AquaCrop parametrisation for quinoa in arid environments

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Highlights

- *13% yield losses when comparing progressive drought with full irrigated treatments.*
- *25% water savings when comparing progressive drought with full irrigated treatments.*
- *Calibrated and validated NRMSE values of 10.0% and 13.3% for biomass, respectively.*
- *Calibrated and validated NRMSE values of 19.2% and 7.3% for yield, respectively.*

Abstract

The resilience of quinoa to drought stress conditions makes the crop suitable for the Sahel region. It can support grain production during the dry season and be considered an alternative crop for alleviating food insecurity within the region. Given the importance of this crop outside the indigenous cultivation area, there is a requisite for the development of crop models to facilitate further expansion of quinoa along the Sahel region. Crop water models are of interest due to increasing pressure on water resources, and the portrayal of irrigation scheduling as the best option for water optimisation. The AquaCrop model was selected, as this model simulates crop development and derives both optimal frequencies and net applications of irrigation. Due to limited water resources in the region, different irrigation regimes [full irrigation, progressive drought (PD), deficit irrigation and extreme deficit irrigation] were proposed for analysing yield and biomass responses to water stress conditions. Results suggest that yields were stabilised at around 1.0 Mg ha^{-1} under PD, thereby prioritising maximum water productivity rather than maximum yields. Water optimisation was attained by watering less at a suggested 310 mm, but with more frequent irrigation events, 28 rather than 20.

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Introduction

Africa is considered as the world's most vulnerable continent to climate change due to a low adaptive capacity (Niang *et al.*, 2014). The Sahel region, consisting of countries within the southernmost parts of the Sahara Desert, is considered a hotspot of climate change, with unprecedented future climate (Mora *et al.*, 2013). Future trends for precipitation over West Africa show an inter-annual variability increase of up to 40% by the end of the century (Yabi and Afouda, 2012; Niang *et al.*, 2014). Specifically, for Burkina Faso, regional climate models estimate a significant precipitation decline over the 2021-2050 period (Ibrahim *et al.*, 2014). Changes in the onset/offset of the rainy season are also being observed. Emphasis on the impact of onset delay has been shown, thereby shortening the growing season of rainfed crops (Biasutti and Sobel, 2009; Alvar-Beltrán *et al.*, 2020a).

Traditional water harvesting practices (zaï, half-moons and stone bunds, among others) are widely used in Burkina Faso to cope with the high rainfall variability (Barbier *et al.*, 2009; Sawadogo *et al.*, 2008). Nonetheless, these techniques are inefficient for coping with changing precipitation patterns. Moreover, only 0.9 % of the surface area for cultivation in the country is irrigated, with most of the area based on surface irrigation systems (FAO, 2011). Furthermore, both the proliferation of and lack of imposed authority on uncontrolled pumping, particularly from small reservoirs and groundwater, are exacerbating the pressure on water resources (de Fraiture, 2014). For this reason, appropriate water management strategies are vital for stabilising crop yields, besides sustaining increasing water demands.

Very few modelling studies, using Hydrus and Cropwat programs, are available with different irrigation regimes and crops for

Burkina Faso. Mermoud *et al*. (2005) affirm that for onion in Kamboinse, less frequent-weekly irrigation increases water storage in the root zone in comparison to daily irrigation that leads to higher evaporation rates due to direct soil evaporation. Wang *et al*. (2009) have estimated the water demand of different rainfed and vegetable crops in Ouagadougou and Banfora, thereby concluding that tailored irrigation regimes are necessary for satisfying crop water demands during critical growing stages. In arid and semi-arid environments water used for crop growing has been scarcely examined from a crop modelling perspective. Overall, there is a perquisite to expand our insights by identifying constraints to crop production and water productivity; particularly relevant for arable crops, for which there is not yet documented literature in the Sahel.

The AquaCrop model is a crop water productivity model developed by the Food and Agriculture Organisation (FAO). This model simulates biomass and yield responses to water for multiple crop and different environmental conditions. It allows to optimize water resources in regions where water is a limiting factor for crop production (Raes *et al*., 2009; Steduto *et al*., 2009; FAO, 2019). Scant use of the AquaCrop model has been made in Sub-Saharan Africa, with most of the research focusing on the modelling of vegetable crops (Karunaratne *et al*., 2011; Sam-Amoah *et al*., 2013; Darko *et al*., 2016). Some validations of the model have been conducted on arable crops, *e.g*. in Nigeria with different levels of nitrogen fertilisation for rainfed maize, as well as in Ethiopia testing deficit irrigation regimes on barley and sorghum (Araya *et al*., 2010; Araya *et al*., 2016; Akumaga *et al*., 2017). Regarding the crop of interest, quinoa (*Chenopodium quinoa* Willd.), both calibration and validation of the model have only been performed in the environment of origin, namely, the Bolivian Altiplano (Geerts *et al*., 2009; Geerts *et al*., 2010).

Given that the AquaCrop model was used previously on quinoa to estimate acceptable economic losses under deficit irrigation in Bolivia, the objective of the present study was to calibrate and validate the AquaCrop model for quinoa under different irrigation regimes during the dry season in Burkina Faso. Additionally, since quinoa is a new crop for the country, optimal irrigation scheduling is crucial for saving farmers expenses, improving yields and preserving water resources. Finally, due to its rapid expansion in new environments facing food insecurity and water related issues, the parametrization of the model's phenological and physiological parameters becomes imperative.

Materials and methods

Experimental site

Quinoa yields and biomass were simulated using the AquaCrop model (version 6.0, 2017) for one location, Institut de l'Environnement et de Recherches Agricoles (INERA), Farako-Ba research station, Bobo Dioulasso (11° 05' N, 4° 19' W, 421 m), Burkina Faso. The two-year experiments were performed in a typical Soudanian savannah climate, with warm mean temperatures and a well-defined rainy season (May-October). The sowing dates were 25/10/2018 and 19/11/2018 for the calibration, and 4/11/2017 and 8/12/2017 for the validation (Table 1). Four different irrigation regimes were used according to the crop evapotranspiration (*Etc*) and were determined as follows: i) full irrigation (FI) (the crop was fully supported by applied water, 100% *Etc*, throughout the growing cycle); ii) progressive drought (PD) (water was withheld in short amounts throughout the growing cycle and the overall *Etc* was 70-90%); iii) deficit irrigation (DI) (the crop was exposed to a certain level of stress of about 50% *Etc* throughout the growing cycle); iv) extreme deficit irrigation (EDI) (the crop was exposed to a very high level of stress, ≤40% *Etc*, being just above wilting point throughout the growing cycle).

Table 1. Crop evapotranspiration (*Etc*) for different irrigation regimes: full irrigation (FI), progressive drought (PD), deficit irrigation (DI) and extreme deficit irritation (EDI).

Experimental year	Calibrated values 2018-2019					Validated values 2017-2018				
Irrigation treatment	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}
Sowing date	25/10	25/10	19/11	19/11	4/11	4/11	4/11	8/12	8/12	8/12
Transplanting date	12/11	12/11	7/12	7/12	22/11	22/11	22/11	26/12	26/12	26/12
Irrigation regimes	FI	EDI	FI	DI	PD	PD	DI	PD	DI	EDI
Irrigation + Precipitation (mm)	421	154	409	191	350	263	198	310	202	98
∑ irrigation events	20	22	21	23	30	29	28	20	21	18
∑ *Etc* (mm)	394	394	416	416	387	387	387	388	388	388
Etc (%)	107	39	98	46	90	70	51	80	52	31
Total water savings (%)	-	62.9	-	54.0	15.7	34.5	52.3	25.3	51.3	76.4
Avg. irrigation (1-3 weeks) (mm)	13.8	7.6	19.3	5.1	7.8	6.6	5.7	18.2	7.7	6.0
Avg. irrigation (4-7 weeks) (mm)	28.0	6.9	18.7	10.0	13.3	11.4	7.7	16.0	12.7	4.7
Avg. irrigation (8-10 weeks) (mm)	24.7	6.5	21.3	10.9	17.5	11.3	9.3	11.2	5.9	6.4
Mean T flowering (°C)	34.6	34.6	33.2	33.2	33.5	33.5	33.5	34.8	34.8	34.8
Max T flowering (°C)	35.5	35.5	35.0	35.0	36.5	36.5	36.5	35.5	35.5	35.5
∑ Irrigation flowering (mm)	73.7	15.9	51.5	36.1	46.3	28.4	18.7	35.4	24.5	19.2
∑ *Etc* flowering (mm)	63.5	63.5	61.5	61.5	49.0	49.0	49.0	53.9	53.9	53.9

Full irrigation (FI) was applied in treatments 1 and 3, progressive drought (PD) in treatments 5, 6 and 8, deficit irrigation (DI) in treatments 4, 7 and 9, and extreme deficit irrigation (EDI) in treatments 2 and 10. The crop evapotranspiration (*Etc*) was calculated by dividing the sum of observed irrigation and precipitation by the accumulated crop evapotranspiration (*Etc*) simulated in AquaCrop as a percentage. Finally, the total water savings were calculated as the difference between the average of full irrigation treatments (T_1 and T_3) and the rest of the irrigation regimes (T_2, T_4, T_5, T_6, T_7, T_8, T_9, and T_{10}).

While the number of treatments (T) used for the calibration was four ($T_{1\text{-}4}$), for the validation was six ($T_{5\text{-}10}$). Overall, the number of treatments were substantiate to draw robust conclusions for both the calibration and validation. In addition, to verify that the selected sowing dates did not have an impact on yields and biomass, and on the crop-water needs, a set of simulations were conducted with net irrigation requirements (defined as the total amount of irrigation water required to keep the water content in the soil profile above an specific threshold). In that way, AquaCrop estimated the amount of net irrigation necessary to avoid any type of water stress throughout the growing cycle, such that water was not a limiting factor in terms of biomass and yield for achieving the potential crop production.

The experimental field used for the calibration (2018-2019) of the AquaCrop model was set-up in a block-design with three irrigation regimes (FI, DI, EDI, corresponding to treatments T_1 to T_4) each having eight replicates (refer to Table 1 of the manuscript). The validation (2017-2018) was similarly made up of three irrigation regimes (PD, DI and EDI, corresponding to treatments T_5 to T_{10}) but, unlike calibration, each treatment was replicated nine times (refer to Table 1 of the manuscript) . The plot sized 12.5 m^2 (2.5 m width × 5.0 m length) for the calibration and 7.5 m^2 (3.0 m width × 2.5 m length) for the validation. The distance between rows was 50 cm with plants spacing 10 cm from each other. The selected quinoa variety was cv. *Titicaca*, characterised by a short growing cycle (approximately 90 days). As transplanting took place 18 days after sowing-DAS, simulations with AquaCrop started on the following dates: 12/11/2018 (for the 25/10/2018 sowing), 22/11/2017 (for the 4/11/2017 sowing), 7/12/2018 (for the 19/11/2018 sowing) and 26/12/2017 (for the 8/12/2017 sowing).

Agronomic practices and irrigation scheduling

The soil was amended with grassland compost (50.2% organic matter) at a rate of 5000 kg ha^{-1} and mixed with Burkina phosphate rock - BPR (26.8% phosphoric anhydride-P_2O_5) at a rate of 400 kg ha^{-1} and broadcasted a week before sowing. The amount of irrigation was calculated using a water counter placed (⌀ 1/2") at the entry of each irrigation block. The timing of irrigation was carried out at post meridiem to avoid losses from direct evaporation, and at a frequency of two to three irrigation events per week depending on the phenological phase and irrigation regime. The drip irrigation system (streamline ⌀ 16 mm) had a flow rate of 1.05 L h^{-1} per emitter and were spaced 30 cm from each other.

The present study used the Hargreaves and Samani (1985) equation for calculating the daily reference evapotranspiration (ET_o) in the field , which required less and more easily available parameters (latitude, maximum, minimum and mean temperatures) than the Penman Monteith equation (crop height, albedo, canopy resistance and evaporation from soil). This choice was based on a cross-comparison of different reference evapotranspiration methods, concluding that the Hargreaves and Samani equation was the most accurate under humid and semi-arid conditions, and concurrently useful in areas with limited climatic data (Tabari *et al*., 2013; Kra, 2014).

Additionally, to better define the irrigation regimes in the field and to calculate the crop evapotranspiration (*Etc*), both precipitation and evaporation (using an evaporation pan) measurements were conducted on daily basis. The crop evapotranspiration (*Etc*) was determined by multiplying the crop coefficient (Kc) by the reference evapotranspiration (ET_o) at a given phenological phase, as follows: 0.52 at emergence, 1.00 at maximum canopy cover and 0.70 at physiological maturity (Garcia *et al*., 2003). The latter Kc values were more suitable, in terms of latitude and energy exchange, for the present study than those recorded by Razzaghi *et al*. (2012) in Denmark (Kc 0.20, 1.20 and 0.40 for initial, mid and late stages).

Sampling and measurements

The heat units used for the calibration of the AquaCrop model were, growing degree-days (GDD) and calendar days (DAT). To describe crop development, the following parameters were monitored: time to emergence, flowering, duration of flowering, senescence and maturity (using 100 samples per plot), grain yield per plant (using 12 samples per replicate), dry biomass at 24, 40 and 60 days after sowing-DAS (using 3 samples per replicate and dried at 60°C for 48 h), canopy cover at 24, 34, 40, 49, 70 and 85 DAS (using 10 samples per replicate), and root depth at harvest (using 1 sample per replicate). The canopy cover was calculated using the Canopeo App. developed by the Oklahoma University in 2015 (Patrignani and Ochsner, 2015). Canopeo readings were made at a 60 cm distance from the top of the canopy, where each image had a 75×50 cm coverage. Six soil samples were collected at a depth of 0-20 cm and 20-40 cm to determine the physical and chemical characteristics of the soil (Table 2).

AquaCrop model

The AquaCrop model simulates crop yield in different steps: crop development, crop transpiration, biomass production and yield formation. Instead of the LAI, AquaCrop uses the canopy cover (CC), the fraction of soil surface covered by the green canopy, for describing leaf development. Evapotranspiration is divided into transpiration and soil evaporation. Transpiration is directly related to the CC, while evaporation is proportional to the soil surface not covered by vegetation. In AquaCrop, the CC is multiplied by the reference evapotranspiration (ET_o) which is determined by the FAO Penman-Monteith equation and by the crop coefficient (Kc) to then calculate the potential crop transpiration. Then, the actual transpiration (Ta) is calculated from potential evapotranspiration. In addition, the Ta is used for calculating crop biomass (B), which is computed by multiplying actual transpiration by the water productivity (WP) (Eq. 1). Finally, the harvest index (HI) allows to obtain the crop yield (Y) by the crop biomass (B) (Eq. 2) (Raes *et al*., 2018a).

$$\text{Crop biomass (B)} = \sum Ta * WP \qquad (1)$$

$$\text{Crop yield (Y)} = HI * B \qquad (2)$$

Statistical analysis

Different statistical indices were used to evaluate the perfor-

Table 2. Soil physic-chemical characteristics.

Parameter	Units	Soil layer (cm) 0-20	 20-40
Sand	%	75.3	59.4
Silt	%	14.8	12.8
Clay	%	9.9	27.8
Texture (USDA)		Loamy Sand	Sandy Clay Loam
pH (H_2O)		6.09	5.87
C	%	0.35	0.30
Organic matter	%	0.60	0.51
N_{total}	%	0.036	0.028
C/N		10	11
$P_{available}$	mg kg^{-1}	44.0	31.3
$K_{available}$	mg kg^{-1}	90.3	115.9
Bulk density	g cm^{-3}	1.61	-

mance of the AquaCrop model. The root mean square error (RMSE, Eq. 3) identified the differences between predicted and observed values (Jacovides and Kontoyiannis, 1995), whereas the normalised-RMSE (NRMSE, Eq. 4) provided further information on the average of the measured data ranges. Mean absolute percentage error (MAPE, Eq. 5) expressed the differences between actual and forecasted values as a percentage. For the NRMSE and MAPE, the model had a very high performance when the differences between observed and simulated values were 5% or lower. A range from 6% to 15% was considered as a good performance, and 16% to 25% as a moderate-good performance (Raes *et al*., 2018b). The Willmott's index of agreement (d, Eq. 6) provided a measure of the agreement of the deviation of modelled and observed values from the observed mean, and where 0 indicated disagreement and 1 perfect agreement between predicted values and observed data (Wilmott, 1984). Pearson's correlation coefficient (r) showed the relationship between different irrigation regimes and different crop parameters (biomass and canopy cover). The coefficient of determination (R^2) calculated the variance of the dependent variable that was predictable from that of the independent variable, and the level of statistical significance (expressed as $P \leq 0.05$) was used to test the null hypothesis. The statistical package used to run the ANOVA and R^2 test was Minitab 19.

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Oi - Pi)^2} \qquad (3)$$

$$\text{NRMSE} = \frac{RMSE}{\hat{O}} \times 100 \qquad (4)$$

$$\text{MAPE} = \sum_{i=1}^{n}\frac{(Oi - Pi)^2}{(Oi)} \times 100 \qquad (5)$$

$$d = 1 - \frac{\sum_{i=1}^{n}(Oi - Pi)^2}{\sum_{i=1}^{n}(P_i' + O_i')^2} \qquad (6)$$

where O_i and P_i are observed and simulated values, respectively; and n is the number of treatments. The RMSE has the same unit as that of the variable being simulated (*e.g.*, Mg ha^{-1} for yield and biomass), whereas the units of NRMSE are in percentage. The closer the value is to zero, the better the model simulation performance. In addition, $O'_i = [O_i - \hat{O}]$ and $P'_i = [P_i - \hat{P}]$ are the differences between an observed and/or simulated value $\hat{O}$ with $\hat{P}$] and as the observed and simulated means.

Results

A set of preliminary simulations were run on AquaCrop with net irrigation requirements (≈360 mm) and ET_o (≈400 mm) confirming that different sowing dates (25/10/2018, 04/11/2017,

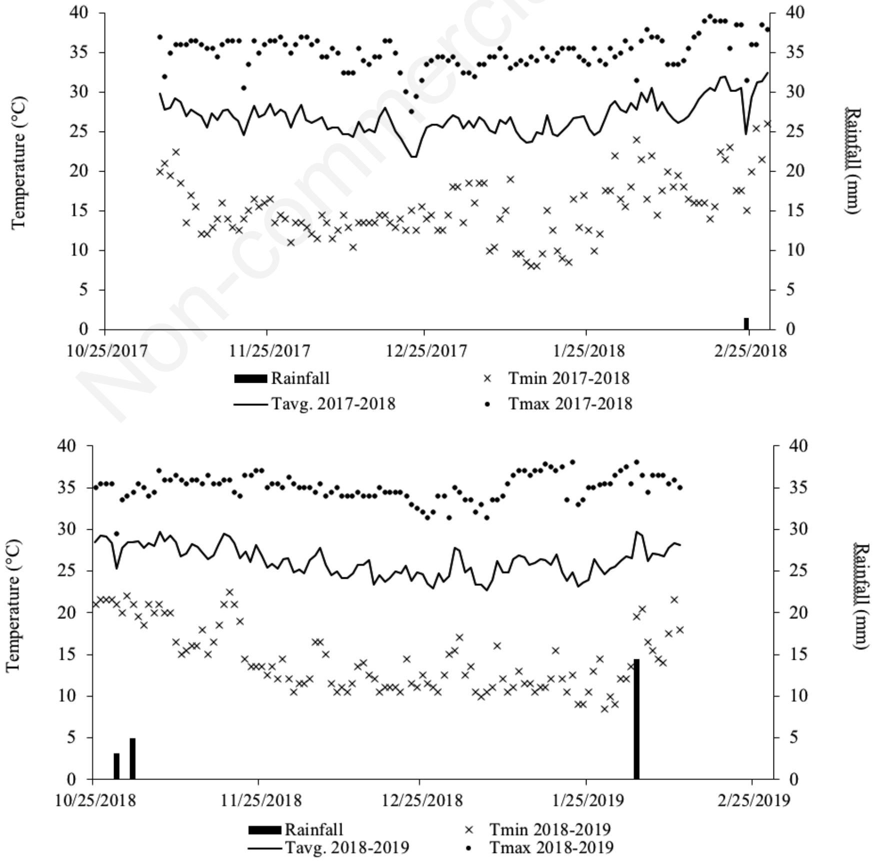

Figure 1. Mean, maximum and minimum temperatures (°C), and precipitation(mm) recorded at Farako-Ba research station during the 2017-2018 (top) and 2018-2019 (bottom) experiments.

19/11/2018 and 08/12/2017) did not have an impact on the yield (1.05-1.06 Mg ha^{-1} min/max value) and biomass (3.00-3.01 Mg ha^{-1} min/max value). These simulations with net irrigation requirements showed slightly higher biomass and yield values, 14 and 7% respectively, when compared to field observations under full irrigation. They also demonstrated that accumulated *Etc* from the field (using Hargreaves and Samani equation) were slightly lower to the *Etc* calculated by AquaCrop (using Penman Monteith equation). This was probably due to the losses derived from direct evaporation, surface runoff and percolation, which were not accounted for when using the Hargreaves and Samani equation.

Field observations

The highest accumulated crop evapotranspiration ($\sum$ *Etc*) was recorded for the sowing date 19/11/2018 (416 mm T_3 and T_4), largely due to constant high temperatures observed during the vegetative stages of quinoa (Figure 1). Additionally, the quinoa plants sown on the 8/12/2017 were adversely affected by heat-stress conditions (above 36°C during four consecutive days) occurring at flowering 25 DAT (Figure 2). A positive relationship was observed between the sum of irrigation events (no.) and final yields (r=0.86 for the validation treatments, T_5–T_{10}), as well as with the amount of irrigation (mm) *versus* final yields (r=0.70 for the validation treatments, T_5–T_{10}), confirming that an appropriate irrigation scheduling was key for obtaining higher yields. Yields were more dependent on the frequency of irrigation (T_{5-7}) rather than on its amount (T_3). For instance, under PD - with a 70-90% *Etc* threshold - (T_5 350 mm and T_6 263 mm water applied) and DI (T_7, 198 mm water applied) the number of irrigation events were of 28 to 30, with yields exceeding, in some cases, 1.0 Mg ha^{-1} (T_6). Given that T_{5-6} and T_7 correspond to PD and DI, respectively, surely it was only feasible to compare it to T_8 and T_9, representing the same type of treatment but a smaller number of irrigation events (20 to 21 events, respectively). Because of an increase in irrigation events, the yields of $T_5 – T_7$ (0.93 Mg ha^{-1} on average) were considerably higher (28%) to those reported by T_8– T_9 (0.67 Mg ha^{-1} on average). Despite the fact that EDI treatments were sown in different years (2017 and 2018) and sowing dates (late October and early December), both T_2 and T_{10} showed alike yields (T_2: 0.35 Mg ha^{-1} and T_{10}: 0.30 Mg ha^{-1}) with similar number of irrigation events (T_2: 22 and T_{10}: 18). Whereas, FI treatments (T_1 and T_3), displayed distant yields (0.97 and 0.73 Mg ha^{-1}) with similar number of irrigation events (20 and 21 events, respectively). Differences in yield between the two were probably due to the timing (specific date during the growing period) of each irrigation event.

Calibration and validation of the AquaCrop model

The wide genetic variability of quinoa, with thousands of genotypes, made the calibration of AquaCrop more complex. The treatments used for the calibration were T_1 to T_4 and for the validation T_5 to T_{10}. The validation was based on a higher number of field experiments, six, as opposed to the calibration, four. In this study, the calibrated parameters on the AquaCrop model were related to climate inputs, crop (development, crop production and response to stresses), management (irrigation and field), soil, and groundwater table. Calibrated values were compared to the AquaCrop's default values for quinoa, displaying significant differences on cycle duration between Burkina Faso and Bolivia (91 DAS and 180 DAS, respectively) (Table 3). In general, the timing and duration of different crop development stages (time and duration of flowering, time for maximum canopy cover and maturity, among other parameters) were halved when comparing the present research to the default values calibrated in Bolivia. High temperatures and short photoperiodicity in Burkina Faso were the principle factors explaining the shortening of the growing period, and consequently of the different phenological phases. For the calibration of air temperature stresses on pollination, the present research adjusted the response of quinoa to heat

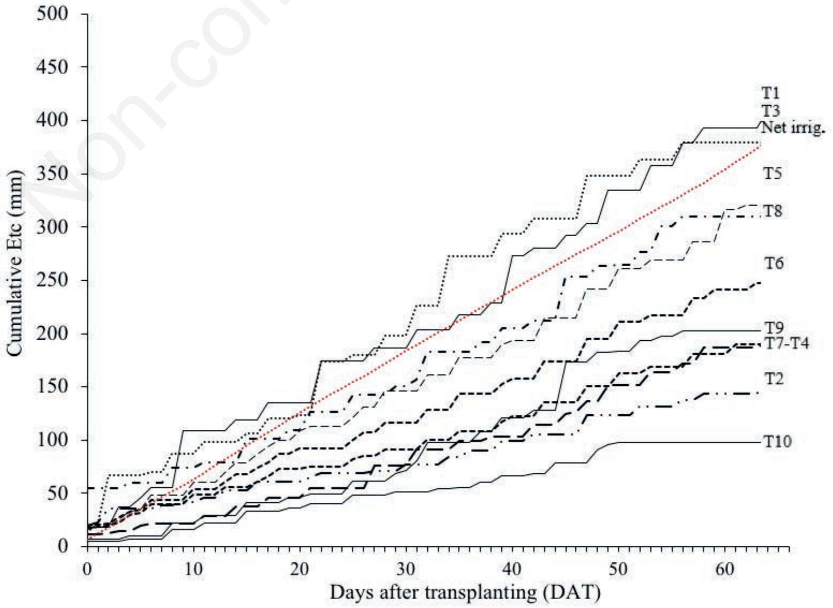

Figure 2. Observed cumulative crop evapotranspiration-*Etc* (mm) under different irrigation regimes. T_1 and T_3: full irrigation (FI) (100% *Etc*); T_5, T_6 and T_8: progressive deficit (PD) (70-90% *Etc*); T_4, T_7 and T_9: deficit irrigation (DI) (50% *Etc*); T_2 and T_{10}: extreme deficit irrigation (EDI) (<40% *Etc*); Net irrigation requirements.

stress (from 40°C to 36°C) on AquaCrop. These values were obtained from field observations and controlled climatic conditions made by Alvar-Beltrán *et al*. (2019a, 2020b), and where 36-38°C was identified as the critical threshold for quinoa pollination. The cv. *Titicaca* was not affected by low N-fertilisation under field conditions in Burkina Faso (Alvar-Beltrán *et al*., 2019b). For this reason, soil fertility was not a limiting factor and, therefore, not considered during the calibration process.

Table 3. Parameters used for the calibration of AquaCrop (Burkina Faso) and default values (Bolivia).

Climate		Burkina Faso	Bolivia
Maximum temperature	°C	Daily data	-
Minimum temperature	°C	Daily data	-
Crop evapotranspiration	mm day^{-1}	Daily data	Daily data
Precipitation	mm day^{-1}	Daily data	Daily data
Mean relative humidity	%	Daily data	-
Crop			
Development			
Plant density	plants ha^{-1}	200,000	200,000
Type of planting method	-	Transplanting	Direct sowing
Transplanting	Days	18	-
Recovered	Days	0	-
Initial canopy cover	%	1.80	1.30
Canopy size seedling	cm^2 plant^{-1}	16.0	6.5
Canopy expansion	% day^{-1}	12.4	10.0
Canopy decline	% day^{-1}	10.7	10.0
Max. canopy cover	DAT / GDD	40 / 790	73 / 1314
Senescence	DAT / GDD	48 / 950	160 / 2880
Maturity	DAT / GDD	73 / 1461	180 / 3240
Max. Canopy cover	%	36	75
Canopy decline	Days	29	28
Flowering	DAT / GDD	25 / 495	70 / 1260
Duration of the flowering	Days / GDD	12 / 234	20 / 360
Length building up harvest index	Days / GDD	48 / 864	90 / 1620
Root deepening	cm	30	100
Crop Production			
Crop water productivity	g m^{-2}	10.5	10.5
Harvest index	%	39	50
Response to stresses			
Canopy expansion	-	Extremely tolerant to water stress	As calibrated value
Stomatal closure	-	Moderately tolerant to water stress	As calibrated value
Early canopy senescence	-	Extremely tolerant to water stress	As calibrated value
Aeration stress	-	Sensitive to water logging	As calibrated value
Salinity class	-	Moderately tolerant to salinity	As calibrated value
Air temperature stresses: pollination	°C	Max (36) / Min (8)	Max (40) / Min (8)
Management			
Irrigation	-		
Method	-	Drip irrigation	-
Irrigation events		According to irrigation schedule	-
Field	-		
Soil fertility	-	Non limiting	-
Mulches	-	None	-
Weed management	-	Perfect	-
Soil			
Texture	USDA	Loamy-Sandy	-
Permanent wilting point*	% v/v	14.8	-
Field capacity*	% v/v	25.9	-
Saturation*	% v/v	47.1	-
Hydraulic conductivity*	mm day^{-1}	557	-
Thickness	cm	120	-
Groundwater table			
Depth	m	2.00	-
Salinity	dS m^{-1}	2.0	-

DAT, days after transplanting; GDD, growing degree days; DAS, days after sowing. Default values for calibrating AquaCrop in the Bolivian Altiplano using genotypes Santa Maria and Real Blanca (Geerts *et al*., 2009; FAO, 2019). Crop default use DAS instead of DAT. *Soil values provided by Leu *et al.* (2010) for similar types of soil and same organic amendment.

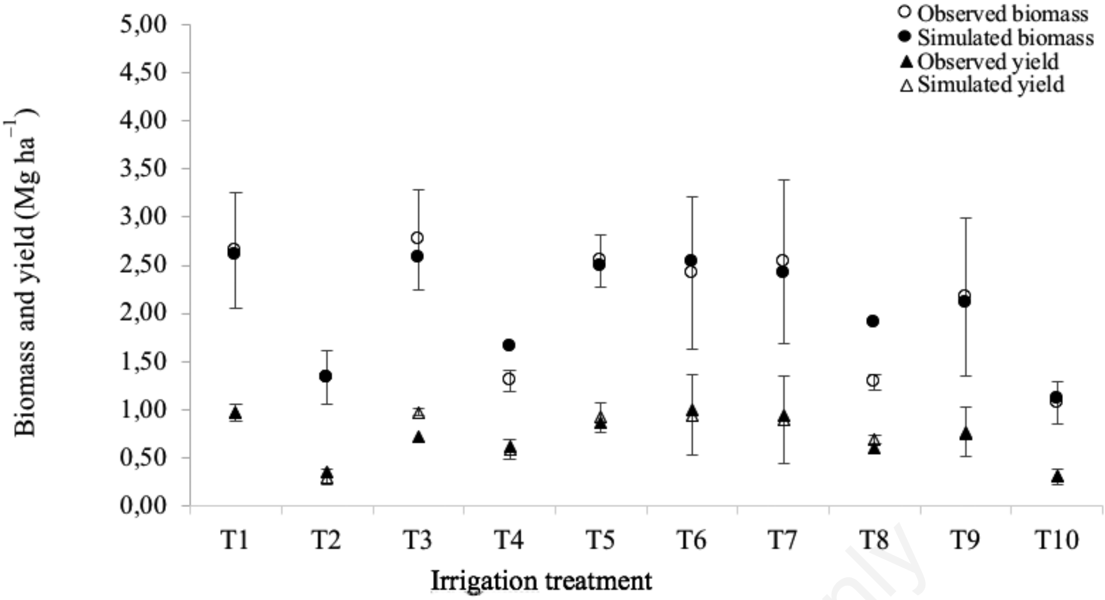

Figure 3. Observed biomass and yield values in the field and simulated biomass and yield using the AquaCrop model.

Table 4. Observed and simulated biomass and yield (Mg ha^{-1}) for different irrigation regimes: full irrigation (FI), progressive drought (PD), deficit irrigation (DI) and extreme deficit irrigation (EDI).

	Calibrated values				Validated values					
	FI (T_1)	EDI (T_2)	FI (T_3)	DI (T_4)	PD (T_5)	PD (T_6)	DI (T_7)	PD (T_8)	DI (T_9)	EDI (T_{10})
Crop outputs										
Obs. biomass (Mg ha^{-1})	2.655	1.338	2.765	1.300	2.545	2.420	2.540	1.285	2.174	1.071
Sim. biomass (Mg ha^{-1})	2.605	1.329	2.575	1.654	2.495	2.541	2.425	1.910	2.118	1.122
Obs. biomass σ (Mg ha^{-1})	1.195	0.555	1.041	0.218	0.534	1.597	1.693	0.173	1.642	0.427
Obs. yield (Mg ha^{-1})	0.967	0.348	0.727	0.612	0.871	1.005	0.943	0.597	0.748	0.303
Sim. yield (Mg ha^{-1})	0.966	0.301	0.976	0.589	0.921	0.941	0.893	0.687	0.771	0.304
Obs. yield σ (Mg ha^{-1})	0.173	0.172	0.062	0.211	0.304	0.838	0.910	0.089	0.518	0.153
Obs. harvest index (%)	36	33	38	42	39	37	37	46	34	28
Sim. harvest index (%)	37	23	38	36	37	37	37	36	36	27
Avg. crop cycle stress*										
Canopy expansion (%)	1	41	3	35	1	1	4	9	10	43
Stomatal closure (%)	1	37	3	31	2	1	4	14	7	52

σ corresponds to the standard deviation of observed biomass and yield values. *Average effect of water-stresses on canopy expansion and stomatal closure during the growing cycle.

Table 5. Performance of AquaCrop calibration when comparing observed and simulated above-ground biomass (Mg ha^{-1}) and canopy cover (%).

	Treatments			
	T1	T2	T3	T4
Above-ground biomass				
Pearson correlation coefficient (r)	1.00***	0.99***	0.98**	1.00***
Root mean square error-RMSE (Mg ha^{-1})	0.200	0.200	0.300	0.200
Wilmott's index of agreement (d)	0.98	0.93	0.97	0.92
Canopy cover				
Pearson correlation coefficient (r)	0.99***	0.99***	0.98**	0.94*
Root mean square error- RMSE (%)	5.3	11.6	4.7	7.5
Wilmott's index of agreement (d)	0.96	0.67	0.96	0.87

***Extremely significant ($P \leq 0.001$); **very significant ($P \leq 0.01$); *significant ($P \leq 0.05$); ns: not significant ($P > 0.05$). Very good ($d \geq 0.9$); good (d 0.8-0.9); moderate-good (d 0.65-0.79); moderate-good (d 0.50-0.64); poor (d 0.25-0.49); very poor ($d \leq 0.25$).

Simulation of yield and biomass on AquaCrop

The simulations of quinoa yields (Mg ha^{-1}) and dry-above-ground biomass (Mg ha^{-1}) by AquaCrop for the two-year experiment (2017-18 and 2018-19) were presented in Table 4 and Figure 3. For FI (T_1 and T_3), the average simulated biomass and yields were 2.59 Mg ha^{-1} and 0.97 Mg ha^{-1}, respectively; while for PD (T_5, T_6 and T_8), the average simulated biomass and yields were 2.32 Mg ha^{-1} and 0.85 Mg ha^{-1}, respectively. However, there were no significant differences ($P>0.05$) when comparing the simulated values of both yield and biomass of PD *versus* FI. Furthermore, under DI (T_4, T_7 and T_9), the average simulated biomass and yield were 2.07 Mg ha^{-1} and 0.75 Mg ha^{-1}, respectively. While for EDI (T_2 and T_{10}), the average simulated biomass and yield decreased to 1.23 Mg ha^{-1} and 0.30 Mg ha^{-1}, respectively (Table 5). When comparing DI and EDI, significant differences ($P\leq 0.05$) were depicted in terms of both biomass and yield.

Statistical analysis of yield, biomass and canopy cover

For the calibration (T_1, T_2, T_3 and T_4), different statistical indicators were used to test the degree of correlation between observed and simulated data (Table 5). For the aboveground biomass and canopy expansion, Pearson's correlation coefficient remained high in all treatments (r 0.98 and $P\leq 0.01$ on average). However, relatively high RMSE values were observed, being the result of a high internal variability within treatments (between 0.2-0.3 Mg ha^{-1} for biomass and 4.7-11.6% for canopy cover). For the canopy cover, the largest RMSE differences were observed in T_2 (11.6%), and to a lesser extent in T_4, T_1 and T_3 with values of 7.5, 5.3 and 4.7%, respectively. The Wilmott's index of agreement (d) for biomass was corroborated with the Pearson's correlation coefficient, with d values between 0.92 and 0.98. This implied very high agreement between predicted and observed readings. Nevertheless, both indices (d and r) strived to depict the internal variability within the treatments, whereas RMSE did not.

For the validation and calibration, a set of statistical indices (NRMSE, RMSE, MAPE and R^2) were used to evaluate the performance of the AquaCrop model in terms of simulated grain yield and biomass (Table 6). The calibrated (T_1–T_4) and validated (T_5–T_{10}) NRMSE values were of 10.0 % and 13.3% for biomass, and 19.2% and 7.3% for yield, respectively. In addition, a higher performance was observed when using the MAPE. The average calibrated and validated MAPE values were of 9.2% and 11.1% for biomass, and 12.9% and 6.0% for yield, respectively. Additionally, R^2 displayed a strong robustness between observed and simulated values both in the calibration (T_1–T_4) and validation (T_5 – T_{10}), with R^2 values of 0.94 ($P\leq 0.01$) and 0.84 ($P\leq 0.01$) for biomass, and of 0.84 ($P\leq 0.05$) and 0.95 ($P\leq 0.001$) for the yield, respectively.

Table 6. Performance of AquaCrop in biomass and yield simulation, average of all treatments.

	RMSE (Mg ha^{-1})	NRMSE (%)	MAPE (%)	r^2
Calibrated crop outputs°				
Biomass	0.298	11.4	9.2	0.94**
Yield	0.127	18.0	12.9	0.84*
Validated crop outputs°				
Biomass	0.301	14.8	11.1	0.84**
Yield	0.639	9.2	6.0	0.95***

RMSE, root mean square error; NRMSE, normalised-root-mean-square-error; MAPE, mean absolute percentage error; R^2, coefficient of determination. ***Extremely significant ($P\leq 0.001$); **very significant ($P\leq 0.01$); *significant ($P\leq 0.05$); ns: not significant ($P>0.05$). °Calibration values (average of T_1 to T_4) and validation values (average of T_5 to T_{10}).

Discussion

The first necessary step was to ascertain the validity of using the AquaCrop model for testing different irrigation regimes for growing quinoa in the Sahel. The main limitation of the model was that key calibrated parameters outputs, *e.g.* yield and biomass, were site-specific and therefore cannot be easily extrapolated elsewhere. Additionally, the model did not account for soil nutrient depletion, pest and diseases (*e.g.*, mildew) affecting quinoa. However, during this research, neither pest nor diseases were reported because of such dry conditions.

The second step was to test the most suitable irrigation regimes for optimising water resources and obtaining the highest quinoa yields. High performance of the AquaCrop model was reflected in the similarities between observed and simulated values. This was shown to be valid for the calibration and validation of the biomass and grain yield in Burkina Faso. An adequate and satisfactory overall performance of the AquaCrop model was reported when modelling crop yield, biomass and canopy cover under different irrigation strategies with cotton (in Syria), Bambara groundnut (greenhouse in UK), soybean (in Nigeria) and maize (in Ethiopia) (Farahani *et al*., 2009; Karunaratne *et al*., 2011; Gebreselassie *et al*., 2015; Adeboye *et al*., 2017). Whilst the model was capable of producing accurate results for biomass and yield, it struggle, to some extent, to produce accurate estimations of the canopy expansion throughout the growing cycle. This was found during early vegetative stages and at leaf senescence, characterised by a very rapid expansion and decline of the canopy typically of environments with warm conditions and short photoperiods.

The concept of thermal time (or GDD) was used to analyse and compare heat units (°C) with time units (days). The observed and simulated GDD values in AquaCrop (°C) were (GDD for seedling and transplanting equal to 1851°C) identical to those reported by Präger *et al*. (2018) in Germany for cv. *Titicaca* (GDD 1874°C). Hence, the present study validated the GDD equation (T_{base} equal to 3°C for quinoa) elaborated by Jacobsen and Bach (1998) and used in AquaCrop. In addition, field experiments conducted in the Sahel, Middle East and North Africa (MENA) (Breidy, 2015; CNRADA, 2015; Djamal, 2015; Hassan, 2015; Saeed, 2015; Alvar-Beltrán *et al*., 2019b; Dao *et al*., 2020a) frequently reported the effect of heat stress on quinoa. The default values on AquaCrop for Bolivia showed that calibrated air temperature stress values in AquaCrop were too high (40°C) for the genotype in study (cv. *Titicaca*), hence having little impact on quinoa pollination (FAO, 2019). However, the present study demonstrated that heat stress adversely affected quinoa pollination, and for this reason calibrated default thresholds in AquaCrop were lowered down from 40°C to 36°C as reported by Alvar-Beltrán *et al*. (2020b) for cv. *Titicaca*. As acknowledged by Hatfield and Prueger (2015), heat stress and water deficits at flowering resulted in pollen dehydration and consequently lowering quinoa yields. The present study also showed that plants sown in December were more sensitive to heat stress conditions occurring at flowering than those sown in late October and along November. Preliminary results from the present study suggest the propensity for improving irrigation by using PD and DI types of irrigation schemes. Some of these research findings elucidated two important aspects regarding drip-irrigated quinoa. The first one was that under PD (T$_6$) and DI (T$_7$) quinoa performed well in terms of yield (around 1.0 Mg ha^{-1}) when irrigated with small and frequent doses, 28 events from transplanting to maturity (10 weeks). As a result, PD and DI were considered optimal water strategies and could be employed during drought-stress conditions. PD and DI water saving irrigation strategies could be embraced and further promoted for drought-tolerant crops and be used as an adaptation measure under increasing rainfall variability in the Sahel region. The second important aspect was that yield losses between FI (T$_1$ and T$_3$ with 0.97 Mg ha^{-1} and 415 mm, averages of yield and water supply) and PD (T$_5$, T$_6$ and T$_8$ with 0.85 Mg ha^{-1} and 307 mm, averages of yield and water supply) were of 13%, but with a water saving benefit of 25%. The results of the present study were in harmony to those of Geerts *et al*. (2008) in the Bolivian Altiplano. The latter experiment concluded that quinoa yields could be stabilised through deficit irrigation strategies, reporting yields of 1.2 to 2.0 Mg ha^{-1} under DI.

Conclusions

This research demonstrates that quinoa is a drought tolerant crop with low water requirements, besides having extraordinary abilities to adapt to drought stress conditions as reported in EDI treatments. The simulations made in AquaCrop indicate that quinoa is also extremely tolerant to water stress in terms of canopy expansion and leaf senescence. The present study shows that irrigation scheduling and drip irrigation systems are crucial for water optimisation. Essentially, the objective for farmers is to save water whilst minimising yield losses to acceptable levels. If sown in early November under PD (T$_6$, with 263 mm water supply) and DI (T$_7$, with 198 mm water supply), quinoa can potentially perform well (≈1.0 Mg ha^{-1}) under frequent irrigation, 28 times in the 10 weeks following transplantation. If water is not a limiting factor, farmers can apply FI less frequently (T$_1$ and T$_3$, with 415 mm water supply) and attain higher yields. However, this option is not supported by this research because of increasing rainfall variability within the region.

If appropriate irrigation scheduling is followed (PD as opposed to FI), savings are incurred as follows: economic losses from fuel for water pumping, benefits alike from grain yields (13% yield reduction from FI to PD), and water preservation, very advantageous to farmers enabling them to save up to 25% of water between FI and PD strategies. The loamy-sandy soil texture typically of the Sahel, emphasised the need to invest more time irrigating but with lower amounts of water. However, farmers can accept yield reductions from PD, as the overall individual and community cost benefits from water preservation are considered as positive.

The present research highlights the need for a more extensive work on irrigation scheduling and on the production of improved modelling with crop and water productivity models, in order to give a real contribution on food security in Africa through water conservation strategies and highly nutritional crops. To that, other drought and heat tolerant crops grown in the Sahel region and having high nutritional properties, *e.g*., pearl millet and fonio, could be tested to better understand the effect of water-stress conditions and increasing temperatures on yield performance.

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