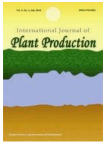

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Developing scenarios to assess sunflower and soybean yield under different sowing dates and water regimes in the Bekaa valley (Lebanon): Simulations with Aquacrop

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Abstract

In a semi-arid environment, the main challenge for crop production is water limitation in space and in time. Considered as appropriate tools, models are used to evaluate the effects of water deficit on crop productivity for better irrigation planning and sustainable yield. The AquaCrop model was tested using data collected during a 4-year experiment on soybean (*Glycine max* L. Merril) and sunflower (*Helianthus annuus* L.) in the Bekaa Valley of Lebanon. The model was found to accurately simulate final crop biomass, yield and cumulative evapotranspiration: in fact the Wilmot index of agreement (IoA) values were 0.97, 0.96 and 0.96, respectively, for soybean and 0.93, 0.95 and 0.93, respectively, for sunflower, while the relative RMSE was 0.04, 0.05 and 0.02, respectively, for soybean and 0.04, 0.06 and 0.04, respectively, for sunflower. The analysis of irrigation scenarios showed that the early planting of sunflower could demonstrate a greater efficiency than late sowing. In addition, applying three irrigations, of 100 mm each, prior to flowering, at mid flowering stage and at the beginning of seed formation could lead to highest yields (ranging between 4.51 and 2.34 t ha^{-1}) and crop water productivity (CWP) (ranging between 1.5 and 0.78 kg m^{-3}). Sunflower yields were low (0.42 t ha^{-1} to 0.37 t ha^{-1}) and unreliable when one single irrigation was performed only at the beginning of seed formation, while highest values (ranging between 1.97 and 1.74 t ha^{-1}) were obtained when it was done prior to flowering. The highest yields and crop water productivity for soybean were obtained when the crop was sown in April and by applying three irrigations, of 100 mm each, at full bloom, at seed enlargement and at mature seeds. Soybean yield values ranged between 3.16 and 2.01 t ha^{-1}, while CWP values varied from 1.05 to 0.67 kg m^{-3}. However, irrigating at seed enlargement and mature seeds, as well as applying only one irrigation of 100 mm at any growth stage, could lead to very low yields and CWP.

Keywords: Crop modelling; Deficit irrigation; *Glycine max* L. Merril; *Helianthus annuus* L.; Water productivity.

Introduction

Shortage of water is one of the greatest threats facing agricultural development in arid and semi-arid regions of the world. In these regions, the resilience and sustainability of water and food systems to the current pressures of water scarcity are closely linked to the optimization of water use in irrigated agriculture. Within this context, simulation modeling can be a useful tool to study and develop scenarios for farmers for enabling local end-users to evaluate and optimize crop yield, irrigation water use, sowing time, etc. (Heng et al., 2007; Liu et al., 2007; Pereira et al., 2009; Raes et al., 2009). Modeling of yield response to water is expected to play an increasingly important role in agriculture (Geerts et al., 2009a; Geerts et al., 2010).

The Food and Agricultural Organization of the United Nations (FAO) in its effort to ensure efficient use of water for food production has developed the AquaCrop model which primarily deals with yield response to water applied (Hsiao et al., 2009; Steduto et al., 2009; Steduto et al., 2012).

The AquaCrop model performances has been evaluated for different field crops, such as maize (Hsiao et al., 2009; Heng et al., 2009; Stricevic et al., 2011; Abedinpour et al., 2012; Shrestha et al., 2013), cotton (Farahani et al., 2009; Garcia-Vila et al., 2009; Hussein et al., 2011), sunflower (Todorovic et al., 2009; Stricevic et al., 2011), quinoa (Geerts et al., 2009b), barley (Araya et al., 2010a; Abrha et al., 2012), teff (Araya et al., 2010b; Tsegay et al., 2012), sugar beet (Stricevic et al., 2011), wheat (Andarzian et al., 2011; Manasah et al., 2012; Soddu et al., 2013; Shrestha et al., 2013; Xiangxiang et al., 2013), canola (Zeleke et al., 2011), bambara groundnut (Karunaratne et al., 2011), tomato (Rinaldi et al., 2011), cabbage (Wellens et al., 2013), in different locations around the world. In many of these studies, there is the evidence that the model adequately simulated crop water productivity under well-watered conditions, while tending to misestimate it under conditions of water stress: such difficulties compromise the use of the model for deficit irrigation scenarios or rainfed situations with expected soil water deficits (Evett and Tolk, 2009).

In the Bekaa valley of Lebanon, water is by far the major constraint to crop production because rainfall is extremely irregular and it is concentrated during the winter months. Moreover, limited water storage capacity of soils during winter associated with high temperatures and evapotranspiration rates during summer reduce water availability for crops in this season. In this valley, soybean (*Glycine max* L. Merril) and sunflower (*Helianthus annuus* L.) production was remarkably reduced in the last two decades as seed yield under rainfed regime was unreliable; consequently their cultivation was limited to areas under irrigation (Karam et al., 2005; Karam et al., 2007). On the other hand, because water scarcity is becoming more prevalent, reducing irrigation quantity for seed production is now the primary concern for farmers in the central Bekaa Valley to reduce pressure on fresh water resources.

The aims of this study were: (i) to test the AquaCrop model for simulating both sunflower and soybean yield under different water regimes and irrigation timings; (ii) to apply the model under different scenarios in order to optimize sowing date and irrigation management of both crops to dry and hot conditions of the central plains of the Bekaa Valley, by evaluating the best crop water productivity (CWP). Exploring different scenarios could help to give recommendations to farmers on the best suitable sowing time and irrigation application that could offer a compromise between water saving and acceptable grain yield.

Material and Methods

Experimental site and climatic conditions

Field trials aiming at examining the response of soybean and sunflower to deficit irrigation were conducted during four cropping seasons 2000-2001 (soybean) and 2003-2004 (sunflower) at Tal Amara Research Station in the Central Bekaa Valley of Lebanon (33° 51' 44" N lat., 35° 59' 32" E long., altitude 905 m a.s.l) characterized by a typical Mediterranean climate: hot and dry from May to October and cool for the rest of the year. Average seasonal rainfall is about 600 mm, with 80% occurring between November and March (Aboukhaled and Sarraf, 1970).

For both crops, sowing occurred in late April–May. For the farming system in the Eastern Mediterranean dry lands this period coincides with the end of the wet season and the beginning of the dry season, during which historically no rain is observed till September. The soil characteristics of the study area are given in Table 1. Weather data, such as air temperature and humidity, wind speed, incoming solar radiation and rainfall were recorded by an automated weather station 100 m far from the experimental site. Monthly long term (1954-2010) rainfall (P) and reference evapotranspiration (ET_o), calculated by using Penman Monteith equation, along with P and ET_o during the four years of experiments and during an average year are given in Figure 1 (a, b).

Crop management and irrigation treatments

Soybean (cv. Asgrow 3803) was planted on 10 May 2000 and on 25 April 2001 at a density of 12 plants m^{-2}. The experimental area consisted of a 2160 m^2; field was divided into four main plots, 540 m^2 each representing four irrigation treatments: (C) control treatment that is fully-irrigated throughout the growing period; (S_1) treatment where irrigation was cut out for a two-week period at full bloom; (S_2) treatment where irrigation was cut out for a two-week period at seed filling; (S_3) treatment where irrigation was cut out for a two-week period at seed maturity. Each plot was subdivided into five sub-plots, or replicates, of 108 m^2 each.

Sunflower (cv. Arena) was planted on 2 June 2003 and on 10 June 2004 at a density of 8 plants m^{-2}. The experimental area consisted of a 2400 m^2 field divided into four main plots, 600 m^2 each representing the four irrigation treatments: (C) control treatment that is fully-irrigated throughout the growing period; (S_1) treatment where irrigation was cut out for a two-week prior to flowering; (S_2) treatment where irrigation was cut out for a two-week period at mid flowering; (S_3) treatment where irrigation was cut out for a two-week period at the beginning of seed formation. Each plot was subdivided into five subplots, or replicates, of 120 m^2 each.

Both experiments have been more detailed described elsewhere (Karam et al., 2005; Karam et al., 2007).

Table 1. Soil properties of Tal Amara experimental field.

Soil properties	0-90 cm soil depth
Texture	Clay
Silt (%)	25
Sand (%)	31
Clay (%)	44
Bulk density (g cm^{-3})	1.41
Field capacity (cm^3 cm^{-3})	0.41
Wilting point (cm^3 cm^{-3})	0.22
Saturation (cm^3 cm^{-3})	0.52
Hydraulic conductivity (mm day^{-1})	42
pH	8
ECe (dS m^{-1})	0.43

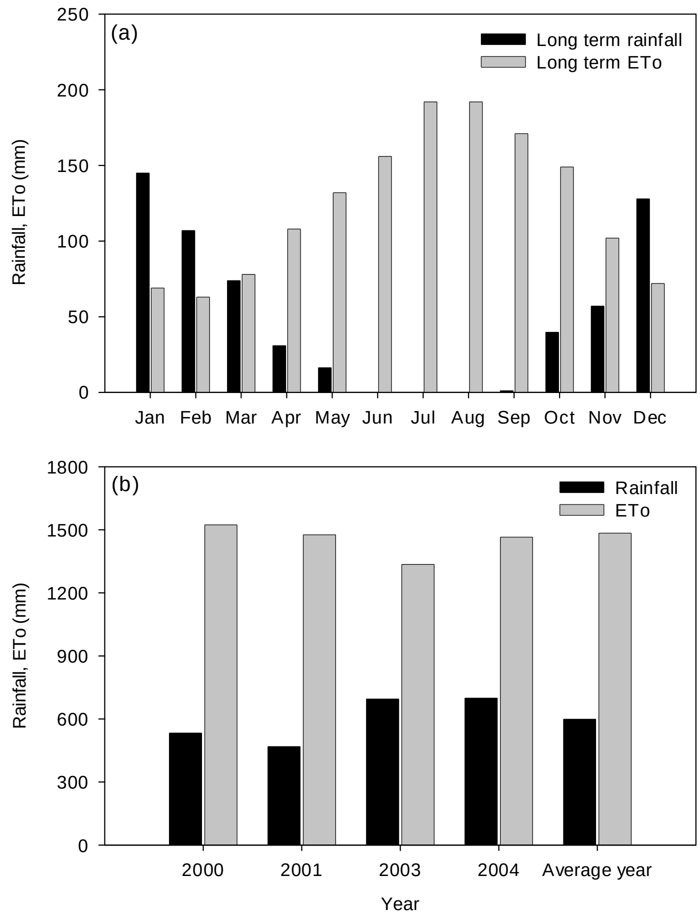

Figure 1. Monthly long term (1954-2010) rainfall and reference evapotranspiration (ET_o)–(a) and annual rainfall and ET_o during the four growing seasons (2000, 2001, 2003 and 2004) and during an average year (b).

Data collection

In both experiments evapotranspiration (mm) was estimated by using the soil-water balance equation:

$$ET = I + P - Dr - Rf \pm \Delta s \qquad (1)$$

Where, I is irrigation application (mm), P is rainfall (mm), Dr is drainage water (mm), Rf is amount of runoff (mm) and Δs is the change in soil moisture content (mm).

Since there was no observed runoff during the experiment, it was assumed to be negligible in the calculation of ET. Similarly, since there was no observed drainage below 90 cm depth (Karam et al., 2007), particularly after applying irrigation at 100% ET, it was considered negligible and, consequently, it was ignored. So the above equation was reduced to:

$$ET = I + P \pm \Delta s \quad (2)$$

Soil water content was gravimetrically measured once before each irrigation, by collecting soil samples in three replicates for each treatment at 0-90 cm of soil depth and 30 cm increment (Karam et al., 2005; Karam et al., 2007). Irrigation volumes of both crops are reported in Table 2.

Table 2. Irrigation volumes supplied to soybean and sunflower during the growing seasons.

Treatment	Soybean		Treatment	Sunflower	
	Volumes applied in 2000 (mm)	Volumes applied in 2001 (mm)		Volumes applied in 2003 (mm)	Volumes applied in 2004 (mm)
C	889	738	C	771	861
S_1	741	647	S_1	540	668
S_2	782	656	S_2	601	725
S_3	801	646	S_3	673	782

Leaf area index (LAI) and aboveground biomass were measured once every two weeks at each plot by taking plant samples: fifteen plants per treatment for soybean and five for sunflower. The leaf area was measured using a leaf area meter (LI 3100, LI-COR, Inc., Lincoln NE), while aboveground biomass was measured after drying it in an oven (80 °C) until biomass reached constant weight. The fractional canopy cover was estimated according to Ritchie (1975):

$$CC = 1 - \exp(-0.65\ LAI) \quad (3)$$

where CC is fractional canopy cover and LAI is the leaf area index.

This equation has been largely used by Heng et al. (2009) for maize, Farahani et al. (2009) and Garcia-Vila et al. (2009) for cotton, Geerts et al. (2009a) for quinoa and Araya et al. (2010b) for teff.

Model description

AquaCrop simulates the attainable yields as a function of water consumption (Steduto et al., 2009; Raes et al., 2009). In AquaCrop, the aboveground biomass growth (AGB) is simulated on a daily basis as:

$$AGB = WP\left(\frac{T_c}{ET_o}\right) \tag{4}$$

where WP is crop water productivity normalized for the reference evaporative demand of the atmosphere, T_c is daily crop transpiration and ET_o is daily reference evapotranspiration, calculated using Penman Monteith equation.

The calculation of yield from biomass is by means of harvest index (HI). The model uses a dynamic harvest index which increases linearly from the yield formation time up to physiological maturity. It can also be adjusted for the effect of water stress occurring at any stage of the growing season, such as before the start of yield formation or during yield formation. The crop phenology can be determined through calendar days or according to the thermal degree days. One of the distinctive features of AquaCrop is that the foliage development of the crop is expressed through canopy cover (CC) and not through LAI. The canopy size can be modulated according to the water stress intensity by taking into consideration coefficients for leaf expansion, growth and senescence.

The model simulates soil-water balance by tracking the incoming and outgoing water fluxes at the boundaries of the root zone. The model can separate soil evaporation from canopy transpiration. Crop response to water deficient conditions is simulated by reducing crop transpiration below its potential value accordingly to the differential sensitivity to water stress of four key plant processes: canopy growth, stomatal closure, canopy senescence and harvest index (HI).

Model calibration

AquaCrop V.4 was used in this study. The model was calibrated using data from full and deficit irrigation treatments (C, S_1, S_2 and S_3) for soybean grown during 2000 and for sunflower during 2003. Calibration started under optimal water conditions. Subsequently, the treatments under limiting water conditions were also considered in calibration. Inclusion of data from the deficit treatments was necessary to correctly parameterize the three stress thresholds which control leaf expansion, stomatal closure and canopy senescence. This approach was widely adopted for AquaCrop calibration (Farahani et al., 2009; Garcia-Vila et al., 2009; Geerts et al., 2009a; Andarzian et al., 2011).

Model calibration was carried out through an iterative process by using the measured crop growth variables, observed phenological stages and default values from the AquaCrop user manual. Parameters were refined so that simulated values fit well with observed data. During calibration of AquaCrop, the WP coefficient was derived from linear regression between the aboveground biomass and the accumulated crop transpiration normalized for reference evapotranspiration. Crop transpiration was simulated directly by the model by using the measured weather, soil, irrigation and canopy cover data. Values of WP were derived separately for the vegetative development (until flowering) and the yield formation (after flowering) phases since AquaCrop distinguishes between these two phases. The two phases are particularly different in sunflower (Steduto and Albrizio, 2005) and soybean; this is mainly due to the increase in respiratory activities, leaf loss and the elevated synthesis of lipids, which is not compensated for by a commensurate accumulation of dry matter in the seeds (Penning de Vries et al., 1974; Albrizio and Steduto, 2005). Other crop input parameters included canopy growth, given as a percentage of canopy cover, flowering period and yield formation duration, rooting depth growth, soil water extraction pattern, crop coefficients at full canopy, three water stress response functions and HI adjustment functions.

Model validation

The AquaCrop model was validated using data sets from full and deficit irrigation treatments for soybean during 2001 and sunflower during 2004 growing seasons, by comparing independently data derived from field experiments with data simulated by the model for the final biomass, harvestable yield, cumulative crop evapotranspiration, soil-water content, canopy cover and CWP.

Performance indicators

The performance of the model was analyzed for the final biomass, yield, cumulative crop evapotranspiration, soil-water content and canopy cover by using the following statistical indicators: root mean squared error (RMSE), relative RMSE ($RMSE_{REL}$), Mean Bias Error (MBE), Maximum

Absolute Error (MAE), modeling efficiency (EF) and Wilmot index of agreement (IoA).

The average difference between simulation outputs and experimental data was described by RMSE as:

$$\mathrm{RMSE} = \left[n^{-1} \sum_{i=1}^{n} \left(P_i - O_i \right)^2 \right]^{0.5} \tag{5}$$

where n is the number of pairs of observed (O_i) values and simulated (P_i) values.

The RMSE was scaled relative to the mean of the observed/measured values ($\overline{O}$) as:

$$RMSE_{REL} = \frac{RMSE}{\overline{O}} \tag{6}$$

The MBE was used to indicate the under/over estimations of biomass and yield by the model as:

$$MBE = N^{-1} \sum_{i=1}^{N} \left(P_i - O_i \right) \tag{7}$$

The MAE was estimated as:

$$MAE = Max \left| P_i - O_i \right|_{i=1}^{N} \tag{8}$$

EF, representing a normalized statistic that determines the relative magnitude of the residual variance compared to the measured data variance (Nash and Sutcliff, 1970; Moriasi et al., 2007), was defined as:

$$EF = 1.0 - \frac{\sum_{i=1}^{n} \left(O_i - P_i \right)^2}{\sum_{i=1}^{n} \left(O_i - \overline{O} \right)^2} \tag{9}$$

The EF was applied to indicate whether the square of the differences between the model simulations and the observations is as large as the variability in the observed data.

The IoA (Wilmot, 1982) was calculated as follows:

$$\mathrm{IoA} = 1 - \frac{\sum_{i=1}^{n}\left(P_i - O_i\right)^2}{\sum_{i=1}^{n}\left(\left|P_i^{'}\right| + \left|O_i^{'}\right|\right)^2} \tag{10}$$

where, $P_i^{'} = P_i - \bar{P}$, $O_i^{'} = O_i - \bar{O}$ and $\overline{P}$ and $\overline{O}$ are average values of simulated and observed data, respectively. IoA is a descriptive parameter that varies between 0 and 1, with the value of 1 indicating perfect agreement. This parameter has been widely used in the literature to assess the performance of models when compared with the measured data (Eitzinger et al., 2004; Singh et al., 2008; Hsiao et al., 2009; Todorovic et al., 2009).

Finally, linear regression was applied to compare measured and simulated values of biomass, yield, cumulative crop evapotranspiration, canopy cover and soil water content.

Model application

As water scarcity is becoming more prevalent, reducing irrigation quantities for seed production is crucial in the central Bekaa valley. Therefore, the AquaCrop model was used to develop different scenarios, in order to optimize the use of water in this region. More specifically, AquaCrop was used to evaluate the effects of different sowing dates and water applications on grain yield and CWP.

The considered sowing times were: 1 April, 15 April, 1 May and 15 May, while the irrigation applications were: 100 mm of water per application at all or only at some of the following critical stages: prior to flowering, at mid flowering stage and at the beginning of seed formation.

Results and Discussion

Model calibration

The crop parameters for simulating growth and development of soybean and sunflower by the AquaCrop model are presented in Table 3. These parameter's values were derived from calibration (c), direct field measurements and observations (m), or by estimation (e). Then, the values obtained by calibration were compared to those given in the AquaCrop user manual as conservative parameters that are presumed to be applicable to a wide range of conditions (Hsiao et al., 2009).

Table 3. Crop parameters used for soybean and sunflower simulations by AquaCrop V4.

Conservative parameters	Soybean	Sunflower	Way of
	Values	Values	determination
Base temperature (°C)	5	6	e
Cut-off temperature (°C)	30	30	e
Canopy cover per seeding at 90% emergence (CC_0) (cm^2 plt^{-1})	5	5	e
Canopy growth coefficient (CGC) (% degree day^{-1})	0.006	0.015	c
Crop coefficient for transpiration at CC = 100%	1.1	1.15	c
Canopy decline coefficient (CDC) at senescence (% degree day^{-1})	0.010	0.007	c
Biomass water productivity (WP) normalized for ET_o before yield formation (g m^{-2})	14	26	e
Biomass water productivity (WP) normalized for ET_o during yield formation (% of WP)	60	75	e
Leaf growth threshold p-upper	0.18	0.22	c
Leaf growth threshold p-lower	0.65	0.6	c
Leaf growth stress coefficient curve shape	3	6	c
Stomatal conductance threshold p-upper	0.5	0.6	e
Stomata stress coefficient curve shape	3	2.5	c
Senescence stress coefficient p-upper	0.55	0.8	c
Senescence stress coefficient curve shape	2	4	c
Non-conservative parameters			
Time from sowing to emergence (GDD)	150	150	e
Maximum canopy cover (CC_x) (%)	100	100	m
Time from sowing to flowering (GDD)	1216	800	e
Time from sowing to start senescence (GDD)	1680	1378	e
Time from sowing to maturity (GDD)	2043	1738	e
Maximum effective rooting depth, Z_x (m)	0.9	0.9	m
Maximum effective rooting depth, Z_n (m)	0.3	0.3	d
Reference harvest index, HI_o	45	29	m

c: calibrated, d: default, e: estimated, m: measured.

In the case of soybean, the conservative parameters obtained from local calibration, such as the crop coefficient for transpiration at full canopy cover, namely water productivity (WP) for biomass and soil water depletion thresholds for inhibition of leaf growth, stomatal conductance and for the acceleration of canopy senescence, were the same as given in Raes et al. (2009). In addition, the calibrated canopy growth coefficient (CGC) and the canopy decline coefficient (CDC) were set at 0.006 and 0.01 percent per degree day, respectively and these values were close to the recommended range of 0.004-0.005 percent per degree day for the former and 0.015 percent per degree day for the latter. The parameters that are cultivar-specific or depending on management and environmental conditions were found to be within the range mentioned in the manual, except of the reference harvest index. The measured value of reference harvest index used in the calibration for our soybean cultivar was 45%, whereas the suggested value is 40%. This discrepancy might be related to the genetic specifics of this cultivar. In general, the results of our calibration match the soybean parameters reported in the AquaCrop user manual (Raes et al., 2009).

In the case of sunflower, some of the values of conservative and cultivar-specific parameters were within ranges suggested by FAO, whereas it was not the case for the crop coefficient for transpiration (1.15), canopy decline coefficient (0.007), WP for biomass (26 g m^{-2}), soil water depletion upper and lower thresholds for inhibition of leaf growth (0.6; 0.22), the acceleration of canopy senescence (0.8) and reference harvest index (29%). Some of these parameters, particularly both WP for biomass and soil water depletion thresholds, were similar to those obtained by Todorovic et al. (2009) under the Mediterranean conditions of Southern Italy. Recently, also Stricevic et al. (2011) reported the same WP value for sunflower (26 g m^{-2}) grown in Serbia.

Biomass, yield and evapotranspiration

Observed and simulated results for calibration data sets concerning biomass, yield and cumulative ET parameters of soybean and sunflower are presented in Table 4. For biomass, the largest differences between observed and simulated values were noted for some treatments under deficit irrigation of sunflower (-7.96 and -11.21% for S_1 and S_2, respectively), whereas the percentage of deviation under full irrigation treatment were -0.01% for sunflower and -0.04% for soybean. For yield, the largest differences between observed and simulated values were also reported for deficit irrigation treatments of sunflower (-14.08, -12.61 and -10.36% for S_1, S_2 and S_3, respectively). Stricevic et al. (2011) reported percentage of deviation for sunflower yield that reached 14.2 and 17.6% for irrigated and rainfed treatments, respectively. For cumulative ET, the largest percentage of deviation was noted for treatment S_3 of sunflower with a value of -11.25%, whereas the obtained percentages of deviation under full irrigation were respectively -6.77% for soybean and -4.15% for sunflower. Todorovic et al. (2009) reported similar results for both full irrigated and deficient treatments. In fact, the percentage of deviations for biomass, yield and cumulative ET of sunflower grown under full irrigation treatment, found by Todorovic et al. (2009) were within the same range as those reported in this current study (-0.33% for biomass, 1.18% for yield, 8.69% for cumulative ET).

Table 4. Simulation results for the calibration data set and deviation from measured values.

Variables		Soybean 2000			Sunflower 2003		
		Measured	Simulated	% of deviation	Measured	Simulated	% of deviation
Biomass ($t\ ha^{-1}$)	C	7.65	7.65	-0.04	19.50	19.50	-0.01
	S_1	6.03	5.92	-1.79	16.01	14.74	-7.96
	S_2	7.08	6.96	-1.75	17.16	15.24	-11.21
	S_3	7.50	7.25	-3.35	17.60	16.76	-4.77
Yield ($t\ ha^{-1}$)	C	3.55	3.49	-1.75	5.46	5.50	0.77
	S_1	2.51	2.41	-4.02	3.95	3.39	-14.08
	S_2	3.15	3.05	-3.17	4.63	4.05	-12.61
	S_3	3.43	3.30	-3.86	5.50	4.93	-10.36
Cumulative ET (mm)	C	705	657	-6.77	687	659	-4.15
	S_1	558	550	-1.47	555	525	-5.42
	S_2	614	607	-1.07	576	542	-6.07
	S_3	620	624	0.63	658	584	-11.25

Finally, the performance of the model was evaluated using calibration dataset for each crop by considering all treatments together, in order to account for final biomass, yield, cumulative evapotranspiration (ET). The statistical indicators are reported in Table 5. The RMSE, the $RMSE_{REL}$ the MBE and MAE of biomass were respectively 0.15, 0.02, -0.12 and 0.12 $t\ ha^{-1}$ for soybean, 0.23, 0.07, -1.01 and 1.00 $t\ ha^{-1}$ for sunflower. The IoA, the EF and R^2 were respectively 0.99, 0.94 and 0.98 for soybean, 0.94, 0.90 and 0.94 for sunflower. The RMSE, the $RMSE_{REL}$, the MBE and MAE of yield were respectively 0.14, 0.03, -0.10 and 0.10 for soybean, 0.49, 0.10, -0.42 and 0.44 $t\ ha^{-1}$ for sunflower. The IoA, the EF and R^2 were respectively 0.98, 0.93 and 0.98 for soybean, 0.91, 0.82 and 0.92 for sunflower, confirming the goodness of fit between measured and simulated values.

Table 5. Statistical indices derived for evaluating AquaCrop calibration and validation in terms of final biomass, grain yield and seasonal crop evapotranspiration. The two crops have been separately considered.

Variables	Calibration dataset													
	Soybean 2000							Sunflower 2003						
	RMSE	$RMSE_{REL}$	MBE	MAE	IoA	EF	R^2	RMSE	$RMSE_{REL}$	MBE	MAE	IoA	EF	R^2
Biomass ($t\ ha^{-1}$)	0.15	0.02	-0.12	0.12	0.99	0.94	0.98	0.23	0.07	-1.01	1.00	0.94	0.90	0.94
Yield ($t\ ha^{-1}$)	0.14	0.03	-0.10	0.10	0.98	0.93	0.98	0.49	0.10	-0.42	0.44	0.91	0.82	0.92
Seasonal ET_c (mm)	24.50	0.04	-14.65	16.60	0.93	0.88	0.90	31.76	0.05	-29.19	29.19	0.91	0.80	0.88
Variables	Validation dataset													
	Soybean 2001							Sunflower 2004						
	RMSE	$RMSE_{REL}$	MBE	MAE	IoA	EF	R^2	RMSE	$RMSE_{REL}$	MBE	MAE	IoA	EF	R^2
Biomass ($t\ ha^{-1}$)	0.25	0.04	0.07	0.20	0.97	0.88	0.96	0.82	0.04	-0.78	0.78	0.93	0.88	0.98
Yield ($t\ ha^{-1}$)	0.14	0.05	-0.01	0.13	0.96	0.81	0.93	0.29	0.06	-0.15	0.25	0.95	0.82	0.96
Seasonal ET_c (mm)	13.64	0.02	-3.48	12.95	0.96	0.80	0.94	26.96	0.04	-26.23	26.23	0.93	0.75	0.99

Soil water content and canopy cover

Simulated values of soil water content and canopy cover closely matched measured values for all treatments of both crops, as it is demonstrated by the statistical indicators reported in Table 6. For soybean, RMSE, $RMSE_{REL}$, MBE, MAE, IoA, EF and R^2 varied respectively from 6.78 to 12.91 mm, from 0.03 to 0.05 mm, from -3.28 to 11.81 mm, from 5.73 to 11.81 mm, from 0.90 to 0.95, from 0.73 to 0.82 and from 0.73 to 0.93 for soil water content simulations, whereas they varied respectively from 2.99 to 9.63%, from 0.04 to 0.14%, from -3.93 to -1.07%, from 2.60 to 5.46%, from 0.97 to 0.99, from 0.89 to 0.99 and from 0.91 to 0.99 for canopy cover simulations. For sunflower, RMSE, $RMSE_{REL}$, MBE, MAE, IoA, EF and R^2 varied respectively from 7.45 to 14.96 mm, from 0.03 to 0.05 mm, from -6.29 to 7.18 mm, from 5.32 to 9.61 mm, from 0.89 to 0.95, from 0.80 to 0.86 and from 0.77 to 0.90 for soil water content simulations, whereas they varied respectively from 7.75 to 10.90%, from 0.11 to 0.15%, from -2.67 to -5.72%, from 6.86 to 9.14%, from 0.98 to 0.99, from 0.90 to 0.95 and from 0.95 to 0.98 for canopy cover simulations (Table 6).

Model validation

The parameters obtained in model calibration were used for validating the performance of AquaCrop by using independent data sets (2001 and 2004 growing season dataset for soybean and sunflower, respectively). In order to account for different canopy cover and soil-water contents between treatments, the model was evaluated for its performance for each crop separately by modeling each treatment within each growing season. Moreover, the performance of the model was evaluated for each crop by considering all treatments together, in order to account for final biomass, yield, cumulative evapotranspiration (ET) and crop water productivity (CWP) under different water regimes.

Table 6. Statistical indices derived for evaluating AquaCrop calibration and validation in terms of soil water content and canopy cover. The two crops have been separately considered.

	Calibration dataset															
	Soybean 2000								Sunflower 2003							
	Soil water content				Canopy cover				Soil water content				Canopy cover			
	C	S_2	S_2	S_3	C	S_2	S_2	S_3	C	S_2	S_2	S_3	C	S_2	S_2	S_3
RMSE	9.09	12.91	9.88	6.78	2.99	4.92	4.93	9.63	14.96	10.97	12.87	7.45	7.75	9.00	9.98	10.90
$RMSE_{REL}$	0.03	0.05	0.04	0.03	0.04	0.09	0.07	0.14	0.05	0.04	0.05	0.03	0.11	0.14	0.15	0.15
MBE	4.26	11.81	-0.68	-3.28	-1.07	-2.19	-2.15	-3.93	-6.29	6.11	7.18	4.83	-2.67	-4.98	-5.70	-5.72
MAE	5.87	11.81	6.62	5.73	2.60	3.72	3.68	5.46	9.61	5.32	8.00	6.88	6.86	8.09	9.12	9.14
IoA	0.95	0.93	0.91	0.90	1.00	0.99	0.99	0.97	0.93	0.89	0.89	0.95	0.99	0.98	0.98	0.98
EF	0.82	0.73	0.77	0.73	0.99	0.96	0.97	0.89	0.80	0.86	0.83	0.83	0.95	0.91	0.91	0.90
R^2	0.87	0.93	0.87	0.73	0.99	0.97	0.98	0.91	0.88	0.77	0.81	0.90	0.98	0.97	0.96	0.95
	Validation dataset															
	Soybean 2001								Sunflower 2004							
	Soil water content				Canopy cover				Soil water content				Canopy cover			
	C	S_2	S_2	S_3	C	S_2	S_2	S_3	C	S_2	S_2	S_3	C	S_2	S_2	S_3
RMSE	10.98	19.33	13.05	8.03	12.67	12.07	10.71	15.29	26.43	13.95	10.17	17.18	11.82	13.41	13.24	12.17
$RMSE_{REL}$	0.04	0.08	0.05	0.04	0.11	0.21	0.13	0.18	0.23	0.06	0.04	0.07	0.15	0.20	0.18	0.16
MBE	7.97	10.66	10.65	-0.93	-6.32	-10.16	-7.49	-9.30	-10.22	10.83	6.28	12.74	-3.40	-0.64	0.54	-0.29
MAE	7.99	17.41	10.65	6.60	6.32	10.16	7.49	9.30	10.51	10.83	7.11	12.74	8.24	9.50	9.43	8.98
IoA	0.95	0.85	0.85	0.80	0.95	0.96	0.97	0.94	0.90	0.91	0.83	0.85	0.96	0.94	0.95	0.96
EF	0.82	0.96	0.86	0.89	0.93	0.82	0.91	0.80	0.80	0.82	0.80	0.87	0.88	0.86	0.80	0.79
R^2	0.92	0.73	0.92	0.98	0.91	0.95	0.97	0.90	0.96	0.87	0.69	0.68	0.91	0.80	0.83	0.88

Biomass and yield

The overall results of biomass and yield simulations are reported in Figure 2a and 2b for sunflower and soybean, respectively. There was significant relationship between data predicted by the model and those measured: in fact, the R^2 were 0.96 and 0.93, respectively, for biomass and yield of soybean and 0.98 and 0.96, respectively, for biomass and yield of sunflower. Trendline gradients slightly deviate from the desirable straight line (x=y) for both crops. This was expected, since the studied crops were not exposed to extended periods of water stress; irrigation was cutout for only two weeks at different growth stages.

The simulated sunflower yield (Figure 2a) varied from 3.39 to 5.57 t ha^{-1}, while the measured yield varied from 3.95 to 5.50 t ha^{-1} for full and deficit irrigation treatments during the two cropping seasons. For soybean, the simulated yield (Figure 2b) varied from 2.10 to 3.49 t ha^{-1}, while the measured yield varied from 2.20 to 3.55 t ha^{-1} for full and deficit irrigation treatments during the two cropping seasons. The calculated values of statistical indices are reported in Table 5. The RMSE, the $RMSE_{REL}$, the MBE and MAE of biomass were respectively 0.25, 0.04, 0.07 and 0.20 t ha^{-1} for soybean, 0.82, 0.04, -0.78 and 0.78 t ha^{-1} for sunflower. The IoA, the EF and R^2 were respectively 0.97, 0.88 and 0.96 for soybean, 0.93, 0.88 and 0.98 for sunflower. The RMSE, the $RMSE_{REL}$, the MBE and MAE of yield were respectively 0.14, 0.05, -0.01 and 0.13 for soybean, 0.29, 0.06, -0.15 and 0.25 t ha^{-1} for sunflower. The IoA, the EF and R^2 were respectively 0.96, 0.81 and 0.93 for soybean, 0.95, 0.82 and 0.96 for sunflower (Table 5), confirming the goodness of fit between measured and simulated values.

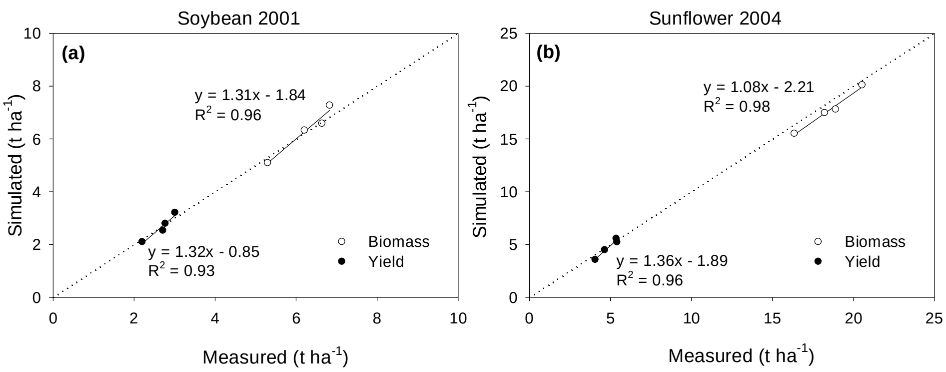

Figure 2. Comparison of simulated *vs.* measured biomass production and grain yield (t ha^{-1}), considering validation treatments for soybean (a) in 2001 and sunflower (b) in 2004.

Soil water content and canopy cover

For soybean, the RMSE, the $RMSE_{REL}$, MBE, MAE, IoA, EF and R^2 varied respectively from 8.03 to 19.33 mm, from 0.04 to 0.08 mm, from -0.93 to 10.66 mm, from 6.60 to 17.41 mm, from 0.80 to 0.95, from 0.82 to 0.96 and from 0.73 to 0.98 for soil water content simulations, whereas they varied respectively from 10.71 to 15.29%, from 0.11 to 0.21%, from -6.32 to -10.16%, from 6.32 to 10.16%, from 0.94 to 0.97, from 0.80 to 0.93 and from 0.90 to 0.97 for canopy cover simulations (Table 6). For sunflower, the RMSE, the $RMSE_{REL}$, MBE, MAE, IoA, EF and R^2 varied respectively from 10.17 to 26.43 mm, from 0.04 to 0.23 mm, from -10.22 to 12.74 mm, from 7.11 to 12.74 mm, from 0.83 to 0.91, from 0.80 to 0.87 and from 0.68 to 0.96 for soil water content simulations, whereas they varied respectively from 11.82 to 13.41%, from 0.16 to 0.20%, from -3.40 to 0.54%, from 8.24 to 9.50%, from 0.94 to 0.96, from 0.79 to 0.88 and from 0.80 to 0.91 for canopy cover simulations (Table 6). Such results put in question the robustness of the AquaCrop water balance module and its reliability to simulate a wide range of water stress conditions for irrigation management planning purposes. In fact, most of published papers on AquaCrop strongly link the model performance results under deficient irrigation to a specific duration and intensity of water stress, occurring during specific growth stages. Therefore, the AquaCrop water balance module should be examined more carefully under such specific water stress conditions.

Crop evapotranspiration

AquaCrop performance for simulating crop evapotranspiration for both crops was presented in Figure 3a and b. The RMSE, $RMSE_{REL}$, MBE and MAE of ET_c, were respectively 13.64, 0.02, -3.48 and 12.95 mm for soybean, 26.96, 0.04, -26.23 and 26.23 mm for sunflower (Table 5). The IoA, EF and R^2 being respectively 0.96, 0.80 and 0.94 for soybean, 0.93, 0.75 and 0.99 for sunflower, confirmed the goodness of fit between measured and simulated crop evapotranspiration calculated by the model.

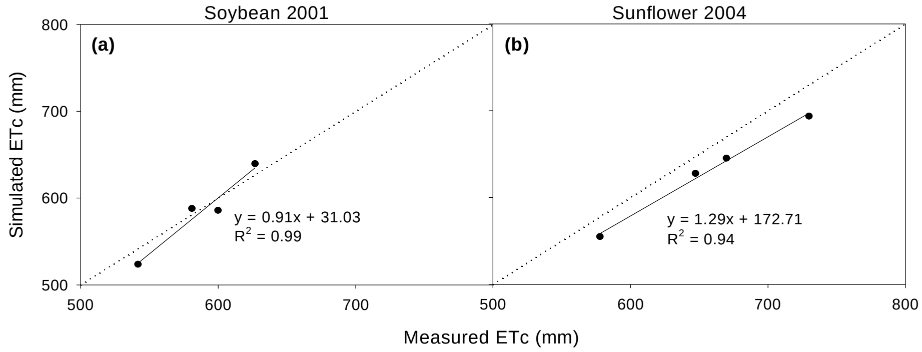

Figure 3. Comparison of simulated *vs*. measured crop evapotranspiration (mm), considering validation treatments for soybean (a) in 2001 and sunflower (b) in 2004.

Crop water productivity

For soybean, the measured CWP values ranged from 0.41 to 0.55 kg m^{-3}, while the simulated CWP values ranged from 0.40 to 0.53 kg m^{-3}. Sincik et al. (2008) observed similar values of soybean CWP, ranging between 0.45-0.58 kg m^{-3} (Figure 4a)

For sunflower, the measured CWP values ranged between 0.70 and 0.88 kg m^{-3}, while the simulated CWP between 0.64 and 0.84 kg m^{-3} (Figure 4b). Flenet et al. (1996) and Connor et al. (1985) observed similar values of sunflower CWP, ranging between 0.72-1.23 kg m^{-3} and 0.78-1.02 kg m^{-3}, respectively. Higher values (between 1.03-1.39 kg m^{-3}) were obtained by Todorovic et al. (2009), by using a very productive sunflower hybrid.

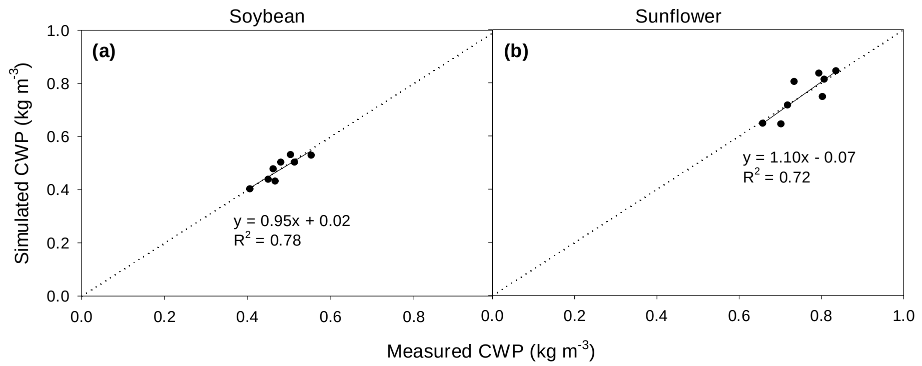

Figure 4. Measured *vs.* AquaCrop model-simulated crop water productivity (CWP) of soybean (a) and sunflower (b) during two cropping seasons under different water regimes. The CWP is expressed as ratio of final dry grain yield to cumulative crop evapotranspiration.

Model application

After calibration and validation of the model under different irrigation regimes, the calibrated AquaCrop model was applied to implement alternative irrigation scenarios for sunflower and soybean by varying the sowing date and applying an amount of 100 mm per irrigation at different growing stages. The different scenarios elaborated for both crops are presented in Tables 7 and 8.

Table 7. Alternative irrigation scenarios implemented in AquaCrop for sunflower crop.

Sunflower						
No. Scenario	Scenario name	Sowing date	Number of irrigation applications	Total irrigation amount (mm)	Grain yield (t ha^{-1})	CWP (kg m^{-3})
1	Irrigation: prior to flowering, at mid flowering stage and at the beginning of seed formation	1-Apr	3	300	4.51	1.50
2		15-Apr	3	300	3.95	1.32
3		1-May	3	300	3.27	1.09
4		15-May	3	300	2.34	0.78
5	Irrigation: prior to flowering and at mid flowering stage	1-Apr	2	200	3.34	1.67
6		15-Apr	2	200	3.19	1.59
7		1-May	2	200	2.74	1.37
8		15-May	2	200	2.28	1.14
9	Irrigation: prior to flowering and at the beginning of seed formation	1-Apr	2	200	2.92	1.46
10		15-Apr	2	200	2.52	1.26
11		1-May	2	200	2.14	1.07
12		15-May	2	200	1.85	0.93
13	Irrigation: at mid flowering stage and at the beginning of seed formation	1-Apr	2	200	3.13	1.57
14		15-Apr	2	200	2.52	1.26
15		1-May	2	200	0.39	0.20
16		15-May	2	200	0.37	0.19
17	Irrigation: prior to flowering	1-Apr	1	100	1.97	1.97
18		15-Apr	1	100	1.86	1.86
19		1-May	1	100	1.81	1.81
20		15-May	1	100	1.74	1.74
21	Irrigation: at mid flowering stage	1-Apr	1	100	2.05	2.05
22		15-Apr	1	100	1.89	1.89
23		1-May	1	100	0.39	0.39
24		15-May	1	100	0.37	0.37
25	Irrigation: at the beginning of seed formation	1-Apr	1	100	0.42	0.42
26		15-Apr	1	100	0.39	0.39
27		1-May	1	100	0.37	0.37
28		15-May	1	100	0.37	0.37

Table 8. Alternative irrigation scenarios implemented in AquaCrop for soybean crop.

Soybean						
No. Scenario	Scenario name	Sowing date	Number of irrigation applications	Total irrigation amount (mm)	Grain yield (t ha^{-1})	CWP (kg m^{-3})
1	Irrigation: at full bloom, at seed enlargement and at mature seeds	1-Apr	3	300	3.16	1.05
2		15-Apr	3	300	2.91	0.97
3		1-May	3	300	2.13	0.71
4		15-May	3	300	2.01	0.67
5	Irrigation: at full bloom and at seed enlargement	1-Apr	2	200	2.54	1.27
6		15-Apr	2	200	2.34	1.17
7		1-May	2	200	2.10	1.05
8		15-May	2	200	1.98	0.99
9	Irrigation: at full bloom and at mature seeds	1-Apr	2	200	2.14	1.07
10		15-Apr	2	200	1.56	0.78
11		1-May	2	200	1.23	0.62
12		15-May	2	200	1.08	0.54
13	Irrigation: at seed enlargement and at mature seeds	1-Apr	2	200	2.29	1.15
14		15-Apr	2	200	0.00	0.00
15		1-May	2	200	0.00	0.00
16		15-May	2	200	0.00	0.00
17	Irrigation: at full bloom	1-Apr	1	100	1.61	1.61
18		15-Apr	1	100	1.23	1.23
19		1-May	1	100	0.90	0.90
20		15-May	1	100	0.00	0.00
21	Irrigation: at seed enlargement	1-Apr	1	100	1.54	1.54
22		15-Apr	1	100	0.00	0.00
23		1-May	1	100	0.00	0.00
24		15-May	1	100	0.00	0.00
25	Irrigation: at mature seeds	1-Apr	1	100	0.00	0.00
26		15-Apr	1	100	0.00	0.00
27		1-May	1	100	0.00	0.00
28		15-May	1	100	0.00	0.00

For sunflower, the highest yields were obtained when sowing in April and applying three irrigations, of 100 mm each, prior to flowering, at mid flowering stage and at the beginning of seed formation. Yield values ranged between 4.51 and 2.34 t ha^{-1}, while CWP values between 1.5 and 0.78 kg m^{-3}. When only two irrigations of 100 mm each were applied prior to flowering and at mid flowering stage, still the highest yields and CWP were obtained when sowing in April rather in May. Yield values varied from 3.34 to 2.28 t ha^{-1}, while CWP values from 1.67 to 1.14 kg m^{-3}. When two irrigations were applied prior to flowering and at the beginning of seed formation, yield values varied from 2.92 to 1.85 t ha^{-1} and CWP values from 1.46 to 0.93 kg m^{-3}. However, irrigating at mid flowering and at the beginning of seed formation could lead to lower yields (3.13-0.37 t ha^{-1}) and CWP (1.57-0.19 kg m^{-3}), mainly when sowing occurs in May. The lowest yields and CWP were obtained when applying only one irrigation of 100 mm during the whole growing cycle. More specifically, yields are very low and unreliable (0.42-0.37 t ha^{-1}) when irrigation is performed at the beginning of seed formation, while better values (1.97-1.74 t ha^{-1}) were obtained when this single irrigation application was done prior to flowering.

These results confirm that flowering was most sensitive phenological stage to water deficiency (Rinaldi, 2001; Göksoy et al., 2004; Karam et al., 2007), while milk to maturity is a quite resistant stage (Stone et al., 1996). Moreover, the early planting of sunflower could demonstrate a greater productivity than late sowing (Soriano et al., 2004).

For soybean, the highest yields were obtained when sowing in April and applying three irrigations, of 100 mm each, at full bloom, at seed enlargement and at mature seeds. Yield values ranged between 3.16 and 2.01 t ha^{-1}, while CWP values between 1.05 and 0.67 kg m^{-3}. When only two irrigations of 100 mm each were applied at full bloom and at seed enlargement, still the highest yields and CWP were obtained when sowing in April rather in May. Yield values varied from 2.54 to 1.98 t ha^{-1}, while CWP values from 1.27 to 0.99 kg m^{-3}. Similar findings were found when two irrigations were applied at full bloom and at mature seeds with yield values ranging between 2.14 and 1.08 t ha^{-1} and CWP values between 1.07 and 0.54 kg m^{-3}. However, irrigating at seed enlargement and mature seeds, as well as applying only one irrigation of 100 mm at any growth stage, could lead to very low yields and CWP.

These simulation results confirm the high susceptibility of soybean to water deficiency during grain filling and flowering, closely matching results of previous studies (Brown et al., 1985; Karam et al., 2005).

Conclusions

The findings of the current study lead us to conclude that the AquaCrop model could be considered a useful model for predicting soybean and sunflower yield under the semi-arid conditions of the Central plain of Bekaa Valley. This was confirmed through the statistical performance evaluation that showed a close agreement between observed and simulated canopy cover, soil water content, evapotranspiration biomass and yield. The results also showed, that AquaCrop can be used to evaluate water productivity, as well as to assess yield under different scenarios addressed to manage water according to alternative strategies. The analysis of irrigation scenarios showed that, planting sunflower and soybean in early April can give higher yields. If 300 mm of water were available, farmers would be recommended to irrigate sunflower prior to flowering, at mid flowering and at the beginning of seed formation and soybean at full bloom, seed enlargement and mature seeds. If only 200 mm of water were available, farmers would be recommended to irrigate sunflower prior to flowering and at mid flowering, while soybean at full bloom and seed enlargement. Finally, farmers should avoid to grow these crops if only 100 mm of water are available, since yields could be drastically reduced.

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