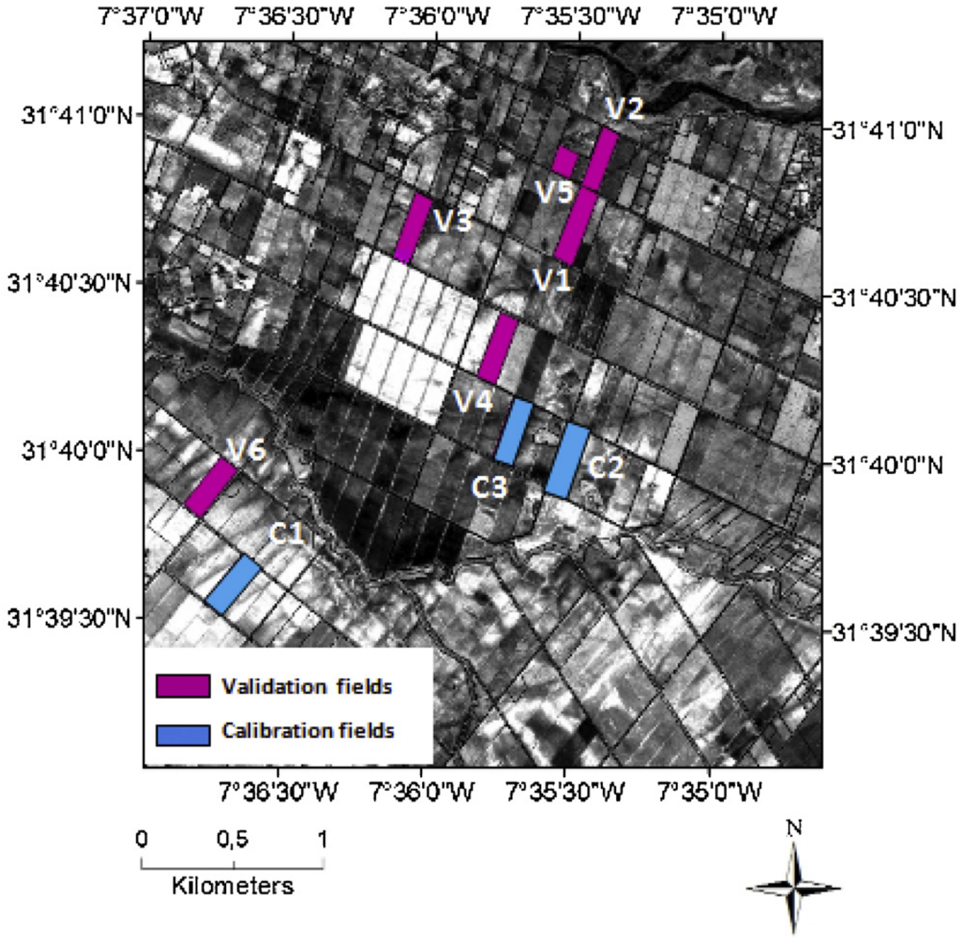

Fig. 2. Location of the fields study used for the calibration (C1–C3) and the validation (from V1 to V6) during the 2002/2003 and 2003/2004 cropping seasons.

capability of the owner. It was either very poor for C1, C3, V2, V3 and V5, poor (50 Kg/ha) for V1 and V6, and moderate (100 Kg/ha) for C2 and V4 fields. The fertilizer NPK (14–28–14) with nitrogen supply was used in the studied fields. Nitrogen supply was generally null (or negligible) at sowing time although the initial soil quantity was unknown (Ouattar and Ameziane, 1989; Karrou, 2003; Kharrou et al., 2013). An amount of 225 Kg/ha of the fertilizer NPK is considered sufficient for non-limiting soil fertility in the region (Karrou, 2003). In AquaCrop model, the amount of fertilization is given as a percentage by respecting the classes ranging from non-limiting (100%) to very poor (20%) according to the Table 2.12a of Raes et al. (2012). In the case of no application of the fertilization (C1, C3, V2, V3 and V5 fields), only the residual fertilizer in the soil has been considered in AquaCrop model with a percentage of 20%.

2.3. Data description

Climatic data were recorded very close to the fields of interest using a tower installed over a well-watered clipped grass and equipped with classical automatic sensors: incoming solar radiation (CNR1, Kipp & Zonen, The Netherlands), air temperature and vapour pressure (HMP45C, Vaisala, Finland), wind speed (A100R anemometer, R.M. Young Company, USA), rainfall (FSS500 tipping bucket automatic rain gauge, Campbell Inc., USA). Daily averaged values of climatic data were calculated in order to compute the daily reference evapotranspiration (ET_o) (mm/day), according to

Table 2
Seeding rate plants density and the quantity of fertilizer for the calibration and validation fields.

Field	Seeding rate (Kg/ha)	Plant density (plants/m^2)	Fertilization with nitrogen NPK (14–28–14) (Kg)	Fertilization (%)[b]
C1	150	337.3	–[a]	20
C2	100	225	100	65
C3	150	337.3	–	20
V1	150	337.3	50	45
V2	100	225	–	20
V3	150	337.3	–	20
V4	100	225	100	65
V5	100	225	–	20
V6	140	315	50	45

[a] Means no fertilization was applied.
[b] Fertilization is given as a percentage in AquaCrop model by respecting the classes ranging from non-limiting (100%) to very poor (20%).

the FAO-56 Penman–Monteith equation (Allen et al., 1998). The ET_o temporal pattern during the experiment period is well detailed in Er-Raki et al. (2007, 2011). Fig. 3 shows the evolution of the maximum and the minimum daily air temperature (Tair), solar radiation (Rs), ET_o and rainfall during the 2002/2003 and 2003/2004 growing seasons. By analyzing this figure it can be concluded that the curves of ET_o are typically of semi-arid continental climates. The mean value of ET_o during the 2002/2003 and 2003/2004 growing seasons (between January and May) is 3.76 mm/day and 3.06 mm/day, respectively. Average daily minimum and maximum air temperature over two cropping seasons are similar and are equal to about 9 °C and 22 °C, respectively. Meanwhile, the region is characterized by lower and irregular rainfall, with an accumulative amount around 200 mm between December and May for both seasons. More details about the climatic description are given in Hadria et al. (2007).

In addition to the measurements of classical climatic data, an Eddy Co-variance system (EC) was installed over each field (C1–C3) during the 2002/2003 cropping season. EC measures the actual evapotranspiration (ET_{cact}) using high frequency measurements of the three dimensional (3D) air velocity, temperature and water vapor fluctuations. This system consists of commercially available instrumentation: a 3D sonic anemometer (CSAT3, Campbell Scientific Ltd.) and an open-path infrared gas analyzer (Li7500, Licor Inc.) or fast hygrometer (KH2O, Campbell Scientific Inc., USA). A detailed description of EC measurements as well as the data processing can be found in Duchemin et al. (2006). Finally, the soil moisture was also measured over each field using several soil sampling taken at 5 cm, 10 cm, 20 cm, 30 cm and 50 cm, with a split tube sampler, to represent water contents for the 0–7.5, 7.5–15, 15–25, 25–45, 45–55 cm layers, respectively. These samples were firstly weighed and packed in plastic bags to avoid evaporation. After, they were dried in an oven at 105 °C for about 72 h and weighed again. An average value of soil moisture with minimum and maximum was calculated in each depth. Then, total water content (TWC) in the root zone layer (0–55 cm) was computed as a sum of measured water content in each depth. Those measurements have been used for evaluation of the estimated TWC by AquaCrop model (Raes et al., 2012) in the root zone layer (0–55 cm). The initial value of TWC was determined from the total available water (TAW) based on Fc, PWP and root zone depth (Z_r). As the soil moisture was not measured at the beginning of season and knowing that the sowing of wheat in the region will be after a heavy rainfall event, the farmers sowing when the soil moisture became suitable for ploughing and germination. Following this, the initial soil moisture used in AquaCrop model was between field capacity and wilting point. Therefore, the initial value of soil moisture was set to 0.245 cm^3/cm^3, which is equal to 50% of TAW.

Additionally, measurements of the canopy cover (CC) over each field were made using hemispherical canopy photographs (using a Nikon Coolpix 950 with a FC-E8 fish-eye lens converter, field of view 183°). For more details about this technique and the software processing used for deriving CC, the reader can be referred directly to Duchemin et al. (2006) and Khabba et al. (2009). At the end of May, grain maturity was reached and final grain yield was measured. During two seasons (2002/2003 and 2003/2004), a protocol allowing measurement of the grain yield (GY) was used. In each field, plant sampling was carried out in five quadrates (i.e., area of 0.25 m^2 = 0.5 m × 0.5 m) selected randomly. From each quadrate, subsamples were used to measure the number and weight of grains for the plants selected randomly. This leads to estimate the average and standard deviation of grain yield. During the 2003/2004 cropping season, similar measurements described above were done over one field (V4). For the remaining fields (V1–V3, V5 and V6), only measurements of CC and GY were taken.

2.4. Model description

The AquaCrop model developed by the Land and Water Division of FAO, is a water-driven model for use as a decision support tool in planning and scenario analysis (Steduto et al., 2009; Hsiao et al., 2009). In this section, the basic concepts and fundamental calculation procedures of AquaCrop are summarized in the flowchart presented in Fig. 4 according to Steduto et al. (2009). AquaCrop model relates its soil-crop-atmosphere components through its soil and its water balance (Araya et al., 2010). It uses six input files for simulation: climate file (minimum and maximum air temperature, ET_o, rainfall and CO_2), crop file (time to emergence, maximum canopy cover, start of senescence, and maturity), soil file, management file, irrigation file, and initial soil water conditions.

The AquaCrop model uses canopy cover (CC) instead of leaf area index (LAI) as the basis to calculate plant transpiration (Tr) and soil evaporation (E). Tr is related to CC which is proportional to the extent of soil cover whereas evaporation is proportional to the area of soil uncovered (1-CC) (Araya et al., 2010). The CC is calculated from daily transpiration taking into account some important physiological characteristics of the crop such as leaf expansion growth, canopy development and senescence (Steduto et al., 2009; Araya et al., 2010). The effects of water stress on canopy senescence, stomatal control (gs) of transpiration and leaf growth are expressed through indicators which vary from 0 to 1. The normalized crop water productivity (WP) is considered constant for a given climate and crop, it is set between 15 and 20 $g\,m^{-2}$ for C3 crops and between 30 and 35 $g\,m^{-2}$ for C4 crops (Steduto et al., 2009). The WP parameter in the model is normalized in order to make the model applicable to diverse locations and seasons including future climate scenario (Steduto et al., 2009; Hsiao et al., 2009). Crop yield (GY) is calculated as the product of biomass (B) and harvest index (HI). The latter is simulated by a linear increase with time starting from flowering up to physiological maturity (Steduto et al., 2009).

The parameters used in the AquaCrop model were measured or estimated using experimental data; some were based on field experience, and some used the default values given in the model, regardless of the year (Iqbal et al., 2014). A further detailed conceptual description of AquaCrop is available in Raes et al. (2009a,b) and Steduto et al. (2009).

2.5. Model calibration and evaluation

The AquaCrop model was calibrated on three fields (C1–C3) during 2002/2003 cropping season and then validated on six fields (V1–V6) during the 2003/2004 cropping season. Various parameters affecting CC, ET_{cact}, TWC and GY were calibrated based on the comparison between measurements and the results of simulations. The estimation of CC in AquaCrop consists firstly of determining the initial canopy cover (CC_0) which depends on the seed rate, the seed weight and the estimated germination rate. The CC_0 depends also on the plant density and the initial canopy size per seedling. This parameter is automatically estimated by the model. As some fields have different seeding rate (Table 2), CC_0 will be different from a field to another (see Table 3). Regarding fields (C1, C3, V1, and V3) having the same seeding rate (150 Kg/ha, Table 2), they have the same values of CC_0 (about 5.06%) (Table 3). Afterwards, the canopy expansion rates were automatically estimated by the model after the determination of some phenological dates such as the dates after sowing, emergence, maximum canopy cover (CCx), senescence and maturity. It should be noted that the canopy growth coefficient (CGC), the canopy decline coefficient (CDC), the leaf

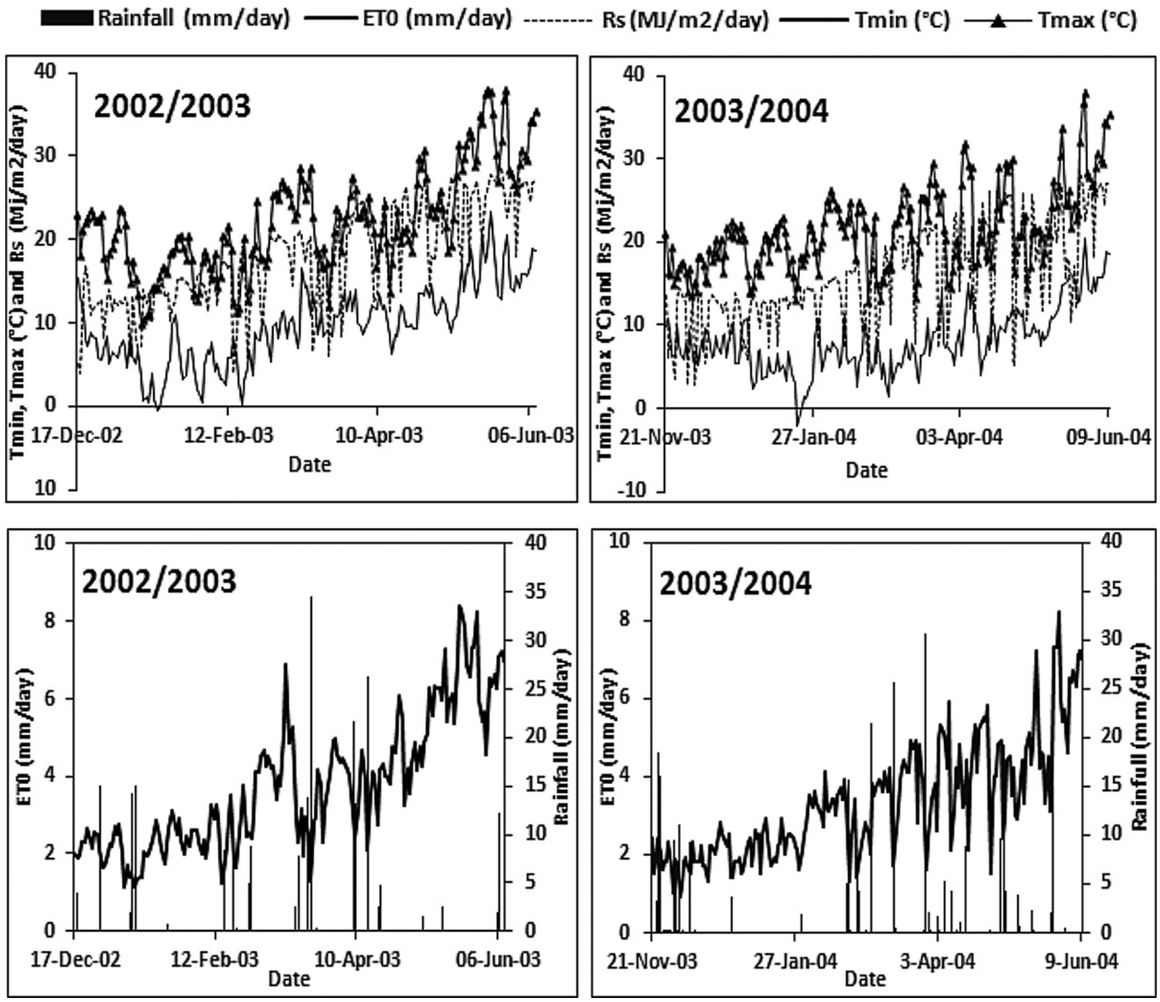

Fig. 3. Daily evolution of climatic parameters during 2002/2003 (left) and 2003/2004 (right) cropping seasons. ET_0: reference evapotranspiration, Rs: solar radiation, T_{min} and T_{max} are the minimum and the maximum of daily air temperature.

expansion and the early senescence are considered as the most important parameters to calibrate the canopy cover (CC). The water stress parameters and the curve shapes were also adjusted to accurately estimate the canopy cover (Table 3).

As heat units, expressed as growing degree-days (GDD) in the AquaCrop model, play an important role for the crop development, it is interesting to determine the cumulative growing degree day (CGDD) in each crop development stage. In AquaCrop model, the calculation of GDD is based on the base temperature (T_{base}) and the upper temperature (T_{upper}) (Table 3). Those two temperatures depend mainly on climate and wheat variety (Sinclair and Seligman, 1996). In the manual of the AquaCrop model, Raes et al. (2012) used 0 and 26 °C for T_{base} and T_{upper}, respectively. However, many studies tested the AquaCrop model for the wheat but they used other values for T_{base} and T_{upper}. In north China plain (Iqbal et al., 2014) and Western Canada (Mkhabela et al., 2012), the values of 5 and 35 °C for wheat were used for T_{base} and T_{upper}, respectively. In north of Iraq, Al-kaisy et al. (2011) used 10 and 30 °C for T_{base} and T_{upper}, respectively. In this study, we used the value 5 for T_{base} and 33 °C for T_{upper} (Table 3), which are adopted for the Moroccan climate and for the variety Karim of wheat (Ouattar and Ameziane, 1989; Karrou, 2003; Hadria et al., 2006).

In AquaCrop model, the canopy evolution during the growing season follows an exponential increase and it is described by four key phenological stages: from sowing to emergence (Emrg), from sowing to maximum canopy cover (MaxCC), from sowing to senescence (Senc) and from sowing to maturity (Mat). The parameters related to the water stress that affect the leaf expansion, stomata conductance, and accelerated canopy senescence are defined in AquaCrop model as the different thresholds characterizing these processes. These thresholds are expressed in terms of the fractional depletion (p) of the total available water in the root zone (TAW) (see Table 3). The leaf expansion is characterized by two parameters ($P_{exp,\ upper}$ and $P_{exp,\ lower}$) while the canopy senescence and the stomata closure are only controlled by one parameter $P_{sen,\ upper}$ and $P_{sto,\ upper}$, respectively.

Regarding the actual evapotranspiration (ET_{cact}), the calibration was based principally on the determination of the appropriate values of crop coefficients: maximum soil evaporation (K_{ex}) for soil evaporation computations and maximum crop transpiration coefficient ($Kc_{Tr,x}$) for calculation of plant transpiration.

Finally, in the absence of the local values of the reference harvest index (HIo) and normalized crop water productivity (WP*), for the Karim variety, these two parameters were also calibrated based on the measured evapotranspiration and GY.

To evaluate the performance of the obtained results of calibration and validation, three parameters were used in this study: (1) the root mean square error (RMSE), which measures the discrepancy of simulated values around observed ones (Jacovides and Kontoyiannis, 1995) and (2) the mean bias error (MBE), which

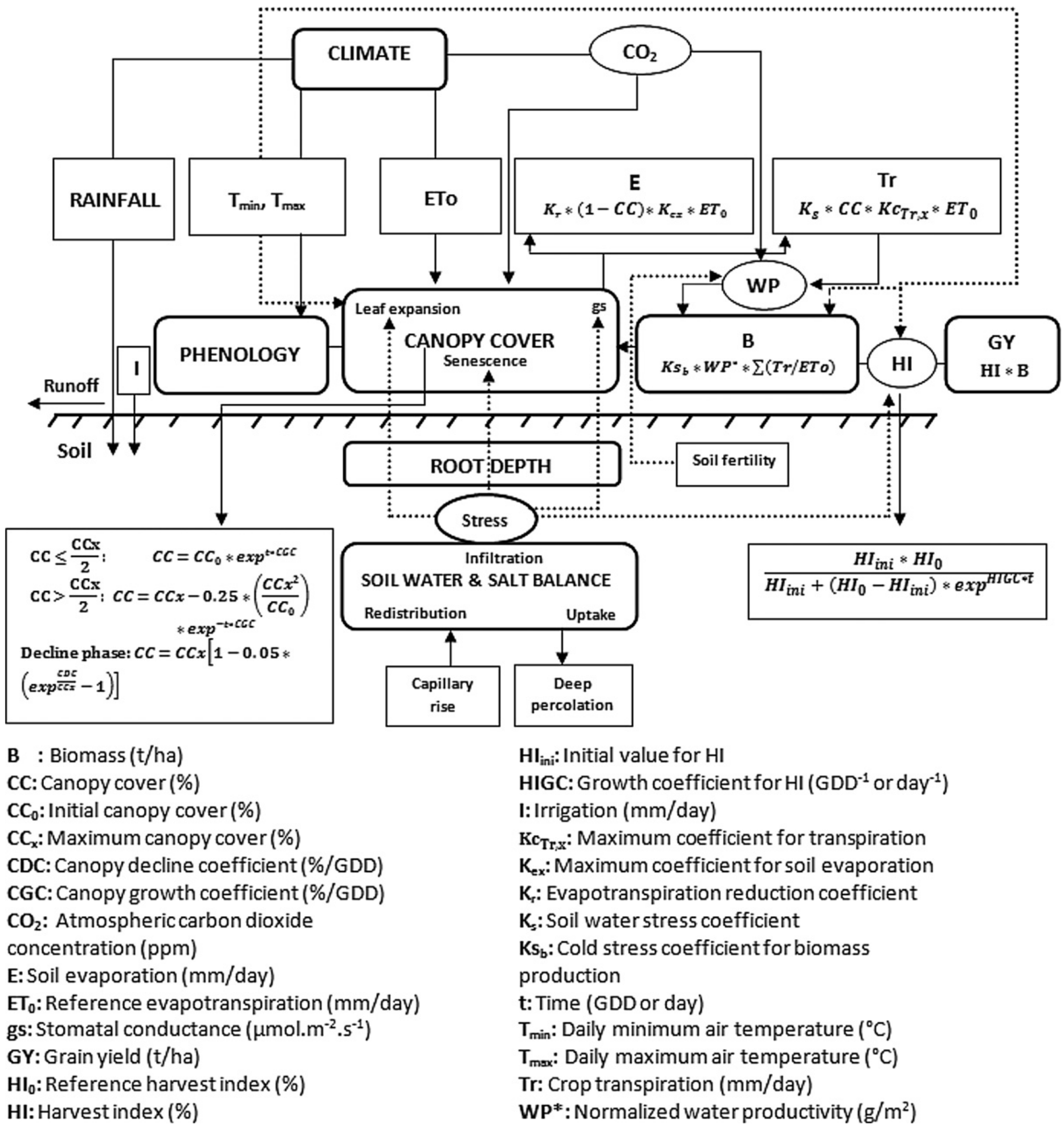

Fig. 4. Flowchart of AquaCrop model indicating the main components of the soil–plant–atmosphere continuum and the parameters driving phenology, canopy cover (CC), plant transpiration (Tr), biomass production (B), and final grain yield (GY). Continuous lines indicate direct links between variables and processes. Dashed lines indicate feedbacks [after Steduto et al., 2009].

indicates the percent of the average deviation of the predicted values from the measured ones (Zacharias et al., 1996) and (3) the Nash–Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970), which determines the relative magnitude of the residual variance compared to the measured data variance and indicates how well the plot of observed versus simulated data fits the 1:1 line. NSE ranges between $-\infty$ and 1.0, with NSE = 1 being the optimal value.

$$\mathrm{RMSE} = \sqrt{\frac{1}{n} \times \sum_{i=1}^{n} (y_{\mathrm{isim}} - y_{\mathrm{iobs}})^2}$$

$$\mathrm{MBE} = \bar{y}_{\mathrm{sim}} - \bar{y}_{\mathrm{obs}}$$

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n} (y_{\mathrm{iobs}} - y_{\mathrm{isim}})^2}{\sum_{i=1}^{n} (y_{\mathrm{iobs}} - \bar{y}_{\mathrm{obs}})^2}$$

where $\bar{y}_{\mathrm{sim}}$ and $\bar{y}_{\mathrm{obs}}$ are the averages of model and observations, respectively, n is the number of available observations, and y_{isim}andy_{iobs} are the daily values of modeled and observed variables, respectively.

2.6. Model application

After calibration and validation, the AquaCrop model was used for irrigation scheduling over two fields with contrasted sowing dates. In the AquaCrop model, the stress indicator for soil water stress is the root zone water depletion (D_r) which is expressed as a fraction (p) of total available water TAW (Raes et al., 2009b, 2012). Water stress starts to affect the plant growth and development process when the root zone depletion exceeds the so-called readily available water (RAW = $p_{\mathrm{upper}} \times$ TAW). For the lower threshold, when the root zone depletion is equal to ($p_{\mathrm{lower}} \times$ TAW), the effect of water stress is at its full strength (Raes et al., 2012). Then,

Table 3
Main input parameters used for the calibration and the validation of the AquaCrop model during 2002/2003 and 2003/2004 growing seasons.

Parameters	Value								
	Calibration fields			Validation fields					
	C1	C2	C3	V1	V2	V3	V4	V5	V6
Conservative									
Base temperature (°C)	5	5	5	5	5	5	5	5	5
Upper temperature (°C)	33	33	33	33	33	33	33	33	33
Initial canopy cover, CC_0 (%)	5.06	3.38	5.06	5.06	3.38	5.06	3.38	3.38	4.72
Canopy cover per seeding (cm^2/plant)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Maximum coefficient for transpiration, $Kc_{Tr,x}$	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07
Maximum coefficient for soil evaporation, K_{ex}	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Upper threshold for canopy expansion, $P_{exp,upper}$	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Lower threshold for canopy expansion, $P_{exp,lower}$	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Leaf expansion stress coefficient curve shape	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
Upper threshold for stomatal closure, $P_{sto,upper}$	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Stomata stress coefficient curve shape	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Canopy senescence stress coefficient, $P_{sen,\ upper}$	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
Senescence stress coefficient curve shape	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Reference harvest index, HI_0 (%)	46	46	46	46	46	46	46	46	46
Normalized crop water productivity, WP* (g/m^2)	16	16	16	16	16	16	16	16	16
Non conservative									
Time from sowing to emergence (CGDD)	114	63	69	82	82	82	82	82	82
Time from sowing to maximum CC (CGDD)	709	679	699	696	696	696	696	696	696
Time from sowing to start senescence (CGDD)	983	944	988	972	972	972	972	972	972
Time from sowing to maturity (CGDD)	1453	1478	1454	1462	1462	1462	1462	1462	1462
Maximum canopy cover, CCx (%)	95	85	73	95	78	95	78	78	88
Canopy growth coefficient, CGC (%/GDD)	0.92	0.93	0.83	0.89	0.89	0.89	0.89	0.89	0.89
Canopy decline coefficient, CDC (%/GDD)	0.67	0.53	0.59	0.6	0.6	0.6	0.6	0.6	0.6
Maximum effective rooting depth, Zx (m)	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55
Minimum effective rooting depth, Zr (m)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

the AquaCrop model can schedule the irrigation by fixing a threshold value of the root zone depletion ($D_{r,\ threshold}$). If the $D_{r,\ threshold}$ is lower than RAW, the model applies irrigation before the plants are stressed. When the threshold is slightly higher than RAW, the model applies irrigation as soon as the plants are stressed. If the $D_{r,\ threshold}$ is near to $p_{lower} \times$ TAW, the plants may suffer from severe water stress, depending on the distribution and the amount of rainfall. After each irrigation or rainfall event, D_r may increase as the soil becomes dryer, and the model calculates the amount of irrigation water needed when D_r becomes higher than the given irrigation threshold ($D_{r,\ threshold}$). To quantify the effect of the water stress on GY and B, we used a series of scenarios for 10 irrigation thresholds ranging from $D_r = 0.1$ to $Dr = 1 \times$ TAW. The best scenario corresponds to the best compromise between yield and quantity of irrigation water.

Before applying the AquaCrop model for irrigation management scenarios, it is more convenient to separate the effect of water and fertilization stresses on the crop response in terms of grain yield (GY) and biomass (B). For this objective, the model was run for all fields in the same agricultural and environmental conditions but without fertilization stress. This study was performed during the 2003/2004 cropping season on two fields (V1 and V6) that differ by their sowing dates (Table 1). V1 and V6 were sown on November 21 and December 24, 2003 respectively. These two fields were considered as typical of early and late sowing in the Tensift region (Karrou, 2003; Er-Raki et al., 2010b).

3. Results and discussions

In this section, we will present the results of the calibration and the validation processes of the AquaCrop model by exploiting the data collected during two successive cropping seasons (2002/2003 and 2003/2004). Calibration was done using the data collected during the first season, and validation with the data collected during 2003/2004 growing season. Note that the AquaCrop model was run on the basis of the growing degree day (GDD).

3.1. Calibration of the AquaCrop model

As mentioned in the previous section, various parameters affecting CC, ET_{cact}, TWC and GY have been calibrated. For CC, in addition to CC_0, CDC, and CGC, the values of CGDD in each crop development stages (Emrg, Max CC, Senc and Mat) were adjusted using the data collected over each field (C1, C2 and C3) during the 2002/2003 cropping season (Fig. 5). This figure showed that these parameters are almost identical for the three calibration fields except for the initial stage (from sowing to emergence) where C1 has a relative higher CGDD in comparison with C2 and C3 fields (see Table 3). This was due to the sowing date and the climate conditions which were different. The field C1 was sown on 17 December where the air temperature is different to the base temperature but C2 and C3 were sown on 11 and 14 January where the air temperature is near to the base temperature and results in low values of CGDD from sowing to emergence (Emrg). However, the values of CGDD

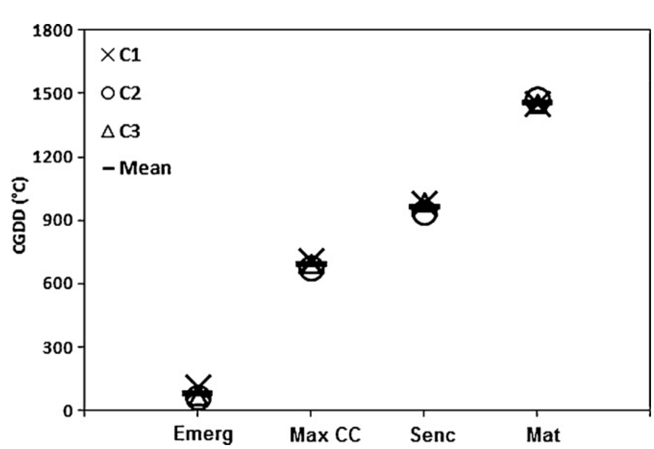

Fig. 5. Cumulative growing degree days (CGDD) of four phenological stages obtained from the calibration fields during 2002/2003 cropping season.

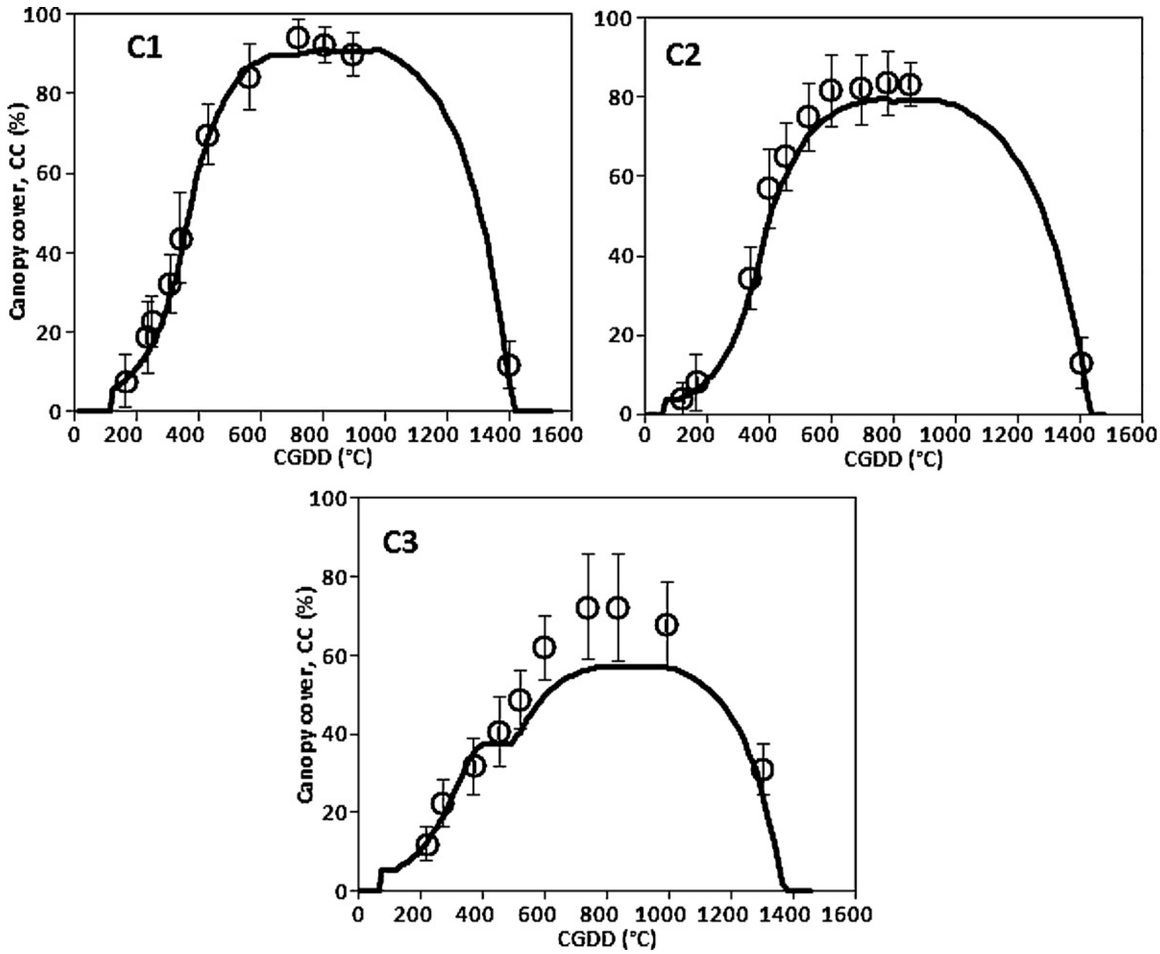

Fig. 6. The observed (circle) and the simulated (continuous line) canopy cover (CC) for the three calibration fields (C1–C3) during the 2002/2003 cropping season. Vertical bars indicate standard deviations.

during the whole growing season (from sowing to maturity) are similar for all fields. For the validation of the AquaCrop model during other season (2003/2004), the average values of CGDD in each phenological stage have been used (see Table 3). Other parameters ($P_{exp,\ upper}$, $P_{exp,\ lower}$, $P_{sen,\ upper}$ and $P_{sto,\ upper}$) affecting CC have been also adjusted and they were equal to 0.3, 0.8, 0.85 and 0.5, respectively (see Table 3). The obtained values are in agreement with other studies testing the AquaCrop model for winter wheat (e.g. Andrazian et al., 2011; Mkhabela et al., 2012; Iqbal et al., 2014).

Fig. 6 displays the comparison between the simulated and the observed canopy cover (CC) for the three calibration fields. This figure shows that the AquaCrop model was able to simulate accurately the CC development which was confirmed by statistical values (Table 4). The coefficient of determination (R^2) and the NSE are close to 1 for all fields except for field C3 where some discrepancies between observed and simulated CC have been observed. Additional statistical results are presented in Table 4. Such discrepancies are due to the wild oat that developed in April (Duchemin et al., 2006) which increased the measured CC whereas the model simulated only the wheat plants. It is also important to note that the AquaCrop model simulated correctly CC from sowing to flowering (when the measurements were available during 2002–2003), which is corroborated by other studies (e.g., Andarzian et al., 2011; Xiangxiang et al., 2013). The AquaCrop model was assessed for the validation fields also after flowering (V1–V6) as the measurements of CC were available during the whole season (see below).

The simulation of actual evapotranspiration (ET_{cact}) was based principally on two parameters: K_{ex} and $Kc_{Tr,x}$. The calibrated values of K_{ex} and $Kc_{Tr,x}$ were 0.25 and 1.07, respectively. The value 0.25 of K_{ex} was determined based on the observed frequency of water supply (≈10 days) and the average value of ET_o (4 mm/day) during the growing season (Allen et al., 1998; Er-Raki et al., 2010b). For $Kc_{Tr,x}$, as CCx was different from 100% for our studied fields, AquaCrop model adjusted the value of $Kc_{Tr,x}$ based on CCx in order to obtain the actual value of plant transpiration (Kc_{Tr}) which is about 0.9 (Er-Raki et al., 2007, 2010b). Fig. 7 displays the time course of measured and simulated ET_{cact} by the AquaCrop model for C1–C3 fields during the 2002/203 cropping season. The AquaCrop model appeared to better simulate the ET_{cact} for both fields C1 and C2 compared to C3. The root mean square error (RMSE) and the mean bias error (MBE) between measured and simulated ET_{cact} values were about 0.69 mm/day, 0.47 mm/day, and −0.05 and 0.11 mm/day, respectively. The values of NSE (0.57 for C1 and 0.77 for C2) were relatively good and showing accurate performance of ET_{cact} by the AquaCrop model. However, an underestimation noted at the C3 field is attributed to the presence of the wild oat developed in April (Duchemin et al., 2006) during the 2002/2003 season, which increased the observed CC (see Fig. 6) and then the measured ET_{cact}. Another factor that may partly explain the difference between measured and simulated ET_{cact} is the flux source area (about 3 ha) measured by eddy covariance which depends on the wind direction. In fact, the eddy covariance system measures the ET_{cact} over a relatively large area (wet and dry) but the model simulates the ET_{cact} over a smaller area likely to be homogeneous (wet or dry). It is also clear that the model tends to underestimate ET_{cact} during the senescence period (e.g., see the ET_{cact} values simulated at

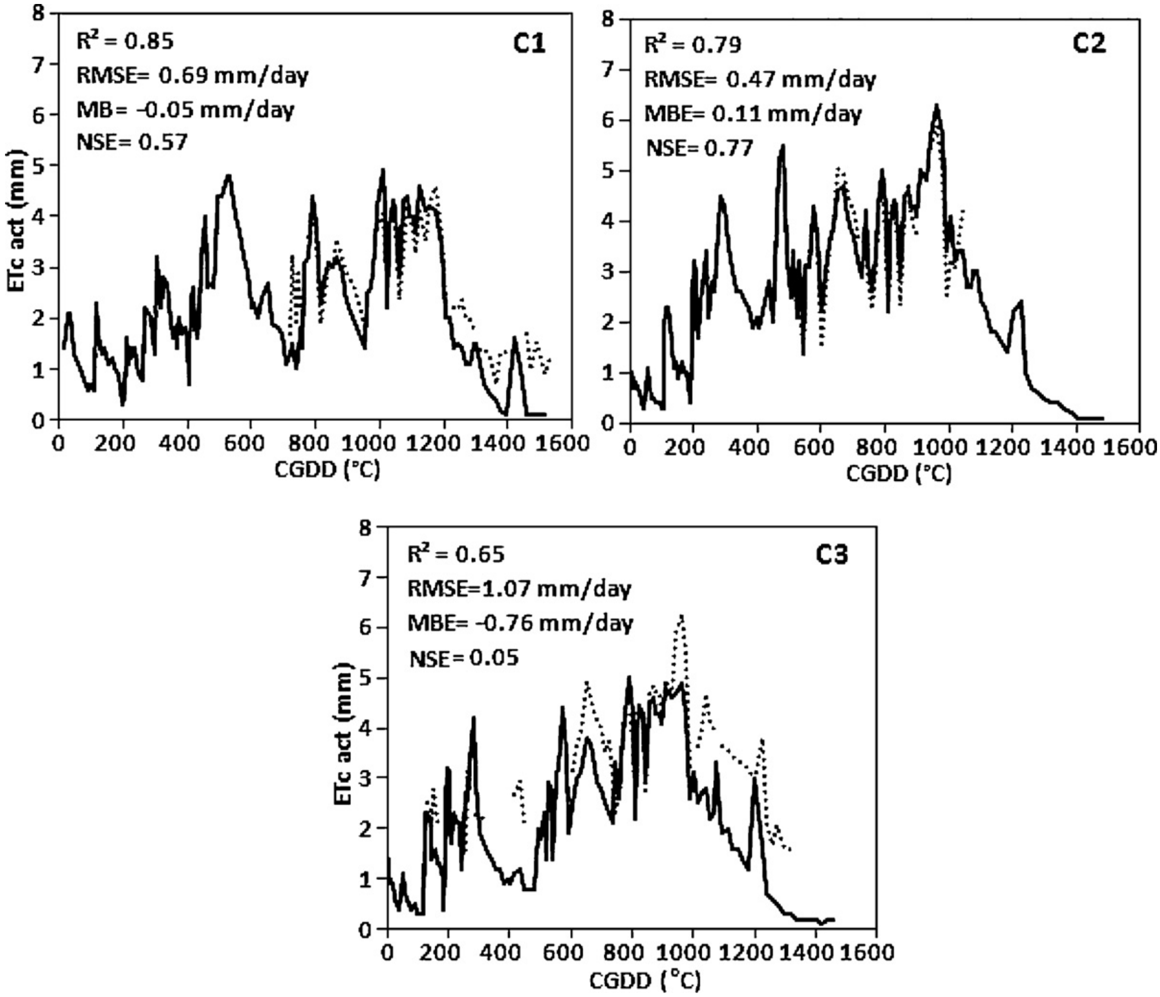

Fig. 7. Time series of the observed (dashed lines) and simulated (continuous line) actual evapotranspiration (ETc act) by AquaCrop model for three calibration fields (C1–C3) during the 2002/2003 cropping season.

the end of season for C1 and C3). The same observations have been reported by Katerji et al. (2013) when applying AquaCrop model under contrasting water stress conditions in the Mediterranean region. As well, Iqbal et al. (2014) reported that AquaCrop model cannot provide satisfactory results between simulated and measured ET_{cact} under severe stress water conditions. The obtained results of the AquaCrop model for estimating ET_{cact} are in concordance with other crop models used in the same study area for winter wheat such as FAO-56 (Er-Raki et al., 2007) and STICS (Hadria et al., 2007).

The total water content (TWC) of the soil profile (0–55 cm), which is the result of soil water balance, was also simulated for C1–C3 fields (Fig. 8). According to this figure, the dynamics of TWC was adequately simulated and followed the trend of the measured values with some over-estimation of TWC for C2 and most of C3. The simulations as well as the measurements respond well to water supply (irrigation and rainfall). In addition, the simulated soil water content remained above PWP for the three calibration fields during the cropping season while some observations dropped below PWP over C2 and C3 fields at the end of season. Statistical results such as RMSE, MBE, R^2 and NSE values for the three calibration fields ranged from about 22 mm to 44 mm, −1.84 mm to 41 mm, 0.57 to 0.67 and −2.62 to 0.55, respectively. RMSE values represent about 26–53% of TAW and 14–28% of the average value of TWC. The neg-

Table 4
Statistical values between the measured and the simulated canopy cover for the calibration and the validation fields during the 2002/2003 and 2003/2004 agricultural seasons.

	Fields	n	R^2	RMSE (%)	Slope	Intercept	MBE (%)	NSE
Calibration fields	C1	11	0.99	3.63	1.03	−4.13	−2.64	0.99
	C2	11	0.99	5.33	0.95	−0.99	−3.86	0.98
	C3	10	0.97	11.41	0.74	4.92	−7.32	0.79
Validation fields	V1	7	0.95	16.79	0.89	21.5	15.34	0.66
	V2	15	0.93	8.25	0.77	17.37	4.32	0.87
	V3	15	0.83	13.75	0.89	8.86	8.54	0.8
	V4	15	0.86	9.73	0.95	4.8	3.26	0.87
	V5	14	0.91	12.97	1.07	8.12	9.91	0.73
	V6	13	0.94	9.39	0.95	7.69	5.98	0.89

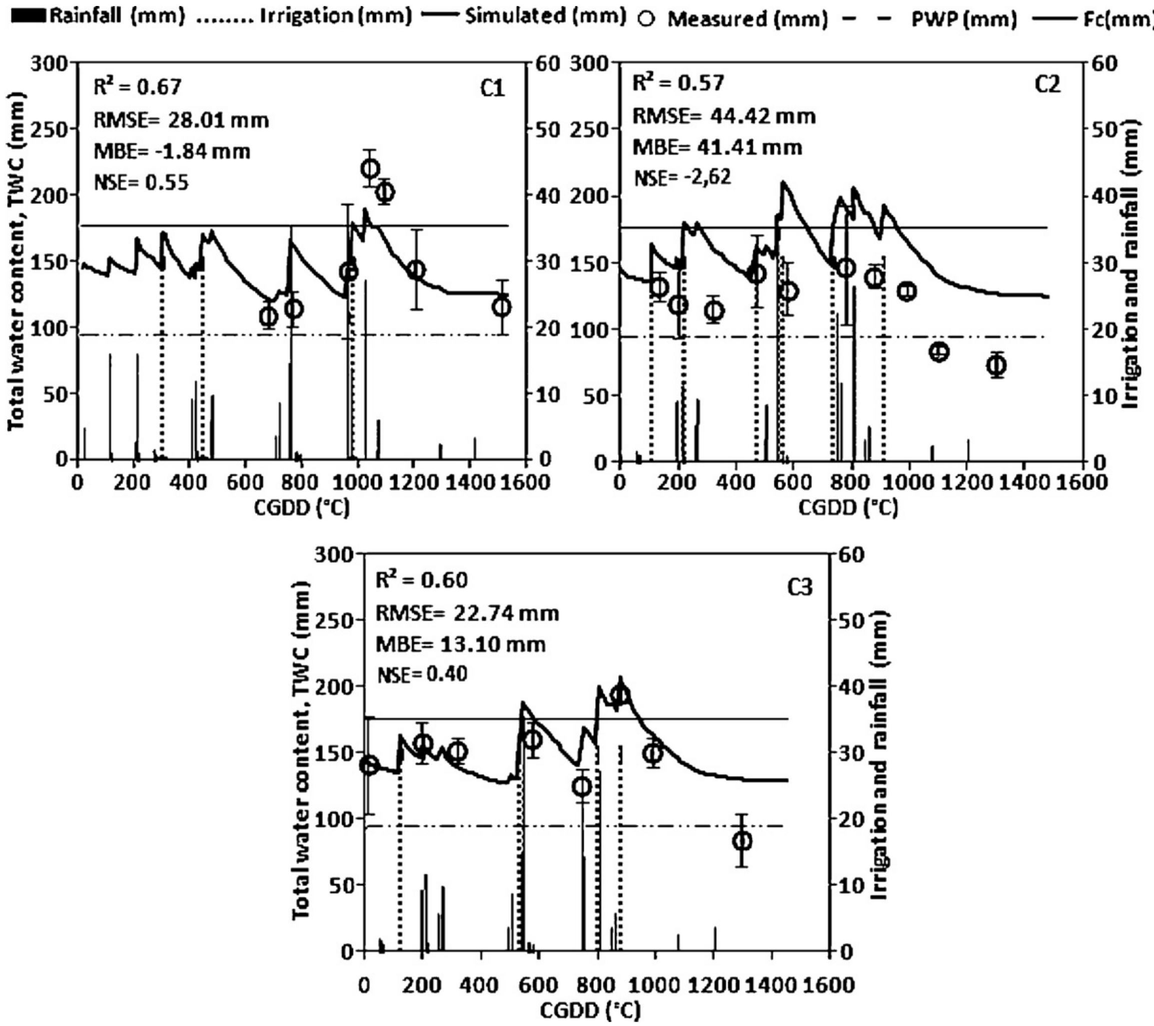

Fig. 8. Comparison of simulated and measured total soil water content (0–55 cm) for the calibration (C1–C3) fields during 2002/2003. Fc, PWP, rainfall and irrigation events are shown in the same figures. Vertical bars indicate standard deviations.

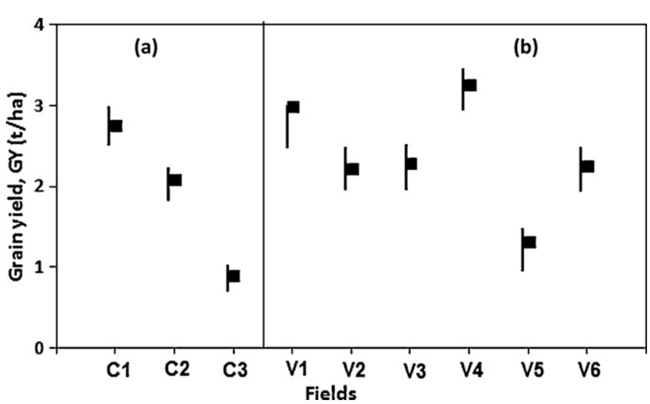

Fig. 9. Comparison between the grain yield simulated by the AquaCrop model and that measured for three calibrations (a) and six validations (b) fields during the 2002/2003 and 2003/2004 growing seasons. The symbol (■) corresponds to the simulated grain yields. Bars correspond to the minimum and maximum of the five replicates of GY measurements.

ative value of NSE obtained for field C2 (Fig. 8) can be explained by a clear overestimation of TWC at low soil water content (below PWP). The same observation has been reported by several studies (e.g., Farahani et al., 2009; Hussein et al., 2011; Mkhabela and Bullock, 2012; Iqbal et al., 2014). They found that AquaCrop model tends to consistently overestimate TWC during the dry conditions, particularly in the deficit irrigation plots.

Finally, the values of HIo and WP* have been obtained based on an accurate model adjustment on the measured GY (C1–C3 fields, Fig. 9a). The corresponding R^2, RMSE and MBE were 0.99, 0.03 t/ha and 0.01 t/ha. The values found are HIo = 46% and WP* = 16 g/m^2 (Table 3). These values are in agreement with other studies performed over the wheat crop in different countries. In the China Loess Plateau, Xiangxiang et al. (2013) reported that the value of WP is 17 g/m^2 for wheat. For HI_0, Jin et al. (2014) found the similar value (46%) where they tested the AquaCrop model on wheat in North China Plain. In other works (e.g., Andarzian et al., 2011; Mkhabela and Bullock, 2012), it was found that the values of WP* and HIo for wheat are slightly different to our finding due to different cultivars.

According to the above results obtained during the calibration stage, AquaCrop model can adequately simulate CC and GY but it is less accurate for ET_{cact} and TWC for winter wheat in the semi-arid region of Tensift Al Haouz.

3.2. Validation of the AquaCrop model

After the calibration of the AquaCrop model, the validation was performed using six fields named V1–V6 during the 2003/2004 cropping season. The simulation was carried out in terms of CC, ET_{cact}, TWC and GY.

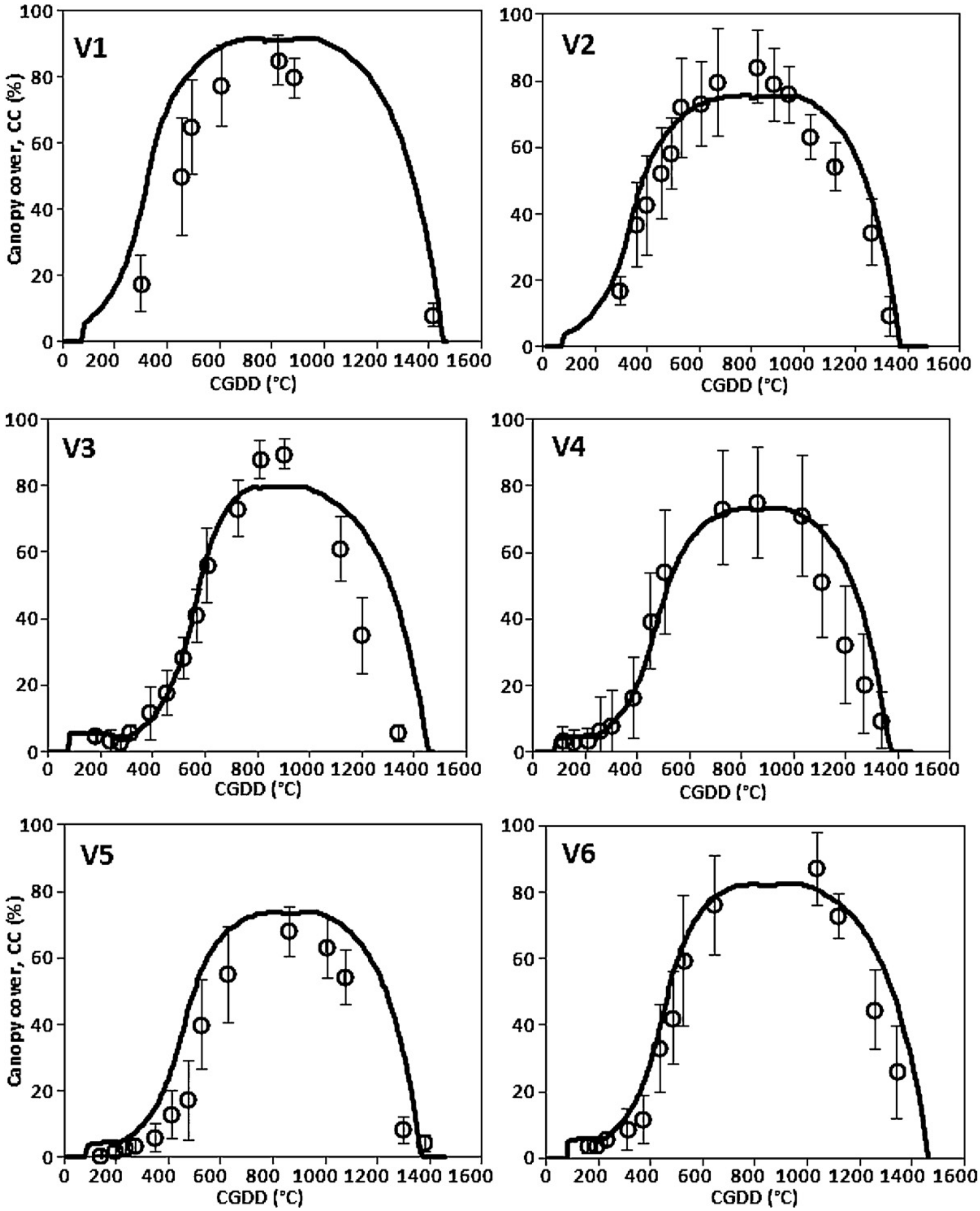

Fig. 10. The comparison between the observed (circle) and simulated (continuous line) canopy cover (CC) for the six validation fields (from V1 to V6) during the 2003/2004 growing season. Vertical bars indicate standard deviations.

Fig. 10 illustrates the comparison between the measured and the simulated CC over the validation fields (V1–V6). This figure shows that AquaCrop model was able to simulate accurately CC. The RMSE, NSE, R^2 and MBE between measured and simulated CC for all validation fields are relatively acceptable (see Table 4). The model provides particularly good performances of CC for fields V2, V4 and V6. However, there are some discrepancies observed at V1 and V5 fields, with measured CC declining slightly faster for V3 field compared to simulated CC. For all fields, the values of CC were generally overestimated from the senescence to the end of the cropping season as also highlighted by Andarzian et al. (2011) for wheat production under full and deficit water conditions in Iran. Overall, the obtained results in estimating CC are satisfactory and are in agreement with other studies using the same model with different crops, such as barley (Araya et al., 2010) and corn, tomato and potato crops (Casa et al., 2013; Katerji et al., 2013).

Fig. 11 presents the comparison between the daily simulated and measured ET_{cact} for one validation field (V4) where the measurements were available during the 2003/2004 cropping season. The RMSE, MBE, NSE, and R^2 values were 0.78 mm/day, −0.01 mm/day, −0.41 and 0.59, respectively. The negative value of NSE indicated that the mean of measured ET_{cact} was better pre-

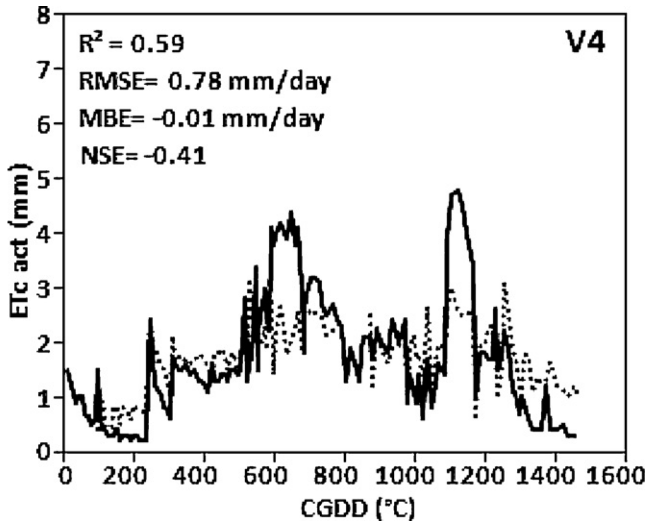

Fig. 11. Time series of the observed (dashed lines) and simulated (continuous line) actual evapotranspiration (ETc act) by AquaCrop model for one validation (V4) during the 2003/2004 cropping season.

dictor than the model. Some discrepancies are observed when soil evaporation is high (after irrigation or heavy rainfall) or when severe stress occurs (e.g., see the ET_{cact} values simulated at the end of season). The same observations have been reported during the calibration stage (see the previous section). Indeed, the AquaCrop adopts the FAO-56 dual approach (Allen et al., 1998) for calculating ET_{cact} and this approach has generated much criticism when applied in the semi-arid Mediterranean region (e.g., Testi et al., 2004; Katerji and Rana, 2006; Lovelli et al., 2007; Orgaz et al., 2007; Er-Raki et al., 2007, 2009, 2010c) as reported by Katerji et al. (2013).

Concerning the validation of AquaCrop predictions of TWC, Fig. 12 shows the comparison between the observed and the simulated TWC for the 0–55 cm profile for V4 field. This simulation showed that the model responds well to the water supply (irrigation and rainfall), but tends to overestimate TWC with some bias along the season (MBE = 0.5 mm and RMSE = 22 mm which represents a relative error of 14%). Bias in TWC simulation by AquaCrop was identified in some previous studies under different growing seasons and under different irrigation regimes of wheat (e.g., Farahani et al., 2009; Hussein et al., 2011; Mkhabela and Bullock, 2012; Iqbal et al., 2014), soybean (Paredes et al., 2015), maize (Paredes et al., 2014) and cotton (Farahani et al., 2009).

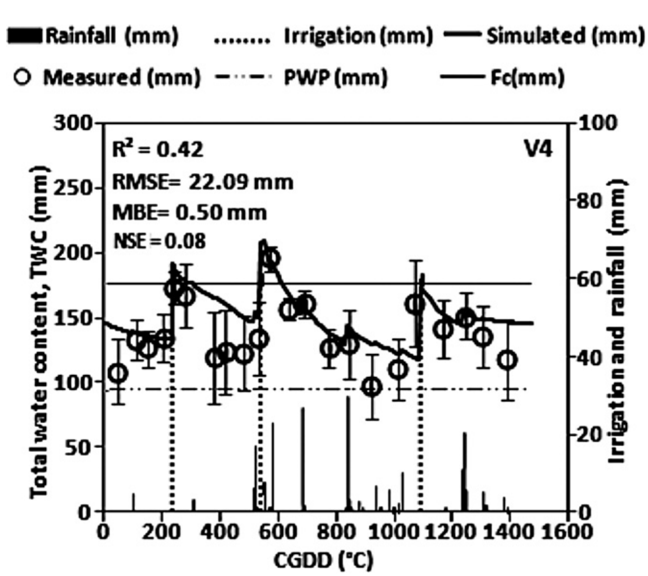

Fig. 12. Evaluation of the total soil water content (0–55) cm for the validation field (V4) during 2003/2004 cropping season. Fc, PWP, rainfall and irrigation events are shown in the same figure. Vertical bars indicate standard deviations.

The performance of the AquaCrop model in simulating TWC for irrigation strategies for winter wheat in Tensift Al Haouz Marrakech can be compared with other models such as PAMII used by Brimelow et al. (2010) who simulated total soil water content in the root zone (top 110 cm) for three sites in Alberta and Canada. They reported that the correlation coefficients (R^2) between simulated and observed TWC varied between 0.65 and 0.90, while the relative errors were typically less than 10%. Meanwhile, in southwestern Saskatchewan, Canada, Kersebaum et al. (2008) simulated soil water content (0–120 cm layer) using the HERMES model (Kersebaum, 1995) and reported that modeled and observed soil water content values during the growing season correlated well with $R^2 = 0.80$ and with a relative error about 14%.

Finally, Fig. 9 highlights the comparison between observed and modeled grain yield (GY) for three calibration fields and six validations fields during the 2002/2003 (Fig. 9a) and 2003/2004 (Fig. 9b) growing season. The obtained results showed that the model has accurately reproduced the GY; the estimated values of the GY for all fields are in the range of the measured values. The values of R^2, RMSE and MBE were 0.98, 0.1 t/ha and −0.04 t/ha for the validation fields. It can be seen also in Fig. 9 that the variations of GY from one field to another were generally well simulated depending on agricultural practices of each field (sowing date, irrigation water and fertilization) (see Tables 1 and 2). The GY is lower for the fields having late sowing dates and where no fertilizer has been supplied(C3 and V5). The higher values of GY are recorded in the fields characterized by early sowing (C1 and V2) dates and/or fertilization supply (V4 and V6). By comparing the GY between two fields (V4 and V5) having the same agricultural practices differing only in the supply of fertilizers, a large difference between GY of V4 (3.14 t/ha) and V5 (1.27 t/ha) was observed which is certainly due to the effect of soil fertility stress. Similar results have been obtained by Hadria et al. (2007) when they used another model (STICS) for simulations of GY and biomass over the same fields of study. They reported that the simulated values of GY are quite consistent with the measured ones, depending on the amount of fertilization supply and water stress. Mkhabela and Bullock (2012) used AquaCrop to simulate also the GY for the spring wheat in Western Canada for five sites from 2003 through 2006 and they found that the model explained 66% of the relationship between simulated and measured wheat grain yield. In the studies by Andarzian et al. (2011) and Du et al. (2011), it has been shown that the AquaCrop model was able to simulate the GY of wheat under different irrigation management systems. Their findings indicate that the AquaCrop model is able to simulate GY well with an error less than 12%.

After calibration and validation of the AquaCrop model for simulating CC, ET_{cact}, TWC and GY, the following section presents the model application for irrigation scheduling.

3.3. Model application for irrigation management scenarios

Irrigation management scenarios were run with the AquaCrop model without fertilization stress. Under this option, Table 5 shows that the difference of B and GY between actual fertilization and non-stress fertilization conditions was substantial. It was between 40% (for V4) and 285% (for C3) for both B and GY. This increase is obviously much higher for the fields where no fertilization has been applied (C1, C3, V3 and V5). But the optimal GY (which is about 8t/ha for the region) was not reached. This is certainly due to the effect of water stress. In order to go further in the evaluation of the impact of the water stress on GY, the AquaCrop model, with no-limiting soil fertility, has been used as a simulation tool in an

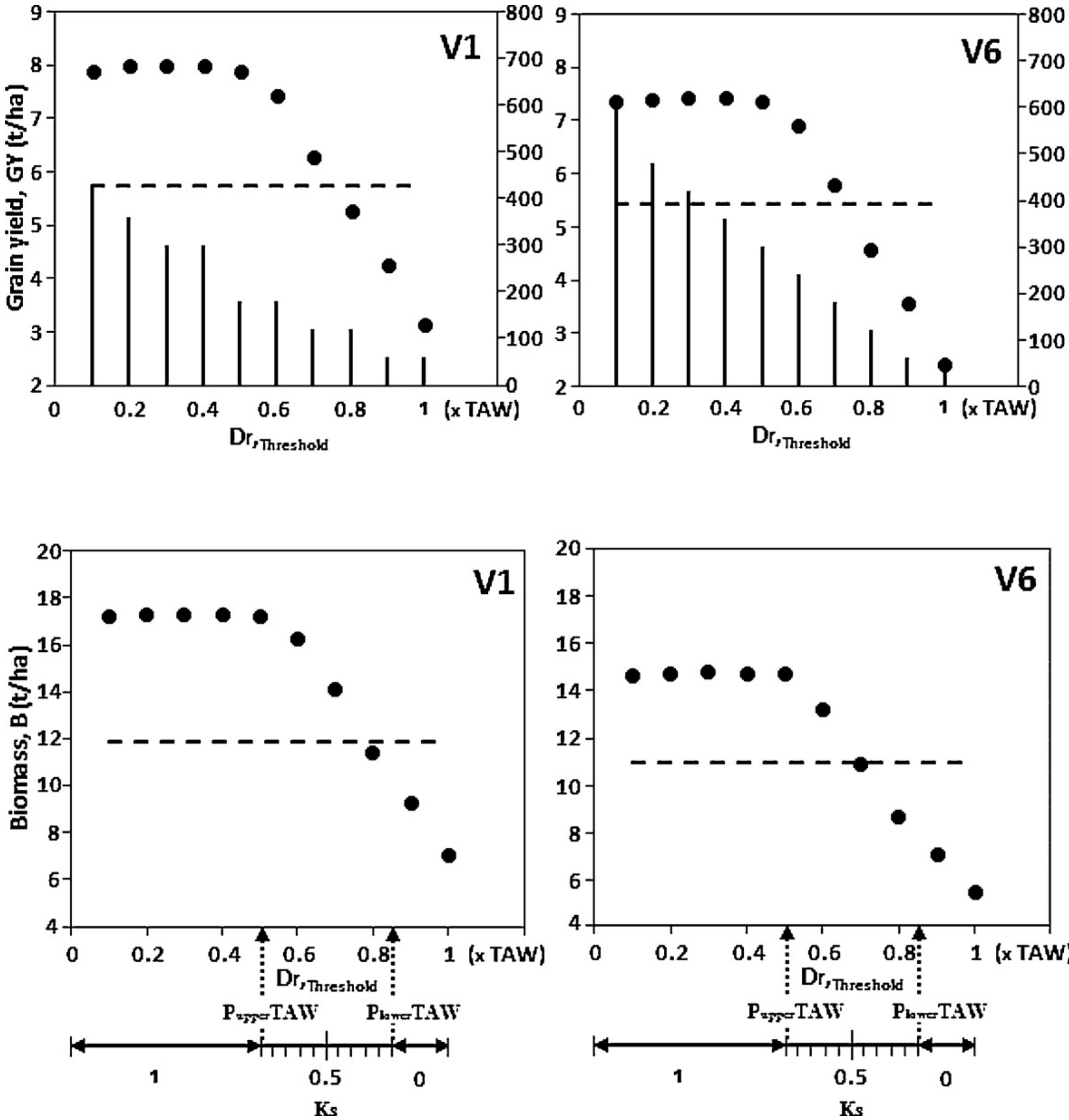

Fig. 13. Estimates of grain yield and biomass of early sowing plot V1 (left) and late sowing plot V6 (right) as a function of the threshold value of the root zone depletion ($D_{r,\ threshold}$). The horizontal dashed lines represent the values of biomass and grain yield estimated by the model when using actual irrigations and no nitrogen stress. The vertical bars, in the top figures, are the seasonal quantity of irrigation supplied by AquaCrop model.

Table 5
Differences between simulated grain yield and biomass with and without stress fertilization.

Field		Simulated biomass (t/ha)		Simulated grain yield (t/ha)		Measured grain yield (t/ha)
		Actual stress fertilization	Without stress fertilization	Actual stress fertilization	Without stress fertilization	
Calibration fields	C1	6.02	11.42	2.76	5.54	2.5–3
	C2	4.58	10.07	2.09	5.05	1.8–2.2
	C3	1.97	7.58	0.9	3.46	0.7–1
Validation fields	V1	6.5	12.16	2.99	5.74	2.5–3
	V2	4.85	12.45	2.23	5.95	2–2.5
	V3	5.04	9.07	2.29	4.12	2–2.5
	V4	6.67	9.4	3.26	4.6	3–3.5
	V5	2,91	9.64	1.32	4.38	1–1.5
	V6	5.01	11.3	2.26	5.54	2–2.5

attempt to explain GY losses caused by a lack of irrigation practices in the test fields of the Haouz plain. For this purpose, we investigated the possibility offered by AquaCrop to manage the irrigation water under the environmental conditions of the Tensift Al Haouz region during 2003/2004 cropping seasons. The maximum amount of irrigation is set by the user in the model. In this study, this amount was 60 mm according to the information supplied by the regional irrigation office during the 2003/2004 cropping season.

Fig. 13 displays the grain yield (GY) and biomass (B) simulations for V1 and V6 as a function of $D_{r,\,threshold}$ and the seasonal amount of irrigation supplied by the AquaCrop model. GY and B decrease when $D_{r,\,threshold}$ increases. The values of GY and B range from 2.4 to 8 t/ha and from 5.5 to 17.3 t/ha, respectively. Indeed, soil water stress affects the development of the canopy cover, the expansion of the root zone, results in stomata closure and a reduction of crop transpiration rate, and finally, alters the Harvest Index (Raes et al., 2012). If the soil water stress is severe, it can result in failure of pollination, and can trigger early canopy senescence (Brisson et al., 2003; Raes et al., 2009b).

As anticipated, the seasonal quantity of irrigation water increased with the decrease of $D_{r,\,threshold}$. For D_r lower than RAW (no plant stress), the amount varied between 180 and 420 mm for field V1 (early sowing) and between 300 and 600 mm for V6 (late sowing). These values are in agreement with the observed wheat water requirement (ET_c) in the region which varied between 380 mm and 520 mm depending upon climatic conditions, sowing dates and wheat variety (Bamouh, 1981; Elqortobi, 1987; Er-Raki et al., 2010b; Kharrou et al., 2011). Likewise, to avoid water stress under Morocco conditions, Le Page et al. (2014) found that the wheat with late sowing requires about 563 mm (about 9 irrigations, well scheduled by the FAO approach and satellite observation).

By analyzing the relationship between water supplied and $D_{r,\,threshold}$, one can see that it has practically a staircase form for early sowing field (V1) and is linear for late sowing field (V6). For early sowing, six groups can be identified based on the values of D_r: 0.1 TAW, 0.2 TAW, (0.3 and 0.4 TAW), (0.5 and 0.6 TAW), (0.7 and 0.8 TAW) and (0.9 and 1 TAW). These groups correspond to supplies of 420, 360, 300, 180, 120 and 60 mm of water irrigation, respectively. In each group, biomass and grain yield are not similar according to the differences in the irrigation scheduling (Hadria et al., 2007). For late sowing (field V6), a decrease of $D_{r,\,threshold}$ by 0.1 TAW corresponds in most cases to one additional irrigation.

Regarding the relationship between the wheat yields (grain and biomass) and the $D_{r,\,threshold}$ (Fig. 13), it has practically the same form for V1 (early sowing) and V6 (late sowing). The performances of V1 are slightly higher in terms of GY and biomass for each $D_{r,\,threshold}$. Indeed, biomass ranged from 7 to 17.3 t/ha for V1 and from 5.6 to 14.8 t/ha for V6. For the grain yield, the values ranged from 3.1 to 8 t/ha and from 2.4 to 7.4 t/ha for V1 and V6, respectively. However, the amounts of water required for the two fields are much different. The amount of irrigation was always higher for V6 than for V1, by an average of 107 mm which represents about two irrigations. In fact, the field V1 (sown in November 21, 2003) benefited from the early effective rainfall occurred at the beginning of the season (Fig. 3), while irrigation was necessary just after V6 sowing (December 24, 2003) to prevent the field from water stress. In addition, the evapotranspiration was much higher at the end of the season (April–May). This period coincides with grain filling stage for V6, which is a critical stage for grain wheat production for which water stress must be avoided(Ouattar and Ameziane, 1989). As a result, there was a difference of about 38% of water consumption between these two fields due to the differences in the sowing dates.

Fig. 13 presents the particular values of biomasses and grain yields (horizontal dashed lines) calculated with the existent cultivation practices and environmental conditions, but without fertilization stress. These yields were obtained for V1 and V6 fields under three irrigations (180 mm, see Table 1) during the 2003/04 wheat season. The same values of biomass and grain yield were also retrieved using a $D_{r,threshold}$ value of $0.7 \times$ TAW and with an irrigation amount of 120 mm and 180 mm for V1 and V6, respectively. This result revealed that an amount of 60 mm could be saved for early sowing.

In the same context of water saving, it is of interest to determine the appropriate value of $D_{r,\,threshold}$ that can give high values of yields but with less amount of irrigation. As shown in Fig. 13, the GY and B for both V1 and V6 are very sensitive to $D_{r,\,threshold}$ values between $0.6 \times$ TAW and TAW by a factor of 2.5. By contrast, this sensitivity is very low for Dr between $0.1 \times$ TAW and $0.6 \times$ TAW. Indeed, for V1, the supply of an additional 240 mm (4 irrigations) allowed a low increase of GY and B by only about 6.2% and 5.9%, respectively. For V6 field, a very important additional amount of irrigation (360 mm which is equivalent to 6 irrigations) is required to obtain a gain of 6.8% and 11.1% of GY and B, respectively. As a conclusion, the scenario corresponding to the value $D_{r,\,threshold} = 0.6 \times$ TAW can be used as an appropriate threshold of Dr to improve the wheat irrigation management. This value of $D_{r,\,threshold}$ corresponds to a stress coefficient of about 0.7 (Fig. 13). This value is consistent with the threshold of the FAO-56 stress coefficient Ks = 0.65 obtained by Jackson et al. (1981) for wheat in Europe, and Ks = 0.7 deduced from the results presented in Fig. 6 of Hadria et al. (2007) for wheat in Morocco.

Finally, it is important to note that this application is only based on simulations, with the hypothesis that wheat do not suffer from fertilization stress. To confirm these conclusions, further validation studies will be necessary. Despite this limitation, these simulations show the potential of the AquaCrop model to improve the cultivation practices in terms of irrigation management, sowing dates, fertilization. In this context, the obtained results revealed that the early sowing date is more appropriate than the late sowing, in terms of saving water and improving grain yield of wheat in the region, as already reported by several studies (Bassu et al., 2009; Bannayan et al., 2013; Andarzian et al., 2014). In addition, the AquaCrop model offers the possibility to manage irrigations in order to avoid (or to reduce) the water stress. In this context, the obtained results indicate that about 60 mm can be saved without grain yield loss in the case of early sowing. This value corresponds to about 33.3% of the quantity of the water available for irrigation in the experimental site during 2003/04 cropping seasons.

4. Conclusion

The first objective of this study was to calibrate and validate AquaCrop model to estimate seasonal canopy cover (CC), actual evapotranspiration (ET_{cact}), total water content (TWC) and grain yield (GY) over winter wheat in the Mediterranean semi-arid region of Tensift-basin (central of Morocco). The second objective was to investigate the potential of AquaCrop model for exploring water saving and improving grain yield of wheat. Evaluation of the AquaCrop model with the experimental data showed that the model simulates reasonably well CC, ET_{cact}, TWC and GY. The average values of the mean bias error (MBE) between observed and measured CC, ET_{cact}, TWC and GY were −4.6%, −0.23 mm/day, 17.56 mm and 0.05 t/ha for the calibration fields, and 7.89%, −0.01 mm/day, 0.5 mm and 0.06 t/ha for the validation fields, respectively.

After calibration and validation of the AquaCrop model for winter wheat, we used this model to generate several scenarios (based on threshold of the root zone water depletion, $D_{r,\,threshold}$) in order to determine the appropriate one for better irrigation management with a good GY productivity. This test was done on two validation fields (V1 and V6) which differed by their sowing dates. These scenarios showed that early sowing is more adequate than late one in saving water and obtaining adequate grain yield. Also, it has been shown that the value 0.6 of $D_{r,\,threshold}$ can be used as appropriate to improve the wheat irrigation management. Consequently, we can conclude that the AquaCrop model can be used as an operational tool for controlling irrigation water of the winter wheat in semi-arid regions.

Finally, it is important to note that the test of AquaCrop for irrigation scheduling is only based on simulations. To confirm these conclusions, further validation studies under real conditions will be necessary. Also, other studies relative to economic and environmental analysis should be performed in future to support appropriate decisions.

Acknowledgements

This research was conducted within the International Joint Laboratory (http://trema.ucam.ac.ma) as well as the project (Recherche Sectorielle, RS/2011/09) financed by the CNRST of Morocco. Additional funding was provided by ANR AMETHYST (ANR-12-TMED-0006-01). Jihad Toumi was awarded a mobility research training grant from PHC Maghreb 32 592VE. Finally, the authors thank also the Editor and two anonymous reviewers for their time and effort for providing excellent comments and suggestions to improve the manuscript.

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