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Optimization of irrigation scheduling for barley crop, combining AquaCrop and MOPECO models to simulate various water-deficit regimes

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Abstract

To optimize the irrigation scheduling of field crops to maximize irrigation water productivity requires expert knowledge of the crop development and its productive response to water deficit. Implementing this idea with commodities such as barley, whose current global profitability is low, and, more specifically, in areas where the availability of water resources for irrigation is limited, requires a proper decision support system. In this research, AquaCrop and MOPECO models were used to compute and compare both the crop-water production and irrigation water productivity functions generated by several irrigation strategies provided by each model for the typical irrigated crop barley grown in the area. Furthermore, we evaluated both models' performance with a 3-year field experiment applying the methodology of optimized regulated deficit irrigation for limited volumes of irrigation water (ORDIL) in barley crop. The results obtained from the production functions show that gross irrigation water depths (GIWD) of more than 310 mm can be useful to attain the potential crop yield, depending on the criteria considered to generate the irrigation scheduling. However, with less GIWD available, the simulated barley development was subjected to water deficit, leading to a reduction in both crop yield and irrigation water productivity, where MOPECO simulated higher crop yields and irrigation water productivity values than those obtained by AquaCrop (between 16% and 27% and between 8.0% and 27.5% respectively) under similar GIWD levels. These differences are mainly due to how the irrigation strategies are outlined in the two models and the different evapotranspiration methodologies they deploy. Finally, both models provided performed appropriately in simulating final crop yield (errors lower than 0.50 x10^3 kg ha^{-1}), as well as canopy cover and aboveground biomass evolution, in the case of AquaCrop, whose goodness of fit indicators were close to 0.90 or higher. In terms of crop evapotranspiration, AquaCrop simulated a 12% higher average value than MOPECO. An in-depth analysis was performed to explain the differences.

Keywords: improved crop models parameterization, crop-water production function, irrigation water productivity, ORDIL, water scarcity

1. Introduction

Worldwide, cereal crops occupy around 51% of the total growing area. In Spain, the seventh largest cereal producer in Europe with a production of 5.8 million Mg in almost 2.6 million ha of cereal planted area (FAOSTAT, 2019), these commodities, especially barley, are a key alternative for field agricultural systems. In semiarid regions, such as the centre and south of Spain, where there is a clear tendency towards water resource scarcity (Cramer et al., 2020), reductions in irrigation water abstraction in both Guadiana and Júcar rivers basins in Castilla-La Mancha (CLM) region (Spain) are already a fact. Applying deficit irrigation techniques (DI), either sustained (SDI) or regulated (RDI) (Fereres and Soriano, 2007), during crop growth, would allow for irrigation strategies that are able to improve crop irrigated water use, without causing significant yield losses. This methodology would help mitigate climate change effects, maximize the production per unit of water consumed, developing more resilient agricultural systems and limiting desertification.

Several papers on the barley crop response to water deficit have reported that the end of the vegetative period, flowering and yield formation are the most sensitive stages, affecting the final crop yield and harvest quality (Abrha et al., 2012; Acevedo et al., 2002; Cossani et al., 2009; Giunta et al., 1993; Ugarte et al., 2007). Barley crop water requirements in CLM are around 400-500 mm, according to cycle length, which varies between 155 and 210 days (Pardo et al., 2020), with the average irrigation water requirements being 250 mm (JCRMO, 2020). Thus, the yield of irrigated barley is between 4 and 5 times higher than under rainfed conditions (ITAP, 2020). However, the current low profitability of this crop, and the increasing tendency of the water authority to limit the volume of water for irrigation in the area (CHG, 2020; CHJ, 2020) are forcing growers and technicians to adopt optimal irrigation techniques to reduce the use of irrigation water with the aim of maximizing economic irrigation water productivity (Pardo et al., 2020).

Several authors have developed algorithms for optimizing irrigation scheduling based on the crop development and its productive response to water deficit (García et al., 2020; Kloss et al., 2012; Kuschel-Otárola et al., 2018; Schütze et al., 2012), as well as on the real-time readings obtained from weather stations and soil moisture sensors installed in the field (Domínguez-Niño et al., 2020). One of these methodologies is called optimized regulated deficit irrigation for limited volumes of irrigation water (ORDIL) (Domínguez et al., 2012a; Leite et al., 2015), the main objective of which is to maximize yield at harvest when the amount of available water is lower than the typical irrigation requirements of the crop (Pardo et al., 2020). This methodology is based on the total available volume of irrigation water at the beginning of the irrigation season, the sensitivity of the crop to water deficit at its different development stages, the evolution of climatic conditions, the amount of water received by the crop at each phenological stage and the amount of irrigation water remaining for the following phenological stages until physiological maturity.

Crop simulation models, when calibrated and validated, can be used as decision support systems for the management of crops, farms or agricultural systems. Among other functions, these models calculate the crop water requirements, determine the irrigation scheduling and simulate crop yields according to the amount of irrigation water supplied during crop development (de Wit et al., 2019; Pereira et al., 2003; Stöckle et al., 2014). MOPECO (Ortega et al., 2004) and AquaCrop (Steduto et al., 2009) were designed to be used by researchers and also by technicians and advanced farmers. Both models are based on FAO methodology (Allen et al., 1998; Doorenbos and Kassam, 1979) and the number of parameters required for the simulation of annual crops is low compared with other models, as reported by López-Urrea et al. (2020), who calibrated the two models for a barley crop using the data set of a three-year experiment carried out in Albacete province (in the CLM region). MOPECO offers several options and tools that may be useful for the management of actual irrigated farms, such as ORDIL, the effect of irrigation uniformity on final yield (López-Mata et al., 2010) or the optimal distribution of crops depending on the available amount of irrigation water and cultivable area (López-Mata et al., 2016). AquaCrop is able to more precisely simulate the development of annual crops and their final biomass depending on the climatic conditions and availability of water in the soil during the growing cycle, providing irrigation scheduling strategies, such as full irrigation, or allowing a certain soil water depletion level at which an irrigation event is applied.

Therefore, the main aim of this research was to assess the applicability of both models as decision support systems for barley crop under the semiarid climatic conditions of CLM. To achieve this aim, the following partial objectives were proposed:

1. To improve the parametrization of both models for a barley crop developed by López-Urrea et al. (2020), determining the average length of the different growing stages of this crop for the different irrigated areas of CLM.
2. To compute and compare the crop-water production functions generated by the tools and strategies provided by each model for the typical conditions of CLM.
3. To evaluate the accuracy of MOPECO and AquaCrop models by comparing their results with those obtained in a three-year experiment conducted in Albacete, where the ORDIL methodology was applied to a barley crop (Pardo et al., 2020).

2. Material and methods

2.1. Description of crop models. Approach simulation

The AquaCrop model (Steduto et al., 2009) maintains the original concept proposed in FAO-33 (Doorenbos and Kassam, 1979) but, in this case, it estimates biomass production from actual crop transpiration through the normalized water productivity (WP) parameter (Steduto et al., 2012), since the model separates soil evaporation from crop transpiration as is also done by FAO-56 methodology (Allen et al., 1998; Pereira et al., 2021a). Crop cycle length is determined by days after sowing (DAS), or calculated by using the growing degree days methodology (GDD, ºC). Finally, crop yield is estimated from the biomass production and the harvest index. Several stress coefficients (soil water, air temperature, soil fertility and soil salinity) are used to adjust the daily green canopy cover, crop transpiration, above-ground biomass and yield formation. AquaCrop model is now designed to be used with annual crops, whose conservative crop parameters are provided in the AquaCrop software for many species (maize, barley, wheat, cotton, rice, soybean, potato, sunflower, tomato, among others; Vanuytrecht et al. 2014). AquaCrop can be used to report the role of different soil-climate systems in water-limited crop production as well as the analysis of different scenarios, such as climate change, water supply, crop type, field management, etc. (Vanuytrecht et al., 2014). In addition, the AquaCrop plug-in program (Raes et al., 2017) and AquaCrop-GIS (Lorite et al., 2013), together with AquaCrop-OS, the open source version (Foster et al., 2017), allow the simulation time to be significantly reduced when both a larger number of simulations are carried out and interpretation and analysis of the results is complex (Vanuytrecht et al., 2014).

MOPECO was conceived to optimize the gross margin of farms through the use of deficit irrigation strategies (De Juan et al., 1996). It is based on FAO-33 (Doorenbos and Kassam, 1979) and FAO-56 (Allen et al., 1998; Pereira et al., 2020, 2021b) methodologies. For the simulation of yield, the model determines the ratio between actual and potential (maximum) crop evapotranspiration (ET_a and ET_m, respectively) for each growing stage (Domínguez et al., 2011), where soil evaporation and crop transpiration components are not separated. Similarly to AquaCrop, the crop development is simulated using both DAS and GDD. Yields for different amounts of irrigated water supplied to the crop are used to determine the “yield vs. irrigation depth” function. The simulation of the irrigation water allocation during the growing period is determined by the optimized regulated deficit irrigation (ORDI) methodology. ORDI maximizes yield for a certain water deficit target by determining the ET_a/ET_m ratios to be applied at each growing stage (Domínguez et al., 2012a). Under real management conditions, where climatic conditions for the growing period are unknown and the amount of available irrigation water is limited, MOPECO uses the ORDIL methodology (Leite et al., 2015). Both methodologies have been applied to different crops: maize (Domínguez et al., 2012a), onion (Domínguez et al., 2012b), garlic (Domínguez et al., 2013; Sánchez-Virosta et al., 2020), carrot (Carvalho et al., 2014), melon (Leite et al., 2015), potato (Martínez-Romero et al., 2019) and barley (Pardo et al., 2020).

2.1.1. AquaCrop model. Irrigation water scheduling

When the actual crop evapotranspiration (ET_a) is calculated, the AquaCrop model separates the soil water evaporative component from the crop transpiration (Steduto et al., 2009). Thus, this model takes into account both the water inputs (net irrigation, rainfall and capillary rise) and outputs (runoff, deep percolation and ET_a) at the crop root zone in order to compute a daily soil water balance. An accurate description of the soil water movement is made by dividing soil depth into several compartments, with the thickness of each one being variable according to user specifications. The AquaCrop manual (Raes et al., 2018) shows a detailed description and the algorithms used to calculate the soil water balance.

From that balance, AquaCrop model simulates the irrigation management in three alternative ways: a) by resolving the net irrigation water requirements of the crop, keeping the soil water depletion at the root zone above a threshold, which is delimited by the user (generally 50% of the readily available water, RAW). These requirements do not take into account the irrigation uniformity effect; b) by considering a previously designed irrigation schedule where each irrigation event is specified by the user; thus, date of irrigation event, net irrigation depth and the quality of water (electric conductivity, ECw) must be given for each irrigation event; c) by allowing AquaCrop to automatically generate an irrigation schedule according to the criteria established by the user.

In the third alternative, users define in AquaCrop the way an irrigation event must be simulated. Thus, two criteria are considered: (i) when the irrigation event has to be triggered (irrigation time criterion, ITC), and (ii) how much water has to be applied through the irrigation system (irrigation depth criterion, IDC), being specified to either all the crop cycle or a certain period of time (Fig. 1a). The ITC can be established by the user, who either fixes a constant number of interval days between irrigation events or selects a soil water depletion threshold (either mm of water or % of RAW; Fig. 1a). The IDC also offers two options, namely, to refill the soil water content up to field capacity or to fix a constant net irrigation depth (mm) (Fig. 1a). The former option allows over-irrigation (uniformity of irrigation system) or under-irrigation (erratic rainfall distribution) to be considered.

Finally, in this third method, which also considers water quality, users cannot generate an irrigation schedule, coordinating two different options for each criterion along the crop cycle, either the ITC or IDC. Graphically, users may compose their own irrigation strategy according to the crop growth stage (initial, development, mid-season, flowering and late season; Fig. 1b) and the different soil water stress thresholds (mainly leaf expansion growth, stomatal closure and canopy senescence, Fig. 1c).

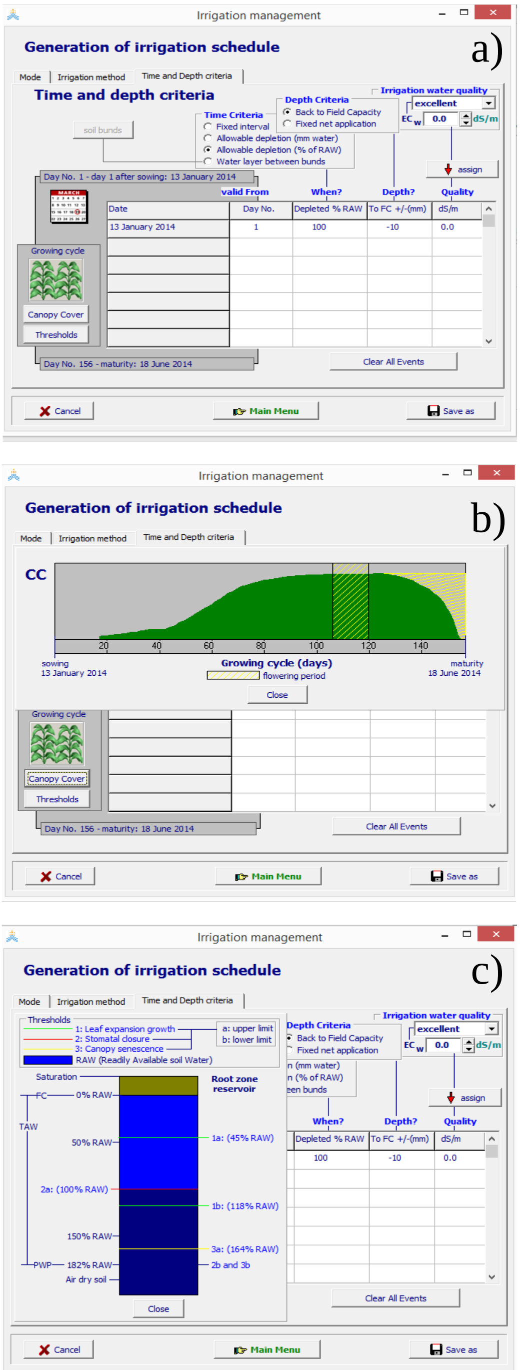


Figure 1. Generation of irrigation schedule with AquaCrop (a) establishing criteria from the different phenological stages along the growing cycle (b) or by available soil water thresholds (c).

Finally, the model distinguishes between different wetted soil fractions, depending on the irrigation system considered. Thus, the percentage of the wetted soil surface fluctuates from 100% (sprinkler, border and basin irrigation) to 0% (subsurface drip irrigation), with intermediate values for other irrigation systems (30-100% in furrow irrigation and 15-40% in trickle (drip)-micro irrigation).

2.1.2. MOPECO model. Irrigation water scheduling

MOPECO calculates the daily soil water content in the root area following the FAO-56 approach (Allen et al., 1998), balancing inputs (net irrigation, precipitation, and deep water reached by roots) and outputs (runoff, crop evapotranspiration and deep percolation) (Domínguez et al., 2011). In this sense, MOPECO computes the total available water (TAW) in the root zone, understanding TAW as the difference in soil water content between field capacity and permanent wilting point; and considers a depletion fraction "p" threshold which is the fraction of TAW that a crop can extract without suffering water stress (Allen et al., 1998; Domínguez et al., 2011).

In addition, the MOPECO irrigation scheduling module requires as input data: (i) the interval of maximum and minimum irrigation depth that can be supplied by the irrigation system per irrigation event (MID and mid, respectively); (ii) minimum and maximum number of interval days to trigger an irrigation event; (iii) maximum level of soil water content that can be refilled by an irrigation event (% TAW) with the aim of decreasing or avoiding percolation when there is unexpected rainfall after an irrigation event.

Thus, three situations can be distinguished: a) maintaining no water deficit along the crop cycle, when the soil water content is always higher than p and the irrigation water depth per event is calculated, in order to refill the soil water content in an intermediate point between field capacity and (1-p)*TAW (%TAW selected by the user); b) reaching a certain global water deficit level for the complete crop cycle (global ETa/ETm ratio defined by the user), with MOPECO aiming to determine the water deficit level to be caused to the crop at each phenological stage in order to maximize final yield; and c) distributing a certain volume of irrigation water during the crop cycle according to the water deficit level for each phenological stage that maximizes yield without exceeding the limited volume according to the progress of climatic conditions. In situations b) and c), MOPECO calculates the daily accumulated ET_a/ET_m ratio from the beginning up to the end of each growth stage. If the daily accumulated ET_a/ET_m ratio at a certain date is higher than the ET_a/ET_m target ratio for that stage, MOPECO does not apply any irrigation unless the maximum number of days without water supply (irrigation or rainfall) is reached, or the daily ET_a/ET_m ratio reaches a minimum value fixed by the user (0.35 is recommended), to avoid excessive depletion of soil moisture. (Domínguez et al. 2011). The global ET_a/ET_m ratio of each crop growth stage is established following the ORDI and ORDIL methodologies (Domínguez et al., 2012a; Leite et al., 2015; Pardo et al., 2020), which produces the highest crop yield for a certain overall deficit target or for a limited irrigation water volume, using non-linear optimization software such as Solver (Microsoft, 2018). MOPECO is sometimes unable to attain the target deficit rate proposed for each growth stage by the user or by the optimizer. In these cases, the irregular distribution of rainfall and/or the high soil water content at the beginning of the simulation are the main causes of this mismatch between the objective and the final deficit rate.

2.1.3. Model parameterization

López-Urrea et al. (2020) described in detail the parameterization of both models (Table 1) for barley crop growth under different irrigation regimes, using the data of a three year experiment (from 2011 to 2013) conducted under the semiarid conditions of Albacete province (Fig. 2).

Table 1. Specific parameters of barley crop for AquaCrop and MOPECO models.

Model	Parameter	Value
AquaCrop	**Crop growth and development**	
	Base temperature, ºC	2
	Upper temperature threshold, ºC	28
	Canopy size of the seeding, cm^2 $plant^{-1}$	1.50
	Canopy growth coefficient, % $ºC^{-1}$ day^{-1}	0.014
	Canopy decline coefficient, % $ºC^{-1}$ day^{-1}	0.644
	Water productivity, g m^{-2}	18.5
	Crop transpiration coefficient	1.10
	Yield formation	
	Reference Harvest Index, % ^{NC}	54
	Soil water stress	
	Possible increase in HI caused by water stress before flowering, %	6
	Positive impact of restricted vegetative growth during yield formation on HI	10 (small)
	Negative impact of stomatal closure during yield formation on HI	7 (moderate)
	Upper threshold for canopy expansion	0.25
	Lower threshold for canopy expansion	0.65
	Upper threshold for stomatal closure	0.55
	Upper threshold for early canopy senescence	0.85
	Shape factor for canopy expansion	3.0
	Shape factor for stomatal closure	3.0
	Shape factor for early canopy senescence	3.0
	Upper threshold for pollination failure	0.90
MOPECO	Kc	
	- Stage I	0.30
	- Stage II	0.30-1.15
	- Stage III	1.15
	- Stage IV	1.15-0.45
	Ky	
	- Stage i	0.20
	- Stage ii	0.55
	- Stage iii	0.30
	- Stage iv	0.15
	Ym ($x10^3$ kg/ha)	9.000
	Base temperature, ºC	2
	Upper temperature threshold, ºC	28

where Stage I: Initial; Stage II: Crop development; Stage III: Mid-season; Stage IV: Late season; Stage i: Vegetative period, which included establishment (Ky i') and vegetative development (Ky i'') periods; Stage ii: Flowering period; Stage iii: Yield formation; Stage iv: Ripening.

2.2. Description of the study area

The study area is located in southeast Spain in a semiarid area where around 70% of water resources used for irrigated crops are from groundwater (Domínguez and De Juan, 2008). The three main affected aquifers are Eastern Mancha, Western Mancha and Campo de Montiel, whose irrigated area is around 350,000 ha distributed over 29,000 km^2 (Fig. 2). Irrigated barley crop is usually managed under a sprinkler irrigation system because the seasonal average rainfall is between 300-350 mm $year^{-1}$, from September to June, and with high reference evapotranspiration (~1150 mm $year^{-1}$) (Domínguez et al., 2013).

The typical soils in this area are characterized by shallow depths (0.40-0.55 m) which are limited by a somewhat fragmented limestone sedimentary rock. They have a slightly basic pH (7.5-8.5), low organic matter content (1.2-1.6%) and their general texture is classified as loam or sandy clay loam soils (Domínguez and De Juan, 2008).

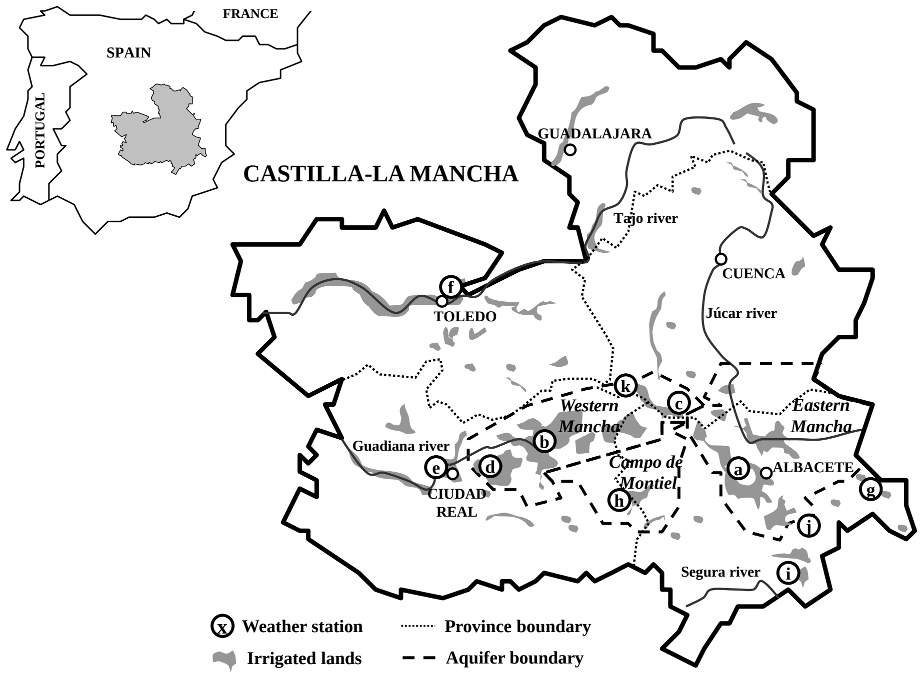


Figure 2. Location of the main irrigated areas in Castilla-La Mancha region.

2.3. Crop cycle length influenced by climatic variability

To determine the average length of the barley crop cycle, as well as its development stages in the study area, 28 crop phenological monitoring studies, carried out by the Irrigation Advisory Service (IAS) of CLM (SIAR-CLM, 2014), were used. This monitoring work included the four main irrigable areas (Fig. 2) over 11 cropping seasons, where short cycle varieties of barley were mainly studied since they are mostly grown under irrigated conditions (sowing date by mid-January and harvest date at the end of June). The BBCH-scale (Bleiholder et al., 2001) was used to determine the phenological growth stages of barley related to the input parameters required by both models (canopy development, mid-season and late season for AquaCrop; Kc and Ky coefficients for MOPECO; Table A1, Annex).

The thermal time duration of the barley growth stages in terms of accumulated GDD was obtained for both models. AquaCrop establishes three different methods to calculate GDD (Mcmaster and Wilhelm, 1997), with the first method (Raes et al., 2018) being used for simulations, while MOPECO uses the double triangulation method (Sevacherian et al., 1977) which is suitable in the area. The mean accumulated GDD value for each growth stage of barley was calculated taking into account the base temperature (T_B) and the upper temperature (T_U) thresholds. Combining a set of values reported from several studies (from 0 ºC to 10 ºC and from 20 ºC to 38 ºC, for T_B and T_U, respectively; López-Bellido 1991; Juskiw et al. 2001; Araya et al. 2010; Abrha et al. 2012) and those shown in Table 1, the selected final threshold values were derived from the lowest standard deviation and coefficient of variation GDD data for all monitoring barley growth stages.

2.4.Typical meteorological year

A typical meteorological year (TMY) represents the conditions considered "typical" over a long period of time, and consists of 12 months selected from individual years and concatenated to form a complete year with daily values (Pardo et al., 2020). In this study, an intermediate TMY ($TMY_{intermediate}$), determined by Leite et al. (2015) with a weather station located in the experimental area (Albacete, southeast Spain ; Fig. 2), was used. The main values computed for $TMY_{intermediate}$ were 1212 mm year^{-1} and 289 mm year^{-1} for reference evapotranspiration (ET_o) computed using the FAO56 Penman-Monteith equation (Allen et al., 1998) and precipitation, respectively.

2.5. Simulating the crop barley yield response to irrigation management

Using the GDD methodology already described and applied for a $TMY_{intermediate}$ in the study area (Leite et al., 2015), the crop barley yield and irrigation water productivity (IWP; expressed as kg of commercial crop yield per m^{-3} of irrigation water supplied to the crop) response to irrigation scheduling were simulated with AquaCrop and MOPECO. The derived crop-water and IWP-water production functions were compared to evaluate the performance of both irrigation scheduling tools.

Four irrigation strategies (IS) were designed to be implemented in the AquaCrop model (IS1_Aq, IS2_Aq, IS3_Aq and IS4_Aq). The four strategies were considered as sustained irrigation through the simulated crop cycle. In two of the IS strategies (IS1_Aq and IS2_Aq), a time criterion was fixed with an interval time between 1 to 27 days, where odd days were used, obtaining 14 simulations for each IS (Table 2). The depth criteria of these IS was different: IS1_Aq applied, at each irrigation event, 23.5 mm of gross water depth; while IS2_Aq refilled the soil water content up to field capacity minus 10 mm as a margin for unexpected rainfall events. The other two IS strategies (IS3_Aq and IS4_Aq) considered the irrigation event was triggered when a certain soil water content was depleted (represented as mm), being 12 simulations per each IS (Table 2), and following the same irrigation depth criteria previously described, i.e. to apply 23.5 mm per irrigation event (IS3_Aq), and to refill up to field capacity minus 10 mm (IS4_Aq).

The gross irrigation depth of 23.5 mm was established since it is the most widely used according to the representative farm area and the daily irrigation time normally used. In addition, barley crop yield was also simulated under rainfed conditions in order to find the ordinate of the crop-water production function. Finally, the regulated deficit irrigation scheduling, taking into account crop growth stages, was not analysed because of the huge number of combinations which may be derived, surpassing, in this case, the goals for managing this model by an intermediate user.

In the case of MOPECO, two irrigation strategies were performed (IS1_ORDI and IS2_ORDIL; Table 2). The first strategy established an optimized regulated deficit irrigation with ten global ET_a/ET_m ratio objectives (between 1.00 y 0.55) (Table 2). To simulate the ORDIL irrigation strategies (IS2_ORDIL), ten gross irrigation water amounts were fixed as the input data model, which derived in different global ET_a/ET_m ratios (Table 2). In the former IS, the maximum simulated irrigation water amount had a global ET_a/ET_m ratio equal to 1.00 (i.e. the same total irrigation depth simulated in IS1_ORDI, 312 mm), and the rest of simulations were run for irrigation depths differentiated at intervals of 20 mm (Table 2). A total of 15 and 2 days were established as maximum and minimum intervals between irrigation events when no rainfall occurs. The gross irrigation water depth per event was set between 4 and 30 mm.

For the simulations, the sowing date was January 13th, the maximum root depth was 1.0 m although its development was limited by the root restrictive layer (0.40 m). The physical and hydraulic soil characteristics were those measured by Pardo et al. (2020) which are representative of this production area. Both models were run in GDD mode, using the average GDD for each growth stage from the GDD methodology previously described, and using the parameterized coefficients shown in Table 1. In this work, a value equal to 85% of irrigation efficiency was established, corresponding to a sprinkler irrigation system. The initial soil water content was established at 80% of field capacity. In the case of AquaCrop, the simulated dry matter yield outputs were normalized to standard commercial yields (12% of moisture content), since yield outputs computed by MOPECO are given as commercial yield.

Table 2. Irrigation strategies simulated by AquaCrop (Aq) and MOPECO (ORDI and ORDIL strategies) and both computed crop yield and crop-water flux results.

IS	AqC	MoC	MIWD	IE	GIWD	RO	DP	Y	IWP	ET_a	ET_a/ET_m
IS1_Aq	1	-	23.5	157	3694	51	2797	6.806	0.184	321	0.714
	3	-	23.5	52	1224	51	612	11.676	0.954	448	0.998
	5	-	23.5	31	729	42	218	11.658	1.598	447	0.994
	7	-	23.5	22	518	41	88	11.275	2.178	425	0.944
	9	-	23.5	17	400	23	34	10.647	2.662	405	0.900
	11	-	23.5	14	329	25	9	9.688	2.941	368	0.818
	13	-	23.5	12	282	23	0	9.230	3.269	342	0.760
	15	-	23.5	10	235	20	0	8.245	3.504	330	0.733
	17	-	23.5	9	212	18	0	7.506	3.544	318	0.706
	19	-	23.5	8	188	30	0	6.541	3.475	288	0.642
	21	-	23.5	7	165	14	0	6.478	3.933	295	0.656
	23	-	23.5	6	141	18	0	6.733	4.769	279	0.624
	25	-	23.5	6	141	15	0	5.590	3.959	280	0.624
	27	-	23.5	5	118	16	0	5.761	4.897	266	0.591
IS2_Aq	1	-	3.4	99	393	37	0	11.685	2.971	445	0.990
	3	-	9.4	38	387	39	0	11.685	3.016	443	0.984
	5	-	12.9	26	378	38	0	11.670	3.086	440	0.978
	7	-	18.3	17	368	42	0	11.384	3.094	429	0.953
	9	-	19.5	14	328	25	0	11.114	3.385	414	0.920
	11	-	19.3	13	303	32	0	10.549	3.485	384	0.854
	13	-	18.9	12	274	20	0	10.205	3.721	366	0.813
	15	-	22.6	9	255	18	0	9.265	3.632	363	0.807
	17	-	23.1	8	235	15	0	8.458	3.595	345	0.768
	19	-	22.0	8	224	29	0	7.831	3.496	323	0.719
	21	-	22.5	7	203	14	0	8.041	3.958	328	0.729
	23	-	16.5	6	129	18	0	6.327	4.921	268	0.597
	25	-	23.7	6	188	12	0	7.185	3.822	313	0.694
	27	-	23.7	5	161	20	0	7.481	4.648	301	0.667
IS3_Aq	12.3	-	23.5	21	494	45	35	11.685	2.365	435	0.967
	27.3	-	23.5	15	353	16	0	11.681	3.310	431	0.958
	29.5	-	23.5	15	353	20	0	11.680	3.309	430	0.957
	31.7	-	23.5	14	329	25	0	11.600	3.521	420	0.935
	34.0	-	23.5	14	329	18	0	11.413	3.465	416	0.925
	36.2	-	23.5	13	306	33	0	10.459	3.419	398	0.887
	38.4	-	23.5	12	282	19	0	9.742	3.450	387	0.863
	40.7	-	23.5	11	259	18	0	8.463	3.270	364	0.811
	42.9	-	23.5	9	212	16	0	8.038	3.795	341	0.760
	45.1	-	23.5	8	188	14	0	6.631	3.523	313	0.698
	47.4	-	23.5	5	118	13	0	4.753	4.040	266	0.589
	49.6	-	23.5	4	94	13	0	4.434	4.711	247	0.546
IS4_Aq	12.3	-	4.8	86	393	37	0	11.685	2.972	445	0.989
	27.3	-	18.0	17	361	29	0	11.619	3.218	436	0.970
	29.5	-	20.0	14	337	19	0	11.597	3.438	431	0.958
	31.7	-	23.5	11	319	16	0	11.630	3.641	421	0.936
	34.0	-	25.2	10	314	14	0	11.550	3.680	417	0.927
	36.2	-	27.5	9	313	28	0	10.782	3.444	403	0.897
	38.4	-	29.4	8	302	31	0	9.839	3.253	388	0.863
	40.7	-	30.9	6	248	24	0	8.940	3.610	358	0.798
	42.9	-	31.2	5	215	12	0	7.766	3.619	337	0.750
	45.1	-	31.5	4	180	19	0	7.272	4.029	313	0.697
	47.4	-	30.2	3	139	14	0	5.177	3.736	270	0.599
	49.6	-	30.3	3	139	19	0	4.885	3.513	254	0.563
IS1_ORDI	-	1.00	19.5	16	312	37	5	11.664	3.740	384	0.999
	-	0.95	17.2	18	310	37	20	11.220	3.619	367	0.961
	-	0.90	14.8	18	266	37	8	11.084	4.167	360	0.934
	-	0.85	9.8	25	244	37	4	10.520	4.311	346	0.903

	-	0.80	10.2	23	234	37	4	10.174	4.343	338	0.876
	-	0.75	9.9	22	217	37	4	9.606	4.430	322	0.830
	-	0.70	10.2	19	194	37	4	9.101	4.697	305	0.784
	-	0.65	9.9	18	179	37	4	8.604	4.808	292	0.743
	-	0.60	8.4	18	151	37	4	7.727	5.103	270	0.696
	-	0.55	6.0	22	131	37	4	7.123	5.435	252	0.657
IS2_ORDIL	-	312	19.5	16	312	37	5	11.664	3.740	384	0.999
	-	292	12.1	24	292	37	4	11.281	4.039	370	0.955
	-	271	13.5	20	271	37	8	10.934	4.039	359	0.936
	-	246	9.4	26	246	37	4	10.528	4.286	347	0.899
	-	232	8.3	28	232	37	4	10.205	4.408	337	0.878
	-	210	8.1	26	210	37	4	9.612	4.569	319	0.836
	-	190	10.0	19	190	37	4	8.936	4.701	302	0.794
	-	170	7.7	22	170	37	4	8.368	4.909	286	0.760
	-	149	8.3	18	149	37	4	7.687	5.156	268	0.701
	-	131	6.9	19	131	37	4	7.116	5.437	253	0.656
RAINFED	-	-	-	-	-	12	0	2.800	-	177	0.398

IS: irrigation strategy; AqC: irrigation event criterion by AquaCrop (IS1_Aq and IS2_Aq: number of interval days; IS3_Aq and IS4_Aq: depleted mm threshold); MoC: irrigation event criterion by MOPECO (IS1_ORDI: global ET_a/ET_m ratio (dimensionless); IS2_ORDIL: limited volumes of irrigation water (mm)); IE: number of irrigation events; MIWD: mean gross irrigation water depth per event (mm); GIWD: total gross irrigation water depth (mm), considering 85% irrigation efficiency; RO: runoff (mm); DP: deep percolation (mm); Y: crop yield (12% of water content; $x10^3$ kg ha^{-1}); IWP: irrigation water productivity (kg m^{-3}); ET_a: actual crop evapotranspiration (mm); ET_m: maximum crop evapotranspiration.

2.6. Experimental dataset using the ORDIL methodology

Evaluating the performance of the AquaCrop and MOPECO models, as well as their inter-comparison, we used several irrigation schedules generated by ORDIL methodology with a limited total irrigation depth (Pardo et al., 2020). Pardo et al. (2020) conducted the field trials in 2015, 2016 and 2017 on an experimental farm located in Albacete (SE Spain). Its geographic coordinates are 1° 53’ 58” W, 38° 56’ 42” N, and the altitude is 695 m above mean sea level. Five treatments of ORDIL irrigation strategies were carried out to analyse their effects on both IWP and crop yield in the “Shakira” barley cultivar. A control treatment (no water deficit, ND) received the full crop water requirements following López-Urrea et al. (2020), while the other four irrigation treatments received a percentage of the net typical irrigation water requirements (T100, 100%; T90, 90%; T80, 80% and T70, 70%) which were adjusted to 2500 m^3 ha^{-1} (Pardo et al. 2020). All irrigation schedules were obtained from Pardo et al. (2020). Those authors carried out four optimizations during the crop cycle length (one per each K_y stage; Table 1) in order to maximize crop yield according to the water deficit (in terms of ET_a/ET_m) applied to each barley K_y stage.

The soil of the experimental plot, classified as clay-loam, was a shallow soil (0.40 m of average soil depth), whose available water content was 0.124 cm^3 cm^{-3} (0.313 cm^3 cm^{-3} for field capacity and 0.189 cm^3 cm^{-3} for permanent wilting point). During the three experimental cropping seasons, ET_o was between 12.5% and 25.0% higher than the $TMY_{intermediate}$ (400 mm), while the total precipitation was lower for 2015 and 2016 experimental seasons (around 20%) and slightly higher for 2017 season (5%) with respect to the $TMY_{intermediate}$ (165 mm) (Pardo et al., 2020). Real-time ET_a/ET_m optimizations for each K_y crop stage were fitted to the weather conditions occurring during the current year. The total water received by crop (rainfall and irrigation) and crop yield obtained for each treatment and experimental seasons are shown in Table 3 (Pardo et al., 2020).

In addition, for each irrigation treatment, during the three experimental seasons, both the total crop biomass and the leaf area index (LAI) evolutions were measured (approximately every 15 days in two subplots of each treatment). Two samples of 0.5×0.5m were collected and measured per treatment by using an electronic meter device (LI−COR-3100C, Licor, Inc., Lincoln, NE) to determine LAI and were introduced into an oven at 70 °C up to constant weight for crop biomass. Crop canopy cover (CC) was estimated from the measured LAI using the Ritchie equation (Ritchie et al., 1985), where the extinction coefficient was established as 0.60.

$$CC = 1 - exp^{(-K \cdot LAI)} \tag{1}$$

where CC is canopy cover; K is extinction coefficient; LAI is leaf area index.

Table 3. Total water received by the crop, commercial yield (12% grain moisture content) obtained at harvest and aboveground biomass and canopy cover evolution during the three experimental seasons.

	Experimental year 2015						Experimental year 2016						Experimental year 2017				
Treatment	**ND**	**100%**	**90%**	**80%**	**70%**		**ND**	**100%**	**90%**	**80%**	**70%**		**ND**	**100%**	**90%**	**80%**	**70%**
Tw (mm)	419.1	384.1	358.6	333.7	308.8		463.8	388.8	355.4	330.8	305.9		541.7	423.8	398.9	375.5	348.6
GIWD (mm)	285.6	250.6	225.1	200.2	175.3		333.4	258.4	225	200.4	175.5		367.9	250	225.1	201.7	174.8
Obs. Yield* (SD)	9.199 (0.619)[#]	8.616 (0.457)	7.620 (0.362)	7.367 (0.169)	6.404 (0.492)		8.877 (0.296)	7.985 (0.301)	7.690 (0.444)	7.214 (0.215)	6.331 (0.148)		9.071 (0.511)	8.032 (0.398)	7.621 (0.250)	7.311 (0.232)	6.283 (0.295)
DAS	**Aboveground biomass ($x10^3$ kg ha^{-1})**					**DAS**	**Aboveground biomass ($x10^3$ kg ha^{-1})**					**DAS**	**Aboveground biomass ($x10^3$ kg ha^{-1})**				
0	0.000	0.000	0.000	0.000	0.000	0	0.000	0.000	0.000	0.000	0.000	0	0.000	0.000	0.000	0.000	0.000
63	0.492	0.492	0.492	0.492	0.492	64	0.9382	0.914	0.9504	0.904	0.8683	77	2.713	2.713	2.4116	2.4116	2.4116
73	1.328	1.328	1.328	1.328	1.328	85	3.6294	3.6468	3.5746	3.5488	3.523	98	7.3166	7.3166	6.8856	6.8856	6.8856
88	4.016	4.016	4.016	4.016	4.016	98	7.5706	7.1241	5.8648	5.775	5.6852	111	10.418	10.239	10.242	9.7012	9.2638
102	7.066	7.066	6.927	6.282	6.066	110	9.7844	9.5912	8.4066	8.0114	7.3342	129	14.509	14.878	13.224	14.02	12.858
114	11.978	11.978	10.52	10.02	9.312	126	11.553	11.553	10.887	10.006	9.3018	146	19.329	16.868	17.272	17.766	16.712
127	16.382	16.382	15.379	14.674	13.963	140	16.7	14.571	13.889	13.737	12.673	150	18.135	15.831	14.923	14.017	11.171
153	16.291	13.859	13.114	12.503	11.187	158	13.92	11.175	10.412	10.136	8.087	-	-	-	-	-	-
DAS	**Canopy cover (%)**					**DAS**	**Canopy cover (%)**					**DAS**	**Canopy cover (%)**				
0	0.0	0.0	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0
56	11.0	11.0	11.0	11.0	11.0	42	11.0	11.0	11.0	11.0	11.0	50	11.0	11.0	11.0	11.0	11.0
63	35.4	35.4	35.4	35.4	35.4	64	49.1	48.7	49.4	48.4	47.1	98	95.0	95.0	93.1	93.1	93.1
73	57.1	57.1	57.1	57.1	57.1	85	94.2	94.3	93.8	93.6	93.4	111	98.4	98.4	97.6	97.6	97.6
88	97.6	97.6	97.6	97.6	97.6	98	99.7	99.5	96.7	95.9	95.6	129	99.3	99.2	98.6	98.7	97.8
102	99.8	99.8	99.6	99.5	99.1	110	97.9	96.8	95.4	93.0	89.8	146	92.8	93.4	91.1	92.7	87.1
114	99.9	99.9	99.8	99.6	99.3	126	92.0	91.3	88.6	82.9	74.0						
127	99.5	99.5	99.2	99.0	98.8	140	79.9	71.5	65.2	36.7	35.2	-	-	-	-	-	-
153	82.4	82.4	83.2	40.8	37.1	158	0.0	0.0	0.0	0.0	0.0	-	-	-	-	-	-

Tw: total water received (irrigation + total rainfall); GIWD: gross irrigation water depth; Obs. Yield: observed yield ($x10^3$ kg ha^{-1}); *: yield performed against yield commercial grain (12% of water content); [#]: values between brackets are the standard deviation (SD); DAS: days after sowing.

2.7. Statistical analysis to evaluate the irrigation schedule tools and model performance

Several statistical indicators were performed to estimate the goodness of fit for both simulated crop-water and the IWP-water production function of each IS (CWPF and IWPPF, respectively), with the gross irrigation-water depth (GIWD) being the dependent variable in both functions. Curvilinear and lineal models were used to fit these functions (Saseendran et al., 2015; Stewart and Hagan, 1973), since a portion of the applied water is not used in evapotranspiration and is lost in different process (Fereres and Soriano, 2007). Thus, the coefficient of determination (R^2), the significance of both model parameters and R^2 (p-value), as well as the standard error (SE) of estimate of the regression model were analysed. Statgraphics® Centurion XVII software was used to calculate these statistics.

$$Z = a + b \cdot GIWD + c \cdot GIWD^2 \quad (2)$$

$$Z = a + b \cdot GIWD \quad (3)$$

where Z is the commercial crop yield (Y; kg ha^{-1}) or irrigation water productivity (IWP; kg m^{-3}); a, b, c are the model's coefficients; GIWD is the gross irrigation water depth (mm).

With respect to the performance of both models in simulating three experimental trials under ORDI methodology, the statistical parameters used to determine the goodness of fit of the simulations were: root mean square error (RMSE), mean bias error (MBE), efficiency model (EF), and index of agreement (d; Willmott 1982).

$$RMSE = [n^{-1} \cdot \sum(S_i - O_i)^2]^{1/2} \quad (4)$$

where RMSE is the Root Mean Square Error; n, is the number of observations; S_i and O_i are the simulated and observed values, respectively.

$$MBE = n^{-1} \sum_{i=1}^{n}(S_i - O_i) \quad (5)$$

where MBE is the mean bias error.

$$EF = 1 - \frac{\sum(S_i - O_i)^2}{\sum(O_i - \bar{O})^2} \quad (6)$$

where EF is the efficiency model.

$$d = 1 - \left(\frac{\sum(S_i - O_i)^2}{\sum\left((S_i - \bar{O}) + (O_i - \bar{O})\right)^2}\right) \quad (7)$$

where d is the index of agreement.

RMSE was used to analyse the variance of the error, which ranges from 0 to positive infinity, with the former indicating good, and the latter poor, model performance. The MBE expresses the average size of the estimated errors and was used to indicate the under- or overestimations of the model. Finally, the EF and d statistics (non-dimensional) were used as the indicator of model quality, where values close to 1 mean there is a good agreement. EF ranges between -∞ to 1, while d index ranges between 0 and 1. These statistics were computed using the number of independent observations for each treatment for canopy cover and biomass progression (only with AquaCrop). However, those statistics were calculated for standard commercial yield (12% of water content) with the data set obtained from the five treatments during the three experimental seasons (both AquaCrop as MOPECO). Finally, the differences between observed and simulated yield values were computed to estimate the performance model following the criteria established by a number of authors (differences between simulated and observed data lower than 10% and with more than 70% of cases achieving the former percentage; (Domínguez et al., 2012c; Farahani et al., 2009; Heng et al., 2009; López-Urrea et al., 2020).

3. Results and discussion

3.1. Duration of barley growing stages in Castilla-La Mancha

Analysing the barley growth stages with all monitoring field data, the lowest values of standard deviation and coefficient of variation were obtained with a temperature combination of 2 ºC and 28 ºC as T_B and T_U thresholds, respectively. These temperatures are similar to those proposed by López-Bellido (1991) and Araya et al. (2010), and the same as those of Abrha et al. (2012) and López-Urrea et al. (2020). These results strengthen the values stipulated by the authors previously cited, whose studies were carried out under similar climatic conditions. The mean length of barley crop stages for CLM conditions are shown in Table 4.

Table 4. Length of barley growing stages in Castilla-La Mancha (accumulated GDD) according to development stages for MOPECO and AquaCrop models.

	MOPECO								**AquaCrop**		
	K_c (I)	**K_c (II)**	**K_c (III)**	**K_c (IV)**	**K_y (i)**	**K_y (ii)**	**K_y (iii)**	**K_y (iv)**	**CnDv**	**MSsn**	**LSsn**
Start	00	21	39	83	00	37	71	85	00	39	71
End	21	39	83	89	37	71	85	89	39	71	89
Average	**290**	**744**	**1087**	**1450**	**645**	**981**	**1186**	**1450**	**715**	**949**	**1395**
SD	46	57	64	69	73	64	59	69	66	71	68
CV (%)	16	8	6	5	11	7	5	5	9	7	5

where K_c (I): Initial; K_c (II): Crop development; K_c (III): Mid-season; K_c (IV): Late season; K_y (i): Vegetative period; K_y (ii): Flowering period; K_y (iii): Yield formation; K_y (iv): Ripening; CnDv: canopy development; MSsn: mid-season; LSsn: late season; 00: First day after sowing; 21: Beginning of tillering: first tiller detectable; 37: Flag leaf just visible, still rolled; 39: Flag leaf stage: flag leaf fully unrolled, ligule just visible; 71: Watery ripe: first grains have reached half their final size; 83: Early dough; 85: Soft dough: grain content soft but dry. Fingernail impression not held; 89: Fully ripe: grain hard, difficult to divide with thumbnail; SD: standard deviation; CV: coefficient of variation.

The methodologies used by both crop models, computing the required thermal time for reaching each development stages, showed similar values when the barley crop attained the same phenological stage (i.e. BBCH scales 39, 71 and 89), obtaining differences lower than 4.0%. In this sense, the accumulated GDD progression at the different crop growth stages (either those used by MOPECO or by AquaCrop) was similar in all monitored cropping seasons (Table A2, Annex), with the GDD variability decreasing (represented as coefficient of variation; Table 4) with time, as has also been observed by other authors using GDD (Lancaster et al., 1996; Marinaccio et al., 2015; Pereira et al., 2015; Piccinni et al., 2009; Ruiz-Corral et al., 2002). Analysing variability in days after sowing, there were differences in duration of between 2 and 11 days for the stages established by both crop models. These numbers of days represent, as a maximum, around 7% with respect to the total crop growth length (150 days). Thus, these variation results can be considered as acceptable, following the same criteria given by Domínguez et al. (2012c) in a maize crop cultivated in the same production area.

Finally, the average thermal time values calculated for the three main phenological stages used by the AquaCrop model (Table 4), were very similar to those calibrated by López-Urrea et al. (2020). These authors parameterized the conservative parameters “Time to maximum canopy cover” and “Length of the Harvest Index accumulation” as 619 GDD and 675 GDD, respectively. Taking into account that the crop canopy development stage

(CnDv) is the same as the first previous parameter described, CnDv was 13.4% higher. This difference for the crop stage may be acceptable since the highest variations are usually found in the first crop growth stage (Table 4). Conversely, the second conservative parameter is represented as the GDD remainder between late-season (LSsn (Table 4) and CnDv, obtaining 680 GDD, which is very close to the stage parameterized by López-Urrea et al. (2020). Therefore, the average thermal time reported in Table 4 will be used to simulate the crop cycle length under the conditions of $TMY_{intermediate}$.

3.2. "Crop vs. irrigation water" production function obtained by the different irrigation tools provided by the models

The four irrigation strategies simulated by AquaCrop with a $TMY_{intermediate}$ reached a maximum yield of 11.70 x10^3 kg ha^{-1} (IS1_Aq, IS2_Aq, IS3_Aq and IS4_Aq; Table 2; Fig. 3a). In the same way, and as expected, similar maximum yields were simulated by MOPECO for the two irrigation strategies simulated (ORDI and ORDIL; Table 2; Fig. 3a). Although the MOPECO model was calibrated for a Ym = 9.00 x10^3 kg ha^{-1} (Table 1), according to the results obtained in the experiments carried out by López-Urrea et al. (2020), the Ym is not a constant value and depends on many factors, such as climatic conditions, soil characteristics and crop management (Sadras et al., 2015). Consequently, this value must be adapted for the conditions of the farm and the year where the simulations were or will be carried out. In this sense, and in order to achieve a proper comparison between both models, the maximum yield obtained by AquaCrop was considered as Ym for MOPECO.

The barley yield simulated by using AquaCrop under rainfed conditions in a $TMY_{intermediate}$ was 2.80 x10^3 kg ha^{-1} (Table 2). This value, as well as the maximum simulated yield can be considered appropriate, according to the crop statistics and field trials carried out in this area (ITAP, 2020; MAPA, 2020). With respect to MOPECO, the rainfed condition was not simulated since simulated yields are unreliable when the computed ET_a/ET_m ratio for one or more development stages is lower than 0.5, as happens under rainfed conditions (Domínguez et al., 2012a; Doorenbos and Kassam, 1979).

Overall, all ISs simulated by both models showed that the maximum yield was reached when gross irrigation water depth (GIWD) was between 300 and 390 mm (Table 2; Fig. 3a). In the case of AquaCrop, and excepting IS1, all ISs simulated yields were close to 11.70 x10^3 kg ha^{-1} when GIWD was higher than 350 mm (Table 2), while slightly lower GIWD values (ranging between 300 and 330 mm) decreased by yield around 12%. In contrast, the two ISs simulated by MOPECO (ORDI and ORDIL) obtained the maximum yield supplying 312 mm of GIWD (Table 2). Simulating GIWD lower than 300 mm, both crop models showed that barley crop was subjected to water deficit (ET_a/ET_m ratio lower than 1; Table 2). Nonetheless, all ISs simulated by MOPECO attained crop yields between 16% and 27% higher than those obtained by AquaCrop, considering similar GIWD applications (Fig. 3a).

Analysing the IS simulated by AquaCrop, IS1, applying irrigation depths fixed at 23.5 mm per event, with an interval time between irrigation events of 1 to 7 days, showed that is not feasible at either economic or environmental level. In this simulated interval time, deep percolation was highly significant (between 88 and 2800 mm; Table 2), causing crop yield not to increase significantly with a GIWD of more than 350 mm (Table 2; Fig. 3a). Thus, IS1 simulated around 18% less crop yield for a GIWD interval between 300 and 390 mm. On the other hand, the irrigation scheduling managed by AquaCrop using the readily available water in the soil (% RAW) as time criterion, showed that, depleting soil water up to a 34 mm, and requiring GIWD between 330 and 490 mm, the simulated crop yield was close to the maximum yield, obtaining ET_a/ET_m ratios of around 0.95 (Table 2), whereas with depletion thresholds higher than 34 mm or by fixing interval time between irrigation events at more than 11 days, the AquaCrop model simulated significant decreases in crop yield, with global ET_a/ET_m ratios lower than 0.85 (Table 2). The AquaCrop results simulating high-frequency irrigation strategies (interval irrigation events between 1 and 5 days or with a depletion threshold between 12 and 27 mm, IS2-Aq and IS4-Aq, respectively), obtained average irrigation depths from 3 mm to 12 mm per irrigation event (Table 2). These irrigation schedules are not useful, according to the typical irrigation amount per event, although they attained the largest ET_a/ET_m ratios (>0.97%; Table 2). Finally, IS4-Aq also simulated irrigation scheduling with low frequency of irrigation events (from 3 to 10 events along crop growth cycle; Table 2) whose average irrigation depths per event were between 25% and 88% higher than the objective irrigation water depth (23.5 mm), and consequently ET_a/ET_m ratios were lower than 0.88 (Table 2).

Regarding the two ISs simulated by MOPECO, both showed that crop yield and ET_a/ET_m ratio had a similar behaviour, since the GIWDs and MIWDs simulated in each case were very close (Table 2), obtaining almost overlapping production function-curves (Fig. 3a). Comparing the number of irrigation events simulated by both models, and under a similar ET_a/ET_m ratio value, the strategies performed by MOPECO provided more frequent irrigation events than AquaCrop. In the case of the simulated ET_a, and comparing data with similar ET_a/ET_m ratios (Table 2), AquaCrop computed around 14% above MOPECO because of the different method of calculating evapotranspiration.

In general, the calculated IWP values ranged between 0.184 kg m^{-3} and 5.435 kg m^{-3} (Table 2). The IWP simulated by AquaCrop showed a higher variability than MOPECO (from 0.184 kg m^{-3} to 4.921 kg m^{-3} vs. from 3.619 kg m^{-3} to 5.435 kg m^{-3}, respectively; Table 2, Fig. 3). Thus, the IWP differences for the four ISs simulated by AquaCrop were significant, with GIWD lower than 200 mm (up to 20% less), while these differences were between 9.5% and 15% with GIWD above 200 mm (Fig. 3b), excepting IS1, whose calculated IWP tended to drop off significantly with respect to the rest of ISs (values lower than 3.0 kg m^{-3}; Fig. 3b). In contrast, the IWP computed by MOPECO had a similar behaviour under the same GIWD (differences lower than 1.0%; Fig. 3b), as was also shown with the simulated crop yield (Fig. 3a). Overall, the MOPECO model computed higher IWP-GIWD relationships than those calculated by AquaCrop, being between 8.0% and 27.5% on average when water deficit was triggered.

The production and IWP function curves obtained with MOPECO contained those generated with AquaCrop (Fig. 3). The main reason for this is the way to outline the different ISs, where the ISs considered for AquaCrop were sustained throughout the crop cycle, whereas the ISs simulated by MOPECO established regulated irrigation management based on the water deficit sensibility of each crop growth stage. Similar differences between ORDI and sustained deficit irrigation (SDI) strategies were computed by the MOPECO model, optimizing the deficit irrigation strategies for maize in the same area (Domínguez et al., 2012a).

The models derived from the simulated ISs with both AquaCrop and MOPECO showed that crop yield-water production functions had a high goodness of fit with the second-degree polynomial model (R^2>92%; Table A3, Annex), while IWP-GIWD relationships for all ISs were faithfully fitted to a linear model (Table A3, Annex). The selected curvilinear model, as well as their parameter values for each IS, were, in most cases, highly significant, with standard errors of the model ranging between 0.17 $x10^3$ and 0.85 $x10^3$ kg ha^{-1} (Table A3, Annex), where the ISs generated by AquaCrop simulated a 67%

larger standard error than MOPECO. In the case of linear models, errors were around 0.01 kg m^{-3} for the ISs simulated by MOPECO and between 0.06 kg m^{-3} and 0.19 kg m^{-3} for those generated with AquaCrop (Fig. 3b). Finally, the curvilinear model adjusted to IS4 showed that the squared term had no significance, being a linear relationship that would achieve highly significant model coefficients. Trout and DeJonge (2017), in a field trial with maize during four cropping seasons, derived consistent and highly significant fits of crop-water production functions to a curvilinear model. These authors, relating crop yield vs. evapotranspiration with the former model, obtained similar results, despite several studies having projected linear relationships in field crops (Doorenbos and Kassam, 1979; Fereres and Soriano, 2007; Saseendran et al., 2015; Steduto et al., 2007; Tanner and Siinclair, 1983). In this sense, reasons such as evaporation losses decreasing as water deficit limits transpiration could partly explain those results (Trout and DeJonge, 2017).

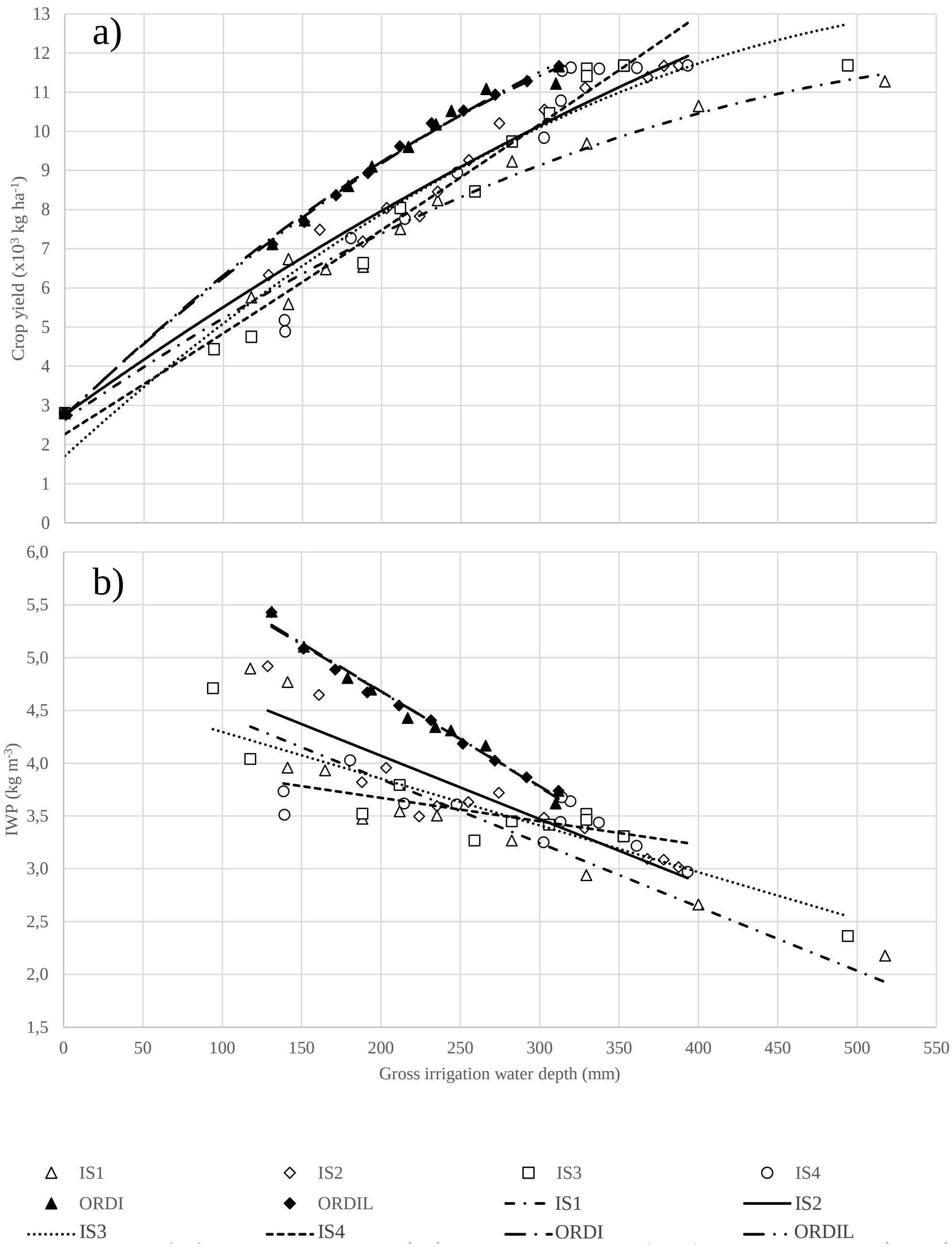


Figure 3. Relationships between barley yield and gross irrigation water depth (GIWD) (a), and irrigation water productivity and GIWD (b) simulated by both AquaCrop (white symbols) and MOPECO (black symbols) models.

3.3. Simulation by AquaCrop of the data from the ORDIL experimental field tests, validation of the results, and comparison with MOPECO outputs

Overall, the AquaCrop model performance simulating the irrigation scheduling derived from different ORDIL levels was appropriate during the three experimental seasons. The progression of the main crop growth variables simulated by AquaCrop (canopy cover, CC; aboveground biomass, AGB), as well as final crop yield (Y) followed a tendency close to the measured data (Fig. 4; Table 5). The calculated statistical indicators between observed and simulated data showed that CC was underestimated with MBE values between 0.6% and 7.1%, and whose variance of error values were around 11.0% for all treatments (Table 5). Most values of EF and d were close to 0.90 or higher, excepting two treatments during the 2016 cropping season (80% and 70%; Table 5), showing that AquaCrop had a good goodness of fit. This slight underestimation of the CC by AquaCrop also resulted in the same trend at that of the measured AGB data (Fig. 4), reporting errors ranging from 0.76 $x10^3$ to 2.17 $x10^3$ kg ha^{-1} (Table 5). Finally, goodness of fit indicators were similar to those computed for CC in this research.

With respect to the simulated crop yield, AquaCrop simulated values close to those observed, including the standard deviation values (Table 5). Thus, the percentage of deviation between both simulated and observed values, for all treatments, was within ±10% (Table 5); obtaining errors between 0.26 $x10^3$ and 0.46 $x10^3$ kg ha^{-1} with high EF and d values (Table 5). The crop yield statistical indicators computed, between the data simulated by MOPECO vs. the observed data, showed similar results to those obtained with AquaCrop, with the RMSE values being somewhat lower (Table 5). Pardo et al. (2020) extensively discussed testing the MOPECO model with the ORDIL methodology, concluding that Ym is the most important variable to fit the potential crop yield to the actual yield, according to phenological stage duration, suitable parameterization of K_c and K_y and optimal volume water distribution along the crop cycle, depending on the actual weather conditions.

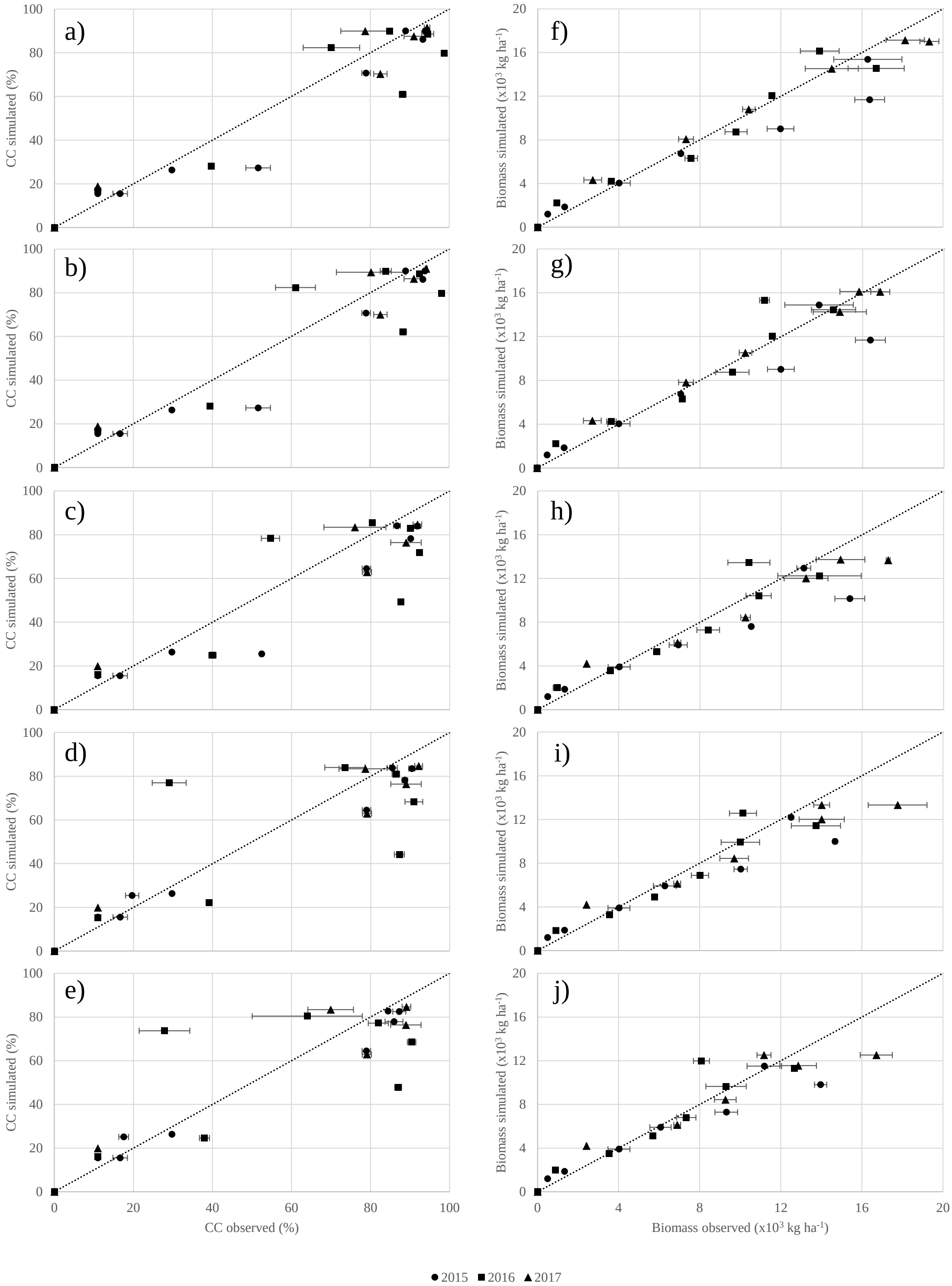
Comparing the former results with those reported by López-Urrea et al. (2020), who parameterized this model for barley under the same climate conditions, it is worth noting that all statistical parameters used to test both models were similar. Thus, these findings confirm the suitability of barley parameterization in AquaCrop and MOPECO and, in addition, the different irrigation strategies developed by ORDIL methodology, and tested in the field, were faithfully replicated by the models.

In terms of evaporative demand simulated by both models, the accumulated maximum and actual crop evapotranspiration (ET_m and ET_a, respectively) simulated by AquaCrop were, respectively, around 17% and 8% higher than those obtained by MOPECO (Table 6). In this sense, both the total actual crop transpiration (T_a) and the total actual soil evaporation (E_a) values simulated by AquaCrop were not satisfied in any irrigation treatment without water deficit (i.e. ND and 100% over 2500) during the three seasons (Table 6). However, the ET_a/ET_m ratio values calculated by MOPECO for ND treatment were fully satisfied, excepting the second experimental season with 0.96 (Table 6). In this sense, López-Urrea et al. (2020) reported differences in the ET_a and ET_m simulated by the models. This research shows again that as water levels are reduced, the differences in simulated ET_a and ET_m across crop models are larger (mean values from 4% and 15% for ND to 11% and 20% for 70%, respectively; Table 6). The main factors that might explain these differences are:

- The single and dual Kc approaches coded in MOPECO and AquaCrop models, respectively. The ET_a/ET_m ratio simulated for ND treatment by MOPECO was almost matched in the three seasons (≈1.0; Table 6), while AquaCrop failed to reach ratios higher than 0.85% because of the low simulated actual evaporation, since actual transpiration was close to the maximum (Table 6).

- Runoff. The simulation of this variable by both models showed large differences, being between 76% and 190% lower for AquaCrop. If the AquaCrop model considered the same water outtake by runoff as MOPECO, the ET_a/ET_m ratio simulated by both models would be reduced from 12% to 8% as the mean value, for the three seasons (Table 7).
- Updating K_{cb} barley. Pereira et al., (2021b) updated the basal crop coefficient (K_{cb}) of field crops, such as grain legumes, oil crops and small grain cereals. In this case, K_{cb} for barley was determined as 1.00. Changing this value in the crop transpiration coefficient (Kc_{TR}=1.10; Table 1), and simulating once again all treatments, the new mean differences in ET_a/ET_m ratio between the two models were around 8% (Table 7); attaining 4% mean difference when the same runoff value was considered (Table 7). This change in Kc_{TR} value did not generate a lower simulated yield for the different treatments, obtaining mean differences of around 1% (Table 7). Therefore, this sensitivity analysis on modifying Kc_{TR} for AquaCrop, would allow differences in ET_a/ET_m ratios between the two crop models to be reduced without significant effects on simulating crop yield and being close to the actual yield data.

Finally, Pohanková et al. (2018), testing the performance of several crop models with spring barley, simulated cumulative ET_a from sowing to maturity with AquaCrop between 350 and 400 mm in three locations of Czech Republic. Although both climate conditions and the crop cycle lengths (given in days) are different to those in this research, the ET_a simulated by these authors were similar to those shown in Table 6. In addition, they calculated the actual crop Transpiration (T_a) as 78% of ET_a on average, being close to values found in the present paper (around 75% for AquaCrop).



661 Figure 4. Comparison between observed canopy cover (a-e) and aboveground biomass (f-j) data vs. those
662 simulated by AquaCrop during the three experimental seasons for the five ORDI treatments (ND: a and f;
663 100%: b and g; 90%: c and h; 80%: d and i; 70%: e and j). The dashed line shows a 1:1 function.

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Table 5. Statistical indicators obtained for yield at harvest with AquaCrop and MOPECO models, and both canopy cover and above ground biomass evolution with AquaCrop.

E.Y.	Treat.	Yield at harvest*														Canopy cover[&]					Above ground biomass[&]				
		Obs. (x 10^3 kg ha^{-1})	Sim. (x 10^3 kg ha^{-1})		Dev. (%)		n	RMSE (x 10^3 kg ha^{-1})		MBE (x 10^3 kg ha^{-1})		EF		d		n	RMSE (%)	MBE (%)	EF	d	n	RMSE (x10^3 kg ha^{-1})	MBE (x10^3 kg ha^{-1})	EF	d
			Aq	MO	Aq	MO		Aq	MO	Aq	MO	Aq	MO	Aq	MO										
2015	ND	9.199 (0.619)[#]	9.465	8.936	-2.89	2.86										9	9.2	-4.8	0.93	0.98	8	2.021	-0.956	0.90	0.97
	100%	8.616 (0.457)	9.007	8.496	-4.54	1.39										9	9.2	-4.8	0.93	0.98	8	2.028	-0.713	0.89	0.97
	90%	7.620 (0.362)	7.525	7.667	1.25	-0.62	5	0.339	0.172	0.021	-0.071	0.92	0.97	0.98	0.99	9	11.5	-7.1	0.89	0.97	8	2.168	-1.025	0.85	0.95
	80%	7.367 (0.169)	6.788	7.174	7.87	3.43										9	7.0	-3.1	0.96	0.99	8	1.922	-0.850	0.87	0.96
	70%	6.404 (0.492)	6.316	6.569	1.38	-2.57										9	6.6	-2.4	0.96	0.99	8	1.668	-0.613	0.88	0.96
2016	ND	8.877 (0.296)	9.728	8.647	-9.59	2.59										9	12.8	-4.6	0.89	0.97	8	1.344	0.013	0.94	0.99
	100%	7.985 (0.301)	8.533	7.250	-6.86	9.21										9	13.7	-2.9	0.87	0.97	8	1.612	0.593	0.90	0.98
	90%	7.690 (0.444)	7.709	7.239	-0.25	5.86	5	0.463	0.450	-0.290	-0.398	0.83	0.71	0.95	0.93	9	17.6	-5.3	0.78	0.94	8	1.363	0.032	0.91	0.98
	80%	7.214 (0.215)	7.085	6.758	1.79	6.32										9	23.8	-2.8	0.57	0.88	8	1.333	-0.163	0.91	0.98
	70%	6.331 (0.148)	6.486	6.211	-2.45	1.89										9	22.6	-1.3	0.58	0.88	8	1.540	0.361	0.85	0.96
2017	ND	9.071 (0.511)	9.057	8.994	0.16	0.85										6	7.7	0.0	0.96	0.99	7	1.174	-0.079	0.97	0.99
	100%	8.032 (0.398)	8.088	7.684	-0.69	4.33										6	7.5	-0.6	0.96	0.99	7	0.759	0.181	0.98	1.00
	90%	7.621 (0.250)	8.073	7.350	-5.93	3.56	5	0.256	0.253	-0.194	-0.218	0.91	0.92	0.98	0.98	6	10.0	-3.3	0.93	0.98	7	1.809	-0.969	0.91	0.97
	80%	7.311 (0.232)	7.606	6.966	-4.03	4.72										6	9.8	-3.8	0.93	0.98	7	2.058	-1.052	0.88	0.96
	70%	6.283 (0.295)	6.464	6.230	-2.88	0.84										6	10.8	-1.8	0.91	0.98	7	1.912	-0.562	0.88	0.96

E.Y.: experimental year; Treat.: treatment; *: yield performed against yield commercial grain (12% of water content); [&]: statistical indicators obtained from the simulated values with AquaCrop model; [#]: values between brackets are the standard deviation; Obs.: observed; Sim.: simulated; Aq: AquaCrop; MO: MOPECO; Dev.: deviation; n: number of data point; RMSE: root mean square error; MBE: mean bias error; EF: model efficiency; d: Willmot's index of agreement.

Table 6. Comparison of the evapotranspiration and runoff values simulated by AquaCrop and MOPECO models for the three experimental seasons.

E.Y.	**Treat.**	**Aq. variables**			**Sim. ET_a (mm)**			**Sim. ET_m (mm)**			**Sim. ET_a/ET_m (%)**			**Sim. runoff (mm)**		
		T_a (mm)	**T_a/T_m (%)**	**E_a/E_m (%)**	**Aq**	**MO**	**Dif. Aq-MO**	**Aq**	**MO**	**Dif. Aq-MO**	**Aq**	**MO**	**Dif. Aq-MO**	**Aq**	**MO**	**Dif. Aq-MO**
2015	ND	335.9	96	72	422.1	386.2	9	498.2	387.7	22	85	100	-18	11.9	25.1	-111
	100%	320.6	93	68	401.4	364.3	9	498.2	387.7	22	81	94	-17	11.9	25.1	-111
	90%	281.2	88	68	375.6	332.3	12	497.8	380.7	24	75	87	-16	12.4	25.1	-102
	80%	259.5	85	67	354.4	309.6	13	497.9	376.5	24	71	82	-16	12.4	25.1	-102
	70%	240.5	83	63	330.5	284.0	14	497.7	372.4	25	66	76	-15	12.0	25.1	-109
2016	ND	319.0	94	79	427.1	417.3	2	494.0	433.4	12	86	96	-11	14.0	24.7	-76
	100%	290.7	86	74	386.2	360.3	7	494.0	428.8	13	78	84	-7	14.1	26.3	-87
	90%	259.6	84	73	366.9	354.1	3	493.8	427.8	13	74	83	-11	8.9	0.0	100
	80%	240.5	82	70	344.1	325.0	6	492.3	414.3	16	70	78	-12	6.8	0.0	100
	70%	220.2	78	67	323.9	302.5	7	493.7	414.3	16	66	73	-11	6.7	0.0	100
2017	ND	355.3	98	79	455.2	448.5	1	506.8	448.8	11	90	100	-11	26.4	68.9	-161
	100%	324.9	91	68	399.8	375.3	6	506.9	443.5	13	79	85	-7	22.3	64.6	-190
	90%	278.0	87	70	375.3	360.1	4	506.3	446.9	12	74	81	-9	22.3	52.0	-133
	80%	264.7	84	69	360.2	326.0	9	506.3	423.4	16	71	77	-8	22.4	45.8	-104
	70%	239.7	81	69	335.5	293.8	12	506.3	415.6	18	66	71	-7	22.7	44.4	-96

E.Y.: experimental year; Treat.: treatment; Tw: total water received (mm); I: gross irrigation; Aq.: AquaCrop; MO: MOPECO; Sim.: simulated; ET_a: actual evapotranspiration; ET_m: maximum evapotranspiration; T_a: actual transpiration; T_m: maximum transpiration; E_a: actual evaporation; E_m: maximum evaporation; Dif.: difference in %.

Table 7. Sensibility analysis of the ET_a/ET_m ratios simulated by AquaCrop and MOPECO models during three experimental seasons using the same runoff considered by MOPECO.

E.Y.	**Treat.**	**Sim. ET_a/ET_m (%)[1]**			**Sim. ET_a/ET_m (%)[2]**			**Sim. ET_a/ET_m (%)[3]**			**Crop yield ($x10^3$ kg ha^{-1})[4]**		
		Aq	**MO**	**Dif. Aq-MO**	**Aq**	**MO**	**Dif. Aq-MO**	**Aq**	**MO**	**Dif. Aq-MO**	**Aq (Kc_{TR}=1.00)**	**Aq (Kc_{TR}=1.10)**	**Dif.**
2015	ND	87	100	-14	85	100	-17	88	100	-14	8.940	9.465	-6
	100%	83	94	-14	83	94	-13	85	94	-10	8.776	9.007	-3
	90%	77	87	-13	79	87	-10	81	87	-7	7.627	7.525	1
	80%	73	82	-13	75	82	-9	77	82	-6	7.044	6.788	4
	70%	68	76	-12	70	76	-8	72	76	-5	6.566	6.316	4
2016	ND	88	96	-9	88	96	-10	90	96	-7	9.241	9.728	-5
	100%	80	84	-5	80	84	-4	83	84	-2	8.403	8.533	-3
	90%	73	83	-13	78	83	-6	76	83	-9	7.660	7.709	-1
	80%	69	78	-14	73	78	-7	72	78	-9	7.091	7.085	0
	70%	65	73	-13	69	73	-5	68	73	-7	6.663	6.486	3
2017	ND	98	100	-2	90	100	-10	99	100	-1	8.501	9.057	-6
	100%	86	85	2	81	85	-5	88	85	4	7.810	8.088	-3
	90%	79	81	-2	76	81	-6	81	81	1	7.861	8.073	-2
	80%	75	77	-3	75	77	-3	79	77	2	7.639	7.606	1
	70%	69	71	-3	71	71	0	74	71	4	6.722	6.464	4

E.Y.: experimental year; Treat.: treatment; Sim.: simulated; ET_a: actual evapotranspiration; ET_m: maximum evapotranspiration; [1]: Simulating treatments with the same runoff value computed by MOPECO; [2]: simulating treatments with Kc_{TR}=1.00; [3]: simulating treatments with Kc_{TR}=1.00 and considering the same runoff value as MOPECO; 4: crop yield (12% of water content) simulated by AquaCrop changing the Kc_{TR} value and equal runoff value than MOPECO; Aq: AquaCrop; MO: MOPECO; Dif.: difference in %.

4. Conclusions

The AquaCrop and MOPECO models can be used to evaluate the effect of various irrigation schedules on crop yield and the water productivity response, given that, when both are well calibrated, they show no differences. The results obtained by the AquaCrop model allowed us to compare its performance with a larger number of measured barley growth variables (aboveground biomass, canopy cover and crop yield) than MOPECO (only crop yield). To generate these results, AquaCrop requires a large number of parameters, making its management somewhat more difficult than MOPECO. The range of simulations obtained by AquaCrop is higher than MOPECO, since, under semiarid conditions, it is able to simulate rainfed crop growth. Thus, when the accumulated ET_a/ET_m ratio is lower than 0.5 in one or more crop growth stages, MOPECO's results may not be suitable.

Although AquaCrop software has different options for building an automatic schedule irrigation, the optimized irrigation scheduling based on ORDI and ORDIL methodologies, provided by MOPECO, attained significant irrigation water productivity (IWP). Thus, considering the hypothesis of this research, the IWP simulated by MOPECO was between 8.0% and 28.0% higher than AquaCrop, with different irrigation water amounts applied to the crop. Therefore, if MOPECO is properly parameterized, this methodology can be of great help in establishing irrigation scheduling in areas with limited water resources to improve the IWP. Conversely, AquaCrop users must be sufficiently qualified to plan an irrigation strategy whose IWP levels can be similar than those reached by MOPECO, especially under deficit irrigation conditions.

The effects of four irrigation strategies proposed by ORDIL methodology in both canopy cover and aboveground biomass evolution, as well as the final yield of barley crop during three-field seasons were appropriately simulated by AquaCrop. Therefore, the water deficit levels established by ORDIL for each crop barley development stage were in suitable ranges for simulating this crop with AquaCrop. Finally, we consider that a combination of both crop models may be especially interesting for analysis of the crop's physiological behaviour in response to an optimized deficit irrigation strategy coded by MOPECO. Nevertheless, soil evaporation and crop transpiration data should be used with caution given the differences in findings between the crop models.

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SUPPLEMENTAL MATERIAL

Table A1. Duration of barley phenological stages in Castilla-La Mancha (days) according to development stages for MOPECO and AquaCrop models.

	MOPECO								AquaCrop				Dates	
	K_c (I)	**K_c (II)**	**K_c (III)**	**K_c (IV)**	**K_y (i)**	**K_y (ii)**	**K_y (iii)**	**K_y (iv)**	**CnDv**	**MSsn**	**LSsn**	**Total**	**First day after sowing**	**Maturity**
Start	0	21	39	83	0	37	71	85	0	39	71	00		
End	21	39	83	89	37	71	85	89	39	71	89	89		
							Duration (days)							
2002a	49	60	22	17	102	22	11	13	109	15	24	148	**31st Jan.**	**27th Jun.**
2002b	55	54	26	24	94	34	14	17	109	19	31	159	**10th Jan.**	**17th Jun.**
2002c	76	40	25	23	110	25	11	18	116	19	29	164	**5th Jan.**	**17th Jun.**
2003b	66	47	21	17	103	24	11	13	113	14	24	151	**14th Jan.**	**13th Jun.**
2003b	76	43	22	20	113	23	11	14	119	17	25	161	**2nd Jan.**	**11th Jun.**
2003d	74	43	23	18	110	23	10	15	117	16	25	158	**2nd Jan.**	**8th Jun.**
2003c	73	45	24	19	114	22	10	15	118	18	25	161	**10th Jan.**	**19th Jun.**
2004a	51	64	23	18	108	24	11	13	115	17	24	156	**30th Jan.**	**4th Jul.**
2004c	49	62	32	17	100	35	14	11	111	24	25	160	**12th Jan.**	**20th Jun.**
2004c	56	58	24	16	108	23	11	12	114	17	23	154	**17th Jan.**	**19th Jun.**
2005b	59	41	24	19	95	23	11	14	100	18	25	143	**21st Jan.**	**12th Jun.**
2005e	68	47	23	17	106	25	11	13	115	16	24	155	**7th Jan.**	**10th Jun.**
2005c	67	38	22	23	98	23	13	16	105	16	29	150	**15th Jan.**	**13th Jun.**
2005f	63	43	22	19	99	22	12	14	106	15	26	147	**15th Jan.**	**10th Jun.**
2007c	45	47	23	21	84	25	12	15	92	17	27	136	**7th Feb.**	**22nd Jun.**
2008c	46	52	26	23	85	34	12	16	98	21	28	147	**24th Jan.**	**19th Jun.**
2009g	48	50	20	18	91	20	12	13	98	13	25	136	**1st Feb.**	**16th Jun.**
2009h	39	55	21	20	82	26	15	12	94	14	27	135	**5th Feb.**	**19th Jun.**
2009i	39	53	23	19	87	22	12	13	92	17	25	134	**6th Feb.**	**19th Jun.**
2009c	55	55	24	18	103	24	12	13	110	17	25	152	**19th Jan.**	**19th Jun.**
2010h	67	44	26	22	101	26	16	16	111	16	32	159	**11th Jan.**	**18th Jun.**
2010a	69	51	21	21	113	22	11	16	120	15	27	162	**17th Jan.**	**27th Jun.**
2010g	52	53	21	17	99	22	10	12	105	16	22	143	**2nd Feb.**	**24th Jun.**
2010j	52	42	22	24	87	24	11	18	94	17	29	140	**5th Feb.**	**24th Jun.**
2010k	45	41	31	20	81	30	13	13	86	25	26	137	**5th Feb.**	**19th Jun.**
2011a	61	37	27	26	87	32	17	15	98	21	32	151	**21st Jan.**	**20th Jun.**
2012a	61	42	24	20	93	26	13	15	103	16	28	147	**30th Jan.**	**25th Jun.**
2013a	62	40	29	21	92	32	13	15	102	22	28	152	**30th Jan.**	**30th Jun.**

where K_c (I): Initial; K_c (II): Crop development; K_c (III): Mid-season; K_c (IV): Late season; K_y (i): Vegetative period; K_y (ii): Flowering period; K_y (iii): Yield formation; K_y (iv): Ripening; CnDv: canopy development; MSsn: mid-season; LSsn: late season; 00: First day after sowing; 21: Beginning of tillering: first tiller detectable; 37: Flag leaf just visible, still rolled; 39: Flag leaf stage: flag leaf fully unrolled, ligule just visible; 71: Watery ripe: first grains have reached half their final size; 83: Early dough; 85: Soft dough: grain content soft but dry. Fingernail impression not held; 89: Fully ripe: grain hard, difficult to divide with thumbnail. Irrigable area: a: Las Tiesas; b: Manzanares; c: El Sanchón; d: Daimiel; e: Ciudad Real; f: Magán; g: Almansa; h: Montiel; i: Hellín; j: Ontur; k: El Pedernoso

Table A2. Duration of barley phenological stages in Castilla-La Mancha (GDD) according to development stages for MOPECO and AquaCrop models.

	MOPECO								AquaCrop		
Year	**K_c (I)**	**K_c (II)**	**K_c (III)**	**K_c (IV)**	**K_y (i)**	**K_y (ii)**	**K_y (iii)**	**K_y (iv)**	**CnDv**	**MSsn**	**LSsn**
2002a	296	892	1214	1561	793	1125	1288	1561	875	1103	1509
2002b	256	740	1051	1473	559	952	1165	1473	710	918	1407
2002c	384	754	1031	1400	662	951	1101	1400	716	912	1351
2003b	334	793	1117	1460	666	1007	1190	1460	763	971	1391
2003b	357	751	1076	1448	677	988	1167	1448	722	954	1383
2003d	383	794	1149	1490	706	1019	1206	1490	772	993	1438
2003c	350	771	1134	1521	732	1042	1208	1521	726	995	1451
2004a	297	835	1227	1599	748	1120	1318	1599	812	1088	1529
2004c	232	665	1054	1377	551	918	1172	1377	626	878	1321
2004c	278	705	1031	1336	657	909	1111	1336	666	870	1281
2005b	228	660	1009	1388	582	912	1109	1388	602	853	1294
2005e	216	729	1062	1405	603	951	1143	1405	650	874	1296
2005c	290	672	1000	1438	577	914	1126	1438	598	839	1345
2005f	259	754	1093	1488	647	986	1193	1488	698	927	1395
2007c	295	693	1011	1377	610	936	1111	1377	683	924	1359
2008c	253	705	1033	1374	564	972	1119	1374	683	949	1344
2009g	284	755	1077	1412	661	965	1171	1412	743	948	1377
2009h	222	695	1019	1402	551	905	1153	1402	684	890	1364
2009i	272	798	1175	1550	731	1073	1289	1550	791	1062	1503
2009c	297	793	1178	1524	691	1055	1266	1524	770	1030	1471
2010h	285	734	1021	1361	594	864	1124	1361	718	848	1337
2010a	334	814	1165	1492	757	1041	1241	1492	795	1018	1449
2010g	283	789	1137	1398	733	1038	1218	1398	769	1010	1360
2010j	328	776	1087	1506	708	1000	1212	1506	770	993	1486
2010k	226	660	1053	1363	578	950	1195	1363	648	937	1340
2011a	276	687	1062	1513	567	961	1232	1513	661	935	1465
2012a	283	704	1116	1496	563	962	1206	1496	655	905	1407
2013a	327	728	1059	1437	600	960	1174	1437	705	938	1397
Average	**290**	**744**	**1087**	**1450**	**645**	**981**	**1186**	**1450**	**715**	**949**	**1395**
SD	46	57	64	69	73	64	59	69	66	71	68
CV (%)	16	8	6	5	11	7	5	5	9	7	5

Table A3. Statistical indicators of the crop-water and IWP-water production functions for different irrigation strategies.

PF	**IS**	**SE**	**R^2**	**p-value**	**Parameters**	**Polynomial model values**
Y-GIWD	IS1	393.0	97.3	**	a	2634.020**
					b	28.049**
					c	-0.021**
	IS2	381.1	97.7	**	a	2763.490**
					b	28.887**
					c	-0.014*
	IS3	851.3	92.7	**	a	1708.150*
					b	36.778**
					c	-0.029*
	IS4	724.4	94.4	**	a	2264.760**
					b	25.438**
					c	0.003 ^{ns}
	ORDI	224.1	99.2	**	a	2711.230**
					b	39.640**
					c	-0.035**
	ORDIL	177.6	99.7	**	a	2772.720**
					b	39.262**
					c	-0.033**
IWP-GIWD	IS1	0.19	84.6	**	a	5.06**
					b	-0.01**
	IS2	0.06	90.0	**	a	6.46**
					b	-0.02**
	IS3	0.10	82.1	**	a	4.74**
					b	-0.01**
	IS4	0.07	48.7	**	a	4.12**
					b	-0.0022*
	ORDI	0.02	98.0	**	a	6.50**
					b	-0.01**
	ORDIL	0.01	99.8	**	a	6.22**
					b	-0.01**

PF: production function; Y: yield; GIWD: gross irrigation water depth; IS: irrigation strategy; Aq: AquaCrop; MOP: MOPECO; SE: standard error of the model ($kg\ ha^{-1}$); R^2: coefficient of determination; p-value: model's significance level; ns: not significant, $p>0.05$; *: significant, $0.01\leq p<0.05$; **: highly significant, $p<0.01$