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SOWING STRATEGIES FOR BARLEY (*HORDEUM VULGARE* L.) BASED ON MODELLED YIELD RESPONSE TO WATER WITH AQUACROP

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SUMMARY

AquaCrop, the FAO water productivity model, is used as a tool to predict crop production under water limiting conditions. In the first step AquaCrop was calibrated and validated for barley (*Hordeum vulgare* L.). Data sets of field experiments at seven different locations in four countries (Ethiopia, Italy, Syria and Montana, USA) with different climates in different years and with five different cultivars were used for model calibration and validation. The goodness-of-fit between observed and simulated soil water content, green canopy cover, biomass and grain yield was assessed by means of the coefficient of determination (R^2), the Nash–Sutcliff efficiency (E), the index of agreement (d) and the root mean square error (RMSE). The statistical parameters indicated an adequate accuracy of simulations (validation regression of yield: $R^2 = 0.95$, $E = 0.94$, $d = 0.99$, RMSE = 0.34). Subsequently, sowing strategies in the semi-arid environment of northern Ethiopia were evaluated with the validated model. Dry sowing had a probability of 47% germination failure attributable to false start of the rainy season. On the other hand, delay sowing at the start of the rainy season to eliminate germinating weeds should be kept as short as possible because grain yields strongly reduce in the season due to water stress when sowing is delayed on shallow soils. This research demonstrates the ability of AquaCrop to predict accurately crop performance with only a limited set of input variables, and the robustness of the model under various environmental and climatic conditions.

INTRODUCTION

Geographically, barley (*Hordeum vulgare* L.) is the most widely distributed cereal crop in the world, cultivated from 70 °N up to 53 °S. It is the world's fourth most important crop after rice, wheat and maize in terms of cultivated area (EcoPort, 2010). Beside its use as animal feed, barley is also an important food source. The world average barley

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grain yield in 2008 was 2.8 tons ha^{-1} (FAOSTAT, 2010). However, yields up to 9 tons ha^{-1} are also achievable (Heyland and Werner, 2002).

The morphology of barley is very similar to that of wheat (*Triticum aestivum* L.). In high yielding environments wheat is preferred over barley as a superior source for human food and for its better yield potential. However, in areas with an annual rainfall below 400 mm, barley is favoured for its superior adaptation to drought conditions (Cossani *et al.*, 2007). Barley owes its drought resistance to its extensive root system and its precocity compared with wheat (Fischer and Maurer, 1978; Harlan and Martini, 1936). Nonetheless, significant yield reductions due to water stress have been reported (Jamieson *et al.*, 1995; Wahbi and Sinclair, 2005) with water stress during crop development and anthesis resulting in a reduction of potential grain number per unit land area, while drought stress during the grain filling period reduces mean grain weight (Aspinall, 1965).

A key aspect of an efficient water use lies in enhancing the agricultural water productivity (WP). Under the slogan "*more crop per drop*" FAO has launched the AquaCrop model (Hsiao *et al.*, 2009; Raes *et al.*, 2009; Steduto *et al.*, 2009), software allowing to simulate crop performance for different possible scenarios. AquaCrop proves to be a valuable model especially in cases where water is a key limiting factor. The software only requires a limited set of input variables that are mostly easy to obtain. This makes AquaCrop both a simple and robust model compared with other crop models, although they are still accurate (Raes *et al.*, 2009).

Crop yield prediction models under the given climatic conditions are crucial for planners, extension agents, and relief organisations so that balance of food demand is estimated in relation to the existing population. Preliminary modelling has been performed by Araya *et al.* (2010), based on field experiments conducted in the highlands of Tigray, Northern Ethiopia. However, exhaustive calibration and validation of the AquaCrop model for barley production has not so far been done with multi-location and season experimental data. This research aims at obtaining a complete set of validated crop parameters for barley by analysing field experiments from seven different locations in four countries (Ethiopia, Italy, Syria and Montana, USA). Further-on, as an application, sowing strategies have been assessed with the calibrated model for the highlands in Tigray (Ethiopia).

MATERIALS AND METHODS

Field data

Experimental layout and cultural practices:. Details of the 18 field experiments conducted in different years and at different locations in Ethiopia, Italy, Syria and Montana (USA) are listed in Table 1. Data of the field experiments were obtained from papers (Albrizio *et al.*, 2010; Brown *et al.*, 1987), Master's research dissertations (Delbecque, 2010; Reggers, 2008; Vanuytrecht, 2007; Viaene, 2009) and unpublished data (field codes: MA08, DE08, DE10, ME10, MO77). In Ethiopia, two water treatments (rainfed (RF) and fully irrigated (FI); Table 1) were laid out in a randomised complete block design. Experimental plot size was 3 m × 3 m and treatments were replicated thrice.

Table 1. Details of field experiments with indication of use of data for calibration or validation.

Field code	Location	Coordinates, altitude	Year	Water treatments*	Use of data
ME06	Mekelle (Ethiopia)	13.30 °N–39.29 °E,	2006	FI, RF	Validation
ME07		2212 m asl	2007	FI, RF	Validation
ME10			2010	FI, RF	Validation
DE08a	Dejen (Ethiopia)	13.33 °N–39.37 °E,	2008	FI, RF	Validation
DE08b		2127 m asl	2008	FI, RF	Validation
DE09a			2009	FI, RF	Calibration
DE09b			2009	FI, RF	Calibration
DE10			2010	FI, RF	Validation
MA08a	Maiquiha (Ethiopia)	13.80 °N–39.45 °E,	2008	FI, RF	Validation
MA08b		2078 m asl	2008	FI, RF	Validation
MA09a			2009	FI, RF	Calibration
MA09b			2009	FI, RF	Calibration
IT06	Bari (Italy)	41.05 °N–16.87 °E, 72 m asl	2006	FI RF, PI	Calibration Validation
IT07			2007	FI, RF, PI	Validation
IT08			2008	FI, RF, PI	Validation
SY82a	Breda (Syria)	35.93 °N–37.17 °E,	1982	RF	Validation
SY82b		293 m asl	1982	RF	Validation
MO77	Bozeman (Montana, USA)	45.68 °N–111.03 °W, 1468 m asl	1977	FI	Validation

*FI: full irrigation; RF: rainfed; PI: partly irrigated.

Field crop management practices were performed as per the recommendations of the Tigray Regional Bureau of Agriculture. Land was prepared by ploughing to a depth of 30 cm with "*mahresha*" that was pulled by a pair of oxen. Seeds were sown at a rate of 100 kg ha^{-1} in rows spaced 0.20-m apart. Di-ammonium phosphate (DAP: P_2O_5 46% and N 18%) and urea ($(CO(NH_2)_2)$: N 46%) were applied at a rate of 100 kg ha^{-1} each. DAP was applied all at once during sowing whereas urea was applied half dose at sowing and the second half at tillering stage. In experiments conducted in Bari (Italy), three soil water regimes (RF, FI and 50% of FI, i.e. partly irrigated (PI)) were assigned as main plot factor treatments. Nitrogen fertiliser at a rate of 60 kg ha^{-1} in 2006, and at 120 kg ha^{-1} in 2007 and 2008 were applied for the fertilised sub-plot treatments. Size of experimental plot was 10 m × 14 m where rows were spaced at 0.18-m apart (Albrizio *et al.*, 2010). Similarly, in varietal (Beecher and Arabic Abiad) response to fertiliser experiments performed in Breda, Syria (Brown *et al.*, 1987), P_2O_5 60 kg ha^{-1} at sowing and N 40 kg ha^{-1} with half dose at sowing and the rest at stem elongation were applied. Experimental plot size was 12.5 m × 10.7 m with rows spaced 0.18-m apart. All fields were kept free from pests and diseases.

Soil characteristics:. The soil and soil sampling characteristics for all fields are presented in Table 2. Soil types in Dejen, Maiquiha and Mekelle experimental sites were Luvisol, Leptosol and Cambisol, respectively. In Ethiopia, soil texture and soil water content (SWC) in the root zone throughout the growing season were determined gravimetrically by taking disturbed soil samples at 0–0.20 m, 0.20–0.40 m and (if

Table 2. Soil type, volumetric (%) soil water content at field capacity (FC) and at permanent wilting point (PWP), total available water (TAW), and soil sampling characteristics.

			Volumetric (%) soil water content						
Field code	Textural class	Sampled soil depth (m)	FC	PWP	TAW ($\mathrm{mm\ m^{-1}}$)	Infiltration rate ($\mathrm{mm\ d^{-1}}$)	SWC sampling	pH (pH $\mathrm{H_20}$,1:2.5)	OC (%)
ME06	Clay loam	0.5	34.3	21.5	128	87	*	7.0	1.6
ME07	Clay loam	0.5	38.5	21.0	175	46	*	7.0	1.6
ME10	Sandy clay loam	0.4	34.5	18.0	165	250	*	7.0	1.6
DE08/09a	Loam	0.6	26.3	11.5	148	108	*	8.0	0.5
DE08/09b	Loam	0.6	24.3	10.5	138	300	*	8.0	0.5
DE10	Loam	0.6	29.8	11.27	185	250	*	8.1	0.4
MA08a	Silty loam	0.4	39.0	15.0	240	100	*	7.5	1.0
MA08b	Silty loam	0.4	30.3	11.0	193	150	*	7.5	1.0
IT06/07/08	Sandy clay-loam	0.7	31.0	16.0	150	429	**	7.6	1.9
SY82a/b	Clay loam	1.05	33.0	21.0	120	100	**	**	**
MO77	Silty clay loam	1.8	44.0	21.0	230	120	**	**	**

*Measured gravimetrically at three depths (0–0.2 m, 0.2–0.4 m and, if possible, 0.4–0.6 m) on a one- or two-week basis; **not available.

possible) 0.40–0.60 m depth. Soils in Bari (Italy) were classified as Lithic-Ruptic-Inceptic-Haploxeralfs (Albrizio *et al.*, 2010). For Italy, only the texture class was known. Since soil data were unavailable for Montana and Syria, the soil type was based on soil analysis of experiments conducted at similar locations (Babadoost *et al.*, 2004; Matar and Brown, 1989). The SWC at field capacity (FC), permanent wilting point (PWP) and saturation (SAT) were obtained by means of pedotransfer functions (Saxton and Rawls, 2006). Measurements of infiltration rate by means of the double ring method were taken only for field experiments in Ethiopia. However, since observations showed a large variance, all infiltration rates in Table 2 are default values of AquaCrop for the corresponding soil types. A root restrictive layer was present at the experimental sites of Mekelle (0.5 m), Dejen (0.6 m), Maiquiha (0.4 m) and Italy (0.7 m).

Crop characteristics:. Table 3 summarizes the cultivar, sowing dates, length of the growing cycle (from germination to physiological maturity) in thermal time and the level of sampling for all field experiments used in this research. Measurements of green canopy cover (CC) were obtained by analysing vertically taken pictures with the software Sigma Scan Pro 5.0 (SPSS Inc, 1998) for ME07 and ENVI (Version 3.4, Research Systems) for DE09a, DE09b, MA09a, MA09b and ME10. Leaf area index (LAI) was measured in field experiments conducted in ME06, Italy and Syria. LAI was again converted to green CC according to $\mathrm{CC} = 1 - \exp^{-K\cdot \mathrm{LAI}}$ with the extinction coefficient K assumed to be 0.65 (Belmans *et al.*, 1983; Ritchie, 1972). Dry aboveground biomass was determined by weighing the biomass samples after drying in oven for 48 h at 65 °C. The developmental stages (emergence, flowering, start of senescence and physiological maturity) were followed up during the growing season.

Table 3. Crop characteristics and level of crop sampling.

				Level of sampling		
Field code	Cultivar	Sowing date	Cycle length (GDD)	Canopy cover	Biomass	Crop phenology
ME06	*Birguda*	July 10	1198	**	**	**
ME07	*Birguda*	July 3	1198	**	**	**
ME10	*Birguda*	July 14	1198	**	**	**
DE08a	*Birguda*	July 10	1198	***	**	**
DE08b	*Birguda*	July 18	1198	***	**	**
DE09a	*Birguda*	July 10	1198	**	**	**
DE09b	*Birguda*	July 20	1198	**	**	**
DE10	*Birguda*	July 13	1198	**	**	**
MA08a	*Birguda*	July 11	1198	***	**	**
MA08b	*Birguda*	July 11	1198	***	**	**
MA09a	*Birguda*	July 15	1198	**	**	**
MA09b	*Birguda*	July 22	1198	**	**	**
IT06	*Ponente*	December 7	1520	**	**	**
IT07	*Ponente*	November 27	1520	**	**	**
IT08	*Ponente*	November 24	1520	**	**	**
SY82a	*Arabi Abiad*	November 15	1069	**	**	*
SY82b	*Beecher*	November 15	1069	**	**	*
MO77	*Maris Badger*	April 21	1424	***	***	*

GDD: growing degree days.
**Measured throughout the growing season; *measured at flowering and physiological maturity only; ***not measured throughout the growing season.

Climate and irrigation application:. Rainfall in the Tigray region in Ethiopia is bimodal whereby the long rainy season with 70% of the total amount of rainfall lasts from June to September, and the short season with 30% of annual rainfall lasts from March to May (Araya and Stroosnijder, 2010). Most proportion (80%) of crop production is cultivated in summer (long rainy season; Bewket and Conway, 2007). Even though there is high temporal and spatial seasonal rainfall variability, an average seasonal (June–October) rainfall of 487 mm was observed for the years 1960 to 2010 for Mekelle airport. Nyssen *et al.* (2011) also indicated an average annual rainfall of 500–800 mm for the Tigray region in Ethiopia. The average annual rainfall for the experimental site in Bari (Italy) was 528 mm with most of the rain falling in the autumn and winter months (Albrizio *et al.*, 2010). In Breda, Syria, the long-term mean annual rainfall is 278 mm (Brown *et al.*, 1987).

Weather data for the experimental sites were collected on daily basis. Precipitation and minimum and maximum temperature were recorded at the experimental sites. Missing and additional climatic data were taken from the nearest meteorological station. The daily reference evapotranspiration (*ETo*) was calculated according to the FAO Penman Monteith equation (Allen *et al.*, 1998). Table 4 summarizes the weather characteristics and total applied irrigation over the growing season for all field experiments. The crop was irrigated at different dates after sowing. Irrigation was applied by means of bucket in Ethiopia and by drip in Italy. The irrigation method of Montana is not acknowledged. In experiments conducted in Ethiopia, the amount

Table 4. Summary of data on weather and irrigation applications.

	Total seasonal					Absolute		Mean daily	
		Irrigation (mm)							
Field code	Rainfall (mm)	RF	FI	PI	ET_o (mm)	Minimum temperature (°C)	Maximum temperature (°C)	Minimum temperature (°C)	Maximum temperature (°C)
ME06	521.3	0	170	n.a.	417.0	11.0	28.0	14.4	23.9
ME07	486.0	0	30	n.a.	412.0	12.8	27.0	12.8	24.1
ME10	551.7	0	30	n.a.	308	10.0	26.0	11.4	22.6
DE08a	331.0	0	20	n.a.	394.5	5.8	27.0	12.6	24.1
DE08b	318.0	0	40	n.a.	386.4	5.8	27.0	12.5	24.1
DE09a	301.0	0	25	n.a.	383.1	9.0	30.5	12.6	24.7
DE09b	258.0	0	118	n.a.	377.9	8.0	27.2	12.5	24.2
DE10	430.0	0	24	n.a	276.5	11.0	26.0	13.5	23.7
MA08a	301.0	0	20	n.a.	443.5	6.0	33.5	11.2	26.0
MA08b	301.0	0	40	n.a.	443.5	6.0	33.5	11.2	26.0
MA09a	332.2	0	29	n.a.	444.4	7.5	30.5	12.6	27.5
MA09b	317.4	0	191	n.a.	493.0	7.2	30.5	12.2	27.6
IT06	479.8	0	143	71	462.8	−3.6	35.6	7.6	17.0
IT07	347.3	0	106	53	440.3	0.4	32.4	8.2	18.0
IT08	406.4	0	146	73	462.4	−2.3	35.4	7.9	17.7
SY82 (a+b)	222.1	0	n.a.	n.a.	566.4	−9.8	31.8	2.8	14.8
MO77	214.8	0	250	n.a.	462.9	−0.6	33.3	8.1	23.3

FI: full irrigation; RF: rainfed; PI: partly irrigated; n.a. = not applicable.

of irrigated water (equation 1) was based on the crop evapotranspiration (ETc) and other parameters contributing to the influx of water into the soil of the effective root depth. Reference evapotranspiration was estimated on the basis of the last 20 years of climatic data from the nearby meteorological station (Mekelle Airport). The net irrigation requirement (I_n) was obtained by subtracting the expected gains of water from the crop evapotranspiration:

$$I_n = ETc - P_{\mathrm{eff}} - G_e \tag{1}$$

where I_n is the net irrigation requirement (mm), ETc is the crop evapotranspiration and P_{eff} is the effective rainfall (mm). The equation was simplified by omitting water influx from the groundwater table (G_e) because ground water contribution was nil in all the experiments conducted in Ethiopia. Crop evapotranspiration was calculated on the basis of a single crop coefficient ($Kc = 1.10$) at maximum CC (Allen *et al.*, 1998). During irrigation application, however, the required amount was not applied because water was draining out of the experimental plot. In Bari (Italy) also the amount of irrigation water was based on the daily estimation of the soil water balance in the effective root zone (Albrizio *et al.*, 2010).

Modelling

Model description:. AquaCrop is a water-driven model that simulates crop biomass and yield based on crop transpiration (Raes *et al.*, 2009; Steduto *et al.*, 2009).

Climate, crop, soil and field management are the required input data for the model. Necessary weather data inputs are minimum and maximum temperature, reference evapotranspiration, rainfall and the mean annual atmospheric CO_2 concentration; while soil inputs consist of volumetric SWC at permanent wilting point, at field capacity and at saturation, and saturated hydraulic conductivity at saturation (K_{sat}). Crop parameters are involved to describe phenology, CC, rooting depth, biomass production and harvestable yield. The management component of the model comprises field and water managements. Outputs generated by the model include daily soil water balance, canopy development, biomass production and yield estimation.

The model simulates a daily water balance considering the incoming (rainfall, irrigation water and groundwater) and outgoing water fluxes (evapotranspiration, deep percolation and runoff) within the boundaries of the root zone (Raes *et al.*, 2009; Steduto *et al.*, 2009). The canopy, being an important component of the model, determines the amount of water transpired. This, in turn, determines the amount of biomass produced. The effect of water deficit on the crop is expressed through four stress response coefficients of leaf growth, stomatal conductance, canopy senescence and harvest index (HI). Water stresses have a major impact on productivity and yield depending on timing, severity and duration.

Biomass of the crop is simulated to accumulate over time as a function of the water transpired (Raes *et al.*, 2009; Steduto *et al.*, 2009). Using the normalized water productivity (WP*), the model calculates daily aboveground biomass production from daily transpiration and the corresponding daily evaporative demand of the atmosphere.

Once biomass is calculated by accumulation, the crop yield is obtained by multiplying biomass with HI (Raes *et al.*, 2009; Steduto *et al.*, 2009). Starting from flowering, HI is simulated by a linear increase with time after a lag phase, up to physiological maturity. The reference HI (HI_0) in unstressed conditions serves as the target end point for linear increase. The model adjusts HI in response of the crop-to-water deficits based on the timing and extent of water stress during the crop cycle. Harvest index is adjusted for inhibition of leaf growth, inhibition of stomata, reduction in green canopy duration due to accelerated senescence and for the effect of pre-anthesis stress related to biomass reduction. Pollination failure due to water stress, cold or high temperature is also simulated in terms of impact on HI.

Model calibration and validation:. Data observed during field experiments in 2009 in Dejen and Maiquiha were used for calibration of the conservative crop parameters. The irrigated treatment of IT06 was also used for calibration to determine crop development under non-stressed conditions. Conservative parameters remain constant with time, management practices, geographic location and climate (Raes *et al.*, 2010). The other parameters are user specific, since climate, field management or soil conditions affect these.

Climate, soil, irrigation and initial SWC files were created for all field experiments. A crop file was generated whereby crop development in growing degree days

(GDD) was described from the observed crop development stages under non-stressed conditions (Table 5). In conformity with the literature (EcoPort, 2010), the threshold temperatures for crop development were set at 2 °C (base temperature) to 28 °C (upper temperature). With the exception of time to emergence, crop calendars are identical for similar cultivars. Maximum rooting depth could not be observed in the field due to the presence of root restrictive layers (or no measurements taken). Time to reach maximum effective rooting depth was set between time to maximum CC and start of crop senescence. Effective rooting depth of 1.3 m selected in this paper is in line with Allen *et al.* (1998) that reported a maximum rooting depth of 1.0–1.5 m for barley.

Canopy growth coefficient (CGC), canopy decline coefficient (CDC) and water stress coefficients affecting leaf expansion and early canopy senescence were calibrated in an iterative way on the basis of PI and RF to simulate the development of crop canopy. Water stress factors for canopy expansion of spring wheat (*Triticum aestivum* L.; Raes *et al.*, 2010) were considered as a first step in calibrating thresholds for soil water depletion (p-values) and shape factors for the leaf expansion of barley (Table 6).

Data from DE09 were used to calibrate the WP*. This water productivity was derived by regressing dry aboveground biomass sampled periodically from the crop, which was grown under optimal field management, against crop transpiration normalised for the evaporative demand of the atmosphere (ETo). The daily amount of water transpired was obtained from simulations by AquaCrop. Using default values of the model as a starting point, water stress coefficient and shape factor for stomata closure were selected on the basis of the best match between the observed and simulated biomass development.

Harvest index under non-stressed conditions was taken as HI_0. Water stress coefficients for HI in the model were adjusted through trial and error until the best match between the observed and simulated harvestable yields was obtained.

Conservative crop parameters for barley used in this study are presented in Table 6. Some parameters differ from values proposed previously by Araya *et al.* (2010), when the latter were found to be in contradiction with physiologically meaningful values or field observations.

The proposed crop input parameters for barley (Table 6) were validated on the basis of field data observed in Dejen (2008, 2010), Maiquiha (2008), Mekelle (2006, 2007, 2010), Italy (2006, 2007, 2008), Syria (1982) and Montana (1977). The Goodness-of-fit between the observed and simulated data was assessed by the coefficient of determination (R^2), the Nash–Sutcliffe efficiency (E) (Nash and Sutcliffe, 1970), the index of agreement (d) and the root mean square error (RMSE) (Krause *et al.*, 2005; Loague and Green, 1991).

Sowing strategies

With the validated model, three different sowing strategies in the semi-arid environment of northern Ethiopia were evaluated. Dry sowing before the onset and

Table 5. Crop calendar and crop development characteristics for different cultivars.

						Time from emergence to...				
Cultivar	CC_x (%)	CC_0 (%)	CGC (% °C^{-1} d^{-1})	CDC (% °C^{-1} d^{-1})	Time to emergence (GDD)	CCx (GDD)	Flowering (duration) (GDD)	Senescence (GDD)	Maturity (GDD)	HI0 (%)
Birguda	80–85*	2.7–2.87*	0.870	0.600	45–98-108†	680	769 (160)§	826	1198	29–33¶
Ponente	95	3	0.670	0.600	100–226‡	893	940 (180)	1063	1520	44
A. Abiad	80	2.7	0.870	0.600	134	680	696 (160)	704	1069	45
Beecher	80	2.7	0.870	0.600	134	680	696 (160)	704	1069	38
M. Badger	95	3	0.670	0.600	185	893	940 (180)	973	1424	52

CC_x: maximum canopy cover; CC_0: initial canopy cover; CGC: canopy growth coefficient; CDC: canopy decline coefficient.

*85 and 2.87 for DE09b and ME07; 80 and 2.7 for others.

†45 for DE09b; 108 for MA09b; 98 for others.

‡100 for IT06, 226 for IT07 and IT08.

§Values in parentheses indicate duration of flowering.

¶29 for ME06 and ME07; 33 for others.

Table 6. Crop input parameters for barley in AquaCrop.

Description	Value
Crop transpiration coefficient (Kcbx) (-)	1.10
Normalised water productivity (WP*) (g m^{-2})	15
Base temperature (°C)	2
Cut-off temperature (°C)	28
Water stress factors	
Upper and lower threshold of soil water depletion factor (*p*) for leaf expansion (-)	0.20–0.65
Shape factor for water stress coefficient for leaf expansion (-)	3.0
Upper and lower threshold of soil water depletion factor (*p*) for stomatal closure (-)	0.60–1.00
Shape factor for water stress coefficient for stomatal closure (-)	3.0
Upper and lower threshold of soil water depletion factor (*p*) for early crop senescence (-)	0.55–1.00
Shape factor for water stress coefficient for early crop senescence (-)	3.0
Upper and lower threshold of soil water depletion factor (*p*) for pollination failure (-)	0.85–1.00
Possible increase in HI due to water stress before flowering (%)	5
Coefficient for positive impact of restricted vegetative growth during yield formation on HI (-)	10 (small)
Coefficient for negative impact of stomatal closure during yield formation (-)	5 (moderate)
Anaerobic point (vol.%)	15

wet sowing at the onset of the rainy season were considered. Delayed wet sowing was also evaluated since farmers in the area commonly practice this strategy to remove geminated weeds before sowing. Various strategies were assessed by simulating their risk of germination failure and the quantity of grain yield.

A long series of historical climatic data (daily minimum and maximum air temperature (°C) and daily rainfall (mm)) for the period 1960–2010 at Mekelle Airport (13°28′ N, 39°31′ E, 2257 m asl) was used for the evaluation of sowing strategies. Climatic data of 1980, 1986, 1989 and 1990 were missing and therefore excluded from the analysis. Seasonal rainfall for all the years was tested for data homogeneity using the Rainbow software (Raes *et al.*, 2006). Seasonal rainfall events were normally distributed with $R^2 = 0.95$.

The characteristics of the short-season local variety (*Birguda*) were considered for simulations. Dominant soils for the study area are loamy textured. In the simulations, the soil characteristics of DE10 (Table 2) were taken into account. Although most soils are shallow (up to 0.6 m), simulations were carried out for shallow (0.5-m) and deep (1.3-m) loamy soils.

Simulations started on 1 May at the end of the dry season when the soil was near wilting point. Seeds sown before the onset of the rainy season would only germinate when the topsoil became sufficiently wet. This was simulated by assuming germination when 25-mm rainfall or more occurred in five successive days. Since local farmers would never sow before June 21, this date was considered as the earliest possible date for dry sowing. Wet sowing was determined by the third occurrence of 25-mm rainfall in five successive days. This enabled the rain to reach deep layers to make a good wetting front (Kipkorir *et al.*, 2007; Raes *et al.*, 2004). Delayed wet sowing occurred 10, 20, 30 and 40 days later than dry sowing.

Table 7. Simulated and observed dry aboveground biomass (B) and yield (Y) for calibrated experiments in different years and locations.

Code	Water treatment	Obs. B (tons ha^{-1})	SD (tons ha^{-1})	Sim. B (tons ha^{-1})	Obs. Y (tons ha^{-1})	SD (tons ha^{-1})	Sim. Y (tons ha^{-1})
DE09a	FI	6.74	0.66	7.29	2.16	0.23	2.41
	RF	7.43	0.11	7.18	2.17	0.11	2.36
DE09b	FI	8.02	2.13	7.64	3.42	0.71	2.51
	RF	6.61	1.19	6.78	2.60	0.83	2.05
MA09a	FI	5.16	0.89	5.69	1.45	0.11	1.78
	RF	4.97	1.50	5.50	1.32	0.45	1.63
MA09b	FI	4.94	0.85	5.48	2.17	0.04	1.80
	RF	3.26	0.38	4.53	1.13	0.05	1.18
IT06	FI	12.69	n.a.	12.41	5.57	n.a.	5.46

FI: full irrigation; RF: rainfed; n.a.: not acknowledged.

RESULTS AND DISCUSSION

Modelling

Model calibration:. The calibration results were based on the field experiments conducted at the experimental sites of Dejen and Maiquiha in 2009 and of Italy in 2006 for the irrigated treatment. Since the calibration of Italy was only for the purpose of describing crop development under non-stressed conditions, only calibration results for aboveground biomass at harvest and yield are presented here (Table 7 and Figure 4). The simulated and observed SWC in the root zone is presented in Figure 1, and the development of CC and biomass throughout the growing season for Dejen and Maiquiha are presented in Figures 2 and 3, respectively. Finally, the goodness-of-fit parameters are summarized in Table 8.

The simulated SWC fits well in describing the evolution of the root zone SWC throughout the growing season (Figure 1). The observed SWC at 58 days after sowing for DE09b and 24 days after sowing for MA09a are significantly higher than the simulation. This could not be the result of a rain shower during sampling, since no rainfall was recorded on the considered days. A possible explanation could be insufficient drying of the samples due to technical restrictions. For DE09b this outlier resulted in insufficient goodness-of-fit (Table 8). Nonetheless, visual assessment of the goodness-of-fit still indicates that the root zone SWC was well simulated.

Irrigation activities in experiments conducted in Ethiopia started late in the growing season. AquaCrop does not simulate irrigation applied after the date of maturity (72 days after sowing for MA09a and MA09b, 76 days after sowing for DE09a and DE09b; Figure 1). Therefore, the statistical parameter calculations (Table 8) did not include the SWC data beginning from the period where AquaCrop did not simulate the applied irrigation any longer.

The development of the green CC is presented in Figure 2. Plots for DE09b were characterised by a slightly higher CC, earlier emergence and slightly higher initial CC. For Dejen, both observations and simulations indicate only little water stress for RF plots compared with FI plots. On the contrary, both FI and RF plots in Maiquiha

Table 8. Statistical parameters of goodness of fit for calibration of the soil water content (SWC) in the root zone, green canopy cover (CC), dry aboveground biomass (B) over growing period, and biomass at harvest and yield for barley.

Parameter		R^2 (-)	E (-)	d (-)	RMSE
SWC (%)*	Mean	0.87	0.72	0.94	13.05
	Min.	0.66	0.27	0.87	9.97
	Max.	0.98	0.95	0.99	17.50
CC (%)	Mean	0.93	0.90	0.98	8.36
	Min.	0.81	0.68	0.93	4.85
	Max.	0.98	0.98	0.99	13.79
Biomass (tons ha^{-1})	Mean	0.93	0.83	0.96	1.46
	Min.	0.86	0.41	0.90	0.64
	Max.	0.97	0.95	0.99	6.31
Biomass at harvest (tons ha^{-1})		0.98	0.95	0.99	0.59
Yield (tons ha^{-1})		0.99	0.99	1.00	0.42

*Without IT06FI, since no observed SWC.

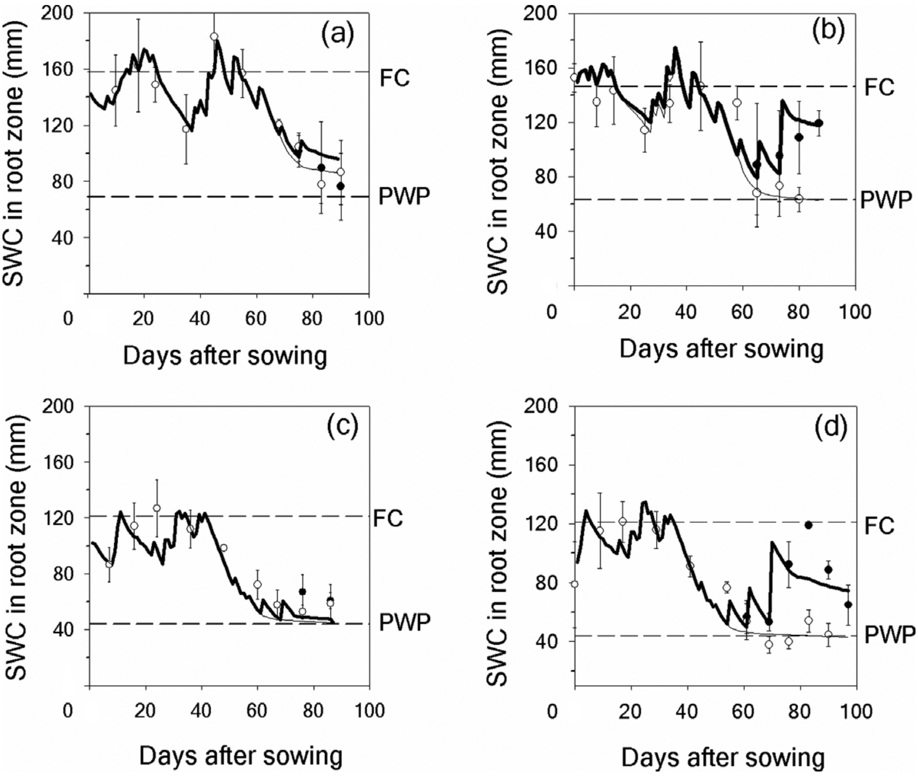

Figure 1. Observed (symbols) and simulated (lines) soil water content (SWC) in the root zone under fully irrigated (dark circle and bold line) and rainfed (white circle and light line) conditions for different field experiments. FC = field capacity; PWP = permanent wilting point. (a) = DE09a, (b) = DE09b, (c) = MA09a, (d) = MA09b. Vertical bars indicate ± standard deviations.

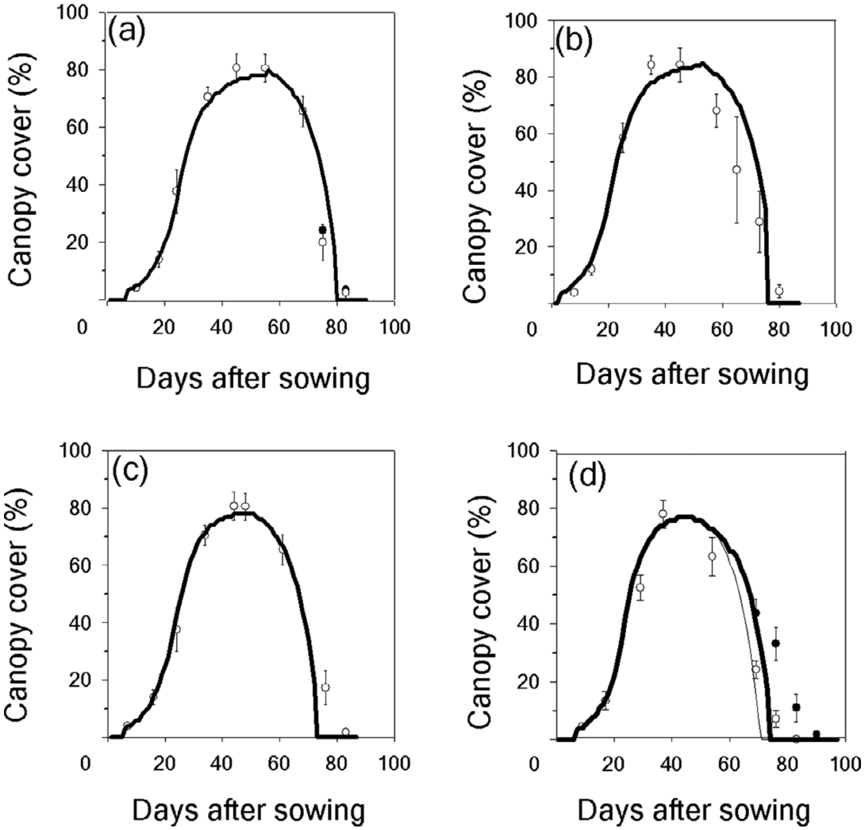

Figure 2. Observed (symbols) and simulated (lines) green canopy cover (CC) under fully irrigated (dark circle and bold line) and rainfed (white circle and light line) conditions for different field experiments. (a) = DE09a, (b) = DE09b, (c) = MA09a, (d) = MA09b. Vertical bars indicate ± standard deviations.

experienced a significant amount of water stress resulting in early crop senescence. Green CC throughout the growing season was well calibrated in all cases (Figure 2 and Table 8). Observations of DE09b suggest early crop senescence, but this is not seen in simulations. Comparison of the simulated and observed SWC (Figure 1) indicates that the root zone SWC was, however, not overestimated.

Figure 3 indicates that biomass development throughout the growing season is well simulated. Yield for DE09b is underestimated, whereas it is overestimated for MA09a (Table 7). These over- and underestimation can be partly subscribed to large standard deviations, and could also be the result of a deviation in the observed HI_0 between different field experiments, while the HI_0 in AquaCrop was set identical for all field experiments. The simulated biomass in most cases is in the range of the observed biomass, whereas yield simulations deviate to some extent from observed yields. Final biomass and yield are also well in range with the observed values (Figure 4). The average statistical parameters of goodness-of-fit (Table 8) indicate a good match between the simulated and observed SWC, CC, biomass and yield using crop input parameters listed in Table 6.

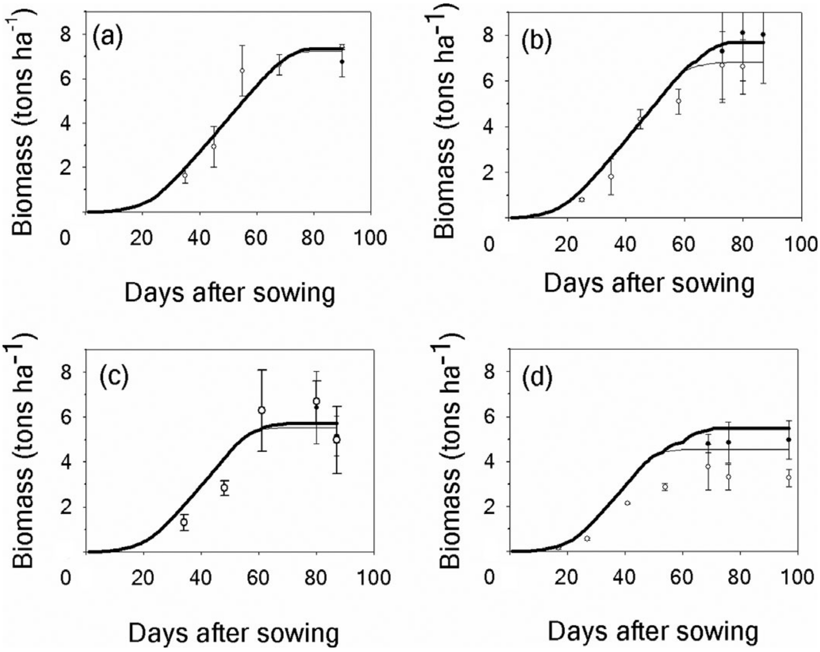

Figure 3. Observed (symbols) and simulated (lines) aboveground dry biomass under irrigated (dark circle and bold line) and rainfed (white circle and light line) conditions for different field experiments. (a) = DE09a, (b) = DE09b, (c) = MA09a, (d) = MA09b. Vertical bars indicate ± standard deviations.

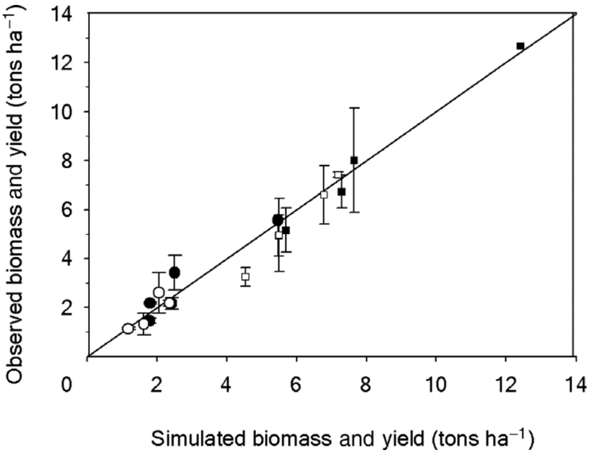

Figure 4. Simulated and observed biomass (square) and yield (circle) in fully irrigated (dark) and rainfed (white) treatments for the calibrated fields. Vertical bars indicate ± standard deviations.

Model validation:. The simulated biomass and yield at harvest for all field experiments discussed in this paper are plotted against their observed values (Figure 5). The corresponding statistical parameters for goodness-of-fit are presented in Table 9.

Table 9. Statistical parameters of goodness-of-fit in the validation of AquaCrop for barley.

Parameter	R^2 (-)	E (-)	d (-)	RMSE (tons ha^{-1})
Biomass at harvest (with ME07)	0.78	0.72	0.94	1.30
Biomass at harvest (without ME07)	0.85	0.81	0.96	1.11
Yield	0.95	0.94	0.99	0.34

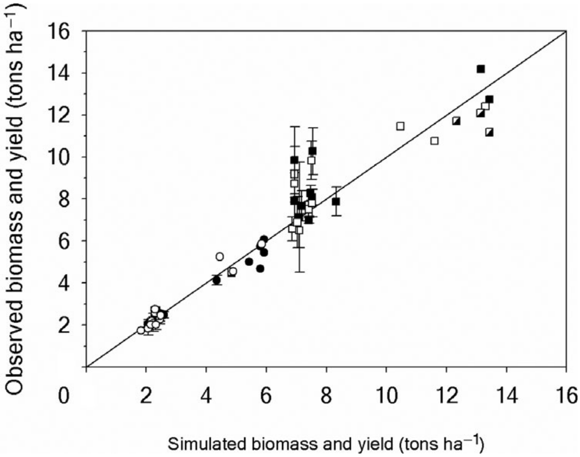

Figure 5. Simulated and observed biomass (square) and yield (circle) in fully irrigated (dark), partly irrigated (right half dark) and rainfed (white) treatments for the validated fields. Vertical bars indicate ± standard deviations.

The biomass and yield simulations for the experiments in Ethiopia are in general well in line with the observed biomass and yield (Table 10 and Figure 5) although biomass simulations for ME07 are much lower than the observations. Reggers (2008), however, mentioned that the observed biomass for ME07 was most likely overestimated. Biomass simulations for MA08a and MA08b are also underestimated to some extent, but they are characterised by higher standard deviations. This could probably be due to overestimation of the observed biomass.

Standard deviations for biomass and yields in Italy are not known; consequently, it was found more difficult to interpret the accuracy of predictions of crop performance. However, biomass and yields of FI plots gave good results. The effect of water stress was well validated for RF plots except for IT06 where the severity of water stress seems to be overestimated. This is probably due to an underestimation of the soil water holding capacity for IT06. Only one soil file was generated for the three consecutive growing seasons, but the root zone SWC could not be validated throughout the growing season. As such, variation in soil characteristics due to field heterogeneity between different field experiments could not be accounted for. Plots receiving only 50% of FI (PI) gave intermediate results. IT06 was well validated for both biomass and yield. The observed biomass for IT07 was most likely underestimated, since it was lower than the RF plots and the yield prediction is acceptable. The biomass prediction for PI for IT08 gave good results. Crop performance in Syria and Montana is also acceptable in all cases.

Table 10. Observed and simulated biomass (B) at harvest and yield (Y) of barley for validated experiments in different years and locations.

Code	Water treatment	Obs. B (tons ha^{-1})	SD (tons ha^{-1})	Sim. B (tons ha^{-1})	Obs.Y (tons ha^{-1})	SD (tons ha^{-1})	SimY (tons ha^{-1})
ME06	FI	7.13	2.62	7.10	2.05	0.21	2.06
	RF	6.50	0.81	7.09	1.84	0.31	2.06
ME07	FI	10.27	1.11	7.54	2.21	0.17	2.23
	RF	9.83	0.92	7.50	2.13	0.43	2.23
ME10	FI	8.29	0.36	7.47	2.48	0.15	2.58
	RF	6.9	1.22	7.03	2.01	0.24	2.32
DE08a	FI	7.00	0.17	7.41	2.36	0.18	2.45
	RF	7.51	0.38	7.41	2.26	0.21	2.45
DE08b	FI	7.67	0.72	7.18	2.24	0.14	2.34
	RF	6.58	0.57	6.86	2.18	0.14	2.17
DE10	FI	8.08	0.36	7.52	2.55	0.09	2.48
	RF	7.80	0.66	7.52	2.46	0.06	2.48
MA08a	FI	9.84	1.59	6.94	2.59	0.17	2.29
	RF	9.18	1.32	6.94	2.59	0.14	2.29
MA08b	FI	7.89	1.35	6.94	2.51	0.37	2.29
	RF	8.74	0.65	6.94	2.75	0.06	2.29
IT06	PI	11.71	n.a.	12.33	5.00	n.a.	5.42
	RF	11.46	n.a.	10.47	5.25	n.a.	4.45
IT07	FI	12.74	n.a.	13.43	6.07	n.a.	5.92
	PI	11.18	n.a.	13.43	5.45	n.a.	5.92
	RF	12.40	n.a.	13.30	5.86	n.a.	5.84
IT08	FI	14.18	n.a.	13.15	5.74	n.a.	5.79
	PI	12.09	n.a.	13.14	4.67	n.a.	5.79
	RF	10.76	n.a.	11.60	4.54	n.a.	4.89
SY82a	RF	4.47	n.a.	4.84	2.01	n.a.	2.15
SY82b	RF	4.54	n.a.	4.84	1.74	n.a.	1.82
MO77	FI	7.88	0.68	8.32	4.13	0.23	4.34

FI: full irrigation; PI: 50% of full irrigation; RF: rainfed; n.a.: not acknowledged.

It is clear from both Figure 5 and Table 9 that the proposed crop input parameters indicated in Table 6 can predict barley biomass and yield acceptably well. Statistical parameters for yield are better than for biomass. However, statistical parameters for biomass improved to a large extent when the overestimated observed biomass for ME07 was omitted.

Sowing strategies

Mean seasonal (June–September) rainfall amount for the Mekelle airport meteorological station was 487 mm. Seasonal rainfall was subjected to high fluctuations and it was below the mean (with negative standardised rainfall anomaly (SRA)) in 42.6% of the cases. Particularly, years 1964, 1979, 1984, 2004 and 2008 had SRA values less of than -1, indicating years with less amount of seasonal rainfall. Von Braun (1991) reported that a 10% decrease in seasonal rainfall from the long-term average generally translates into a 4.4% decrease in the country's food production. In relative terms, however, rainfall distribution in the season is more important than

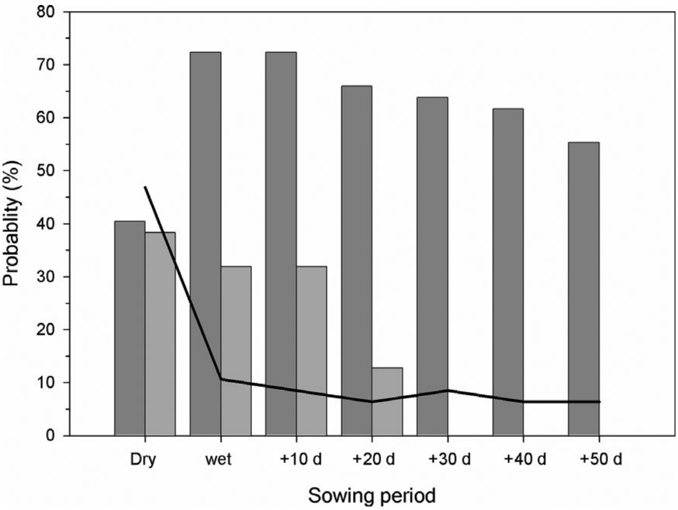

Figure 6. Probability on failure of germination (line) and probability of high grain yield on a deep (dark bars) and shallow (light bars) loamy soil for dry sowing, wet sowing and for delayed sowing by 10, 20, 30, 40 and 50 days.

the amount of rainfall since poor crop harvests are not uncommon in cases with above mean rainfall. Tilahun (2006) also stated the effectiveness of rainfall being more dependent on timing than on its totality during the season. This was also confirmed by the simulations with AquaCrop.

The effect of sowing strategy on germination was significant. In both shallow and deep soils, dry sowing resulted in 47% of germination failure (Figure 6). The failure was due to a false start of the rainy season that caused the very young seedling to die after germination. Germination failure as a result of dry sowing is encountered when the rainy season does not start off immediately (Kipkorir *et al.*, 2007). Germination failure dropped to around 10% for wet and delayed wet sowing (Figure 6).

When the crop can germinate, the grain yield is strongly affected by the time of sowing and soil depth (Figure 6 and Table 11). The probability of high yields (>1.8 tons ha^{-1}) increased from 40% for dry sowing to 72% for wet sowing in deep soils (Table 11). Even when delaying sowing up to one month, the probability does not drop strongly. A too long delay in sowing (50 days and more) results in strong yield decline due to crop maturity after the end of the rainy season. However, on shallow soils high yields are more difficult to obtain because of the limited water storage capacity of the root zone. Dry spells within the season strongly reduce yields. Delaying sowing by more than 10 days resulted in a steep drop in grain yields.

CONCLUSION

AquaCrop is a valuable tool for predicting crop performance under various levels of water stress. AquaCrop was calibrated and validated for barley crop. The proposed conservative crop parameters (Table 6) accurately predicted the SWC, CC, biomass and yield of barley.

Table 11. Probability (%) for different levels of grain yield.

Grain yield (tons ha^{-1})	Dry sowing	Wet sowing	Delay +10 d	Delay +20 d	Delay +30 d	Delay +40 d	Delay +50 d
Deep soil							
>1.8	40.4	72.3	72.3	66.0	63.8	61.7	55.3
1.1–1.8	12.8	12.8	14.9	23.4	21.3	19.1	19.1
0.5–1	0.0	4.3	4.3	2.1	4.3	8.5	12.8
<0.5	0.0	0.0	0.0	2.1	2.1	4.3	6.4
No germination	46.8	10.6	8.5	6.4	8.5	6.4	6.4
Shallow soil							
>1.8	38.3	31.9	31.9	12.8	0.0	0.0	
1.1–1.8	12.8	38.3	38.3	34.0	14.9	8.5	
0.5–1	0.0	10.6	10.6	21.3	12.8	8.5	
<0.5	2.1	8.6	8.6	25.5	63.9	78.8	
No germination	46.8	10.6	8.5	6.4	8.5	6.4	

The general applicability of this research was secured by using data of field experiments conducted at seven different locations in four countries (Ethiopia, Italy, Syria and Montana, USA) with different climates over consecutive growing seasons and with five different cultivars. As such, AquaCrop can be considered a robust model requiring only a limited number of input parameters besides its good accuracy.

Sowing strategies during the main rainy season indicated that dry sowing is very risky and results half of the time in germination failure. Wet sowing at the onset of the rainy season or a small delay of sowing is a good strategy to reduce the risk of crop failure and to harvest acceptable high yields. Sowing later than 10 days after the onset is not advisable in shallow soils because of the limited water storage capacity of the root zone. In deeper loamy soils, delays up to one month still allow high yields. Delayed sowing allows farmers to plough under the germinated weeds at the start of the rainy season.

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