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Aqua-crop module as best tool to estimate water stress in durum wheat (*Triticum durum* Desf.) under semi-arid conditions

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Abstract

Simulation models that clarify the effects of water on crop yield are useful tools for improving farm level water management and optimizing water use efficiency. FAO recently developed a water-driven model for use as a decision support tool in planning and scenario analysis in different seasons and locations with limited sophistication. The objective of this study is to validate the Aqua-Crop model for its ability to simulate wheat (*Triticum durum* Desf.) performance under semi-arid conditions in East of Algeria. The Aqua-Crop model was evaluated with field experimental data collected during five cropping seasons (2010-2016) were total water stress ranged between 20% at Heading-Maturity stage to 66% at Heading-Maturity stage. The results of this study proved the efficiency of the Aqua Crop model to quantify the water stress. The results of reliability indices such as Root Mean Square Error (RMSE), Average Absolute Error (AAE), Index of agreement (d), and Prediction error (Pe) were 3.17, 2.96, 0.54 and 5.41% respectively for grain yield; and 4.29, 4.03, 0.38 and 6.25% respectively for final above-ground biomass. The Aqua-Crop model was able to accurately simulate harvest index giving a d = 0.69, RMSE and AAE of 14.41 and 13.65%, respectively. The Aqua-Crop model can adequately quantify water stress and can be used to explore management options to improve wheat water productivity. His simplicity due to its required minimum input data, which are readily available or can easily be collected, can made it user-friendly for users.

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Introduction

Demand for cereal is predicted to increase in the future as the global population increases. With the world's population estimated to reach 9.6 billion by 2050, wheat production will have a crucial bearing on food security and the global economy in the coming decades (USDA Foreign Agricultural Service 2014).Wheat is one of the most important cereal crops in the world, which is grown both in arid and semiarid regions of the world (Akbar *et al.*, 2001; Tunio *et al.*, 2006). Current estimates indicate that 25% of the world's agricultural land is now affected by drought stress. It can be said that drought stress is one of the most devastating environmental stresses that depress wheat yield productivity in many parts of the world. (Ahmad *et al.*, 2003).

Crops demonstrate various morphological, physiological, biochemical, and molecular responses to tackle drought stress. Plants' vegetative and reproductive stages are intensively influenced by drought stress (Nezhadahmadi *et al.*, 2013). The crop water need is related to moisture sensitive periods. Salter and Goude (1967) declined such periods as "certain development phases in which the plant is, or appeared by its observed response, to be more sensitive to moisture conditions than at other stages of development". If moisture sensitive periods could be identified for wheat crop under field conditions, it would have an important implication for irrigation practices. Efficient and purposeful utilization of water is, therefore, important under water shortage conditions. FAO has developed a yield-response to water model, Aqua-Crop, a crop water productivity simulation model resulting from the revision of the FAO Irrigation and Drainage Paper No. 33- Yield Response to Water (Doorenbos and Kassam, 1979). Aqua-Crop is for use as a decision support tool in planning and scenario analysis in different seasons and locations (Steduto *et al.*, 2009; Hsiao *et al.*, 2009). It simulates crop yield response to water, and is particularly suited to address conditions where water is a key limiting factor in crop production. For parameterization calibration, one changes model parameters and even coding in order to obtain accurate prediction versus observed data. On the other hand, validation is the process whereby the model is run against independent data, without any modification of model parameters or code (Nain and Kersebaum, 2007; *Andarzian et al.*, 2008; Salazar *et al.*, 2009). The objective of the study is the validation of Aquacrop model and evaluation of it performance to quantify the water stress under semi-arid conditions in East of Algeria using four durum wheat (*Triticum durum* Desf.) varieties chosen for their reputed differences in yield performance and water stress tolerance (Oued Zenati, Bousselam, Altar and Mexicali 75).

Materials and methods

Aquacrop Model

Estimating attainable yield under water-limiting conditions will remain central in arid, semi-arid and drought-prone environments. To address this need, FAO has developed a yield-response to water model, Aqua-Crop, a crop water productivity simulation model resulting from the revision of the FAO Irrigation and Drainage Paper No. 33 —Yield Response to Water (Doorenbos and Kassam, 1979). For over two decades, this paper has been a key reference for estimating the yield response of field, vegetable and tree crops to water. Similarly to many other crop-growth models, Aqua-Crop further develops a structure (sub-model components) that includes: the soil, with its water balance; the crop, with its development, growth and yield; the atmosphere, with its thermal regime, rainfall, evaporative demand and carbon dioxide concentration (CO_2); and the management, with its major agronomic practice such as irrigation and fertilization. Simulation runs of Aqua-Crop are executed with daily time steps, using either calendar days or growing degree days. Several features distinguish Aqua-Crop from other crop growth models achieving a new level of simplicity, robustness and accuracy (Steduto *et al.*, 2009). The FAO crop model, Aqua-Crop (Steduto *et al.*, 2009), simulates attainable yields of major herbaceous crops as a function of water consumption under rainfed, supplemental, deficit, and full irrigation conditions.

The growth engine of Aqua-Crop is water-driven, in that transpiration is calculated first and translated into biomass using a conservative, crop-specific parameter (Geerts *et al.*, 2009), the biomass water productivity, normalized for atmospheric evaporative demand and air CO2 concentration. The normalization is to make Aqua-Crop applicable to diverse locations and seasons. Simulations are performed on thermal time, but can be on calendar time, in daily time-steps.

The model uses canopy ground cover instead of leaf area index (LAI) as the basis to calculate transpiration and to separate soil evaporation from transpiration. Crop yield is calculated as the product of above-ground dry biomass and harvest index (HI). Starting at flowering, HI increases linearly with time after a lag phase, until near physiological maturity. Other than for the yield, there is no biomass partitioning into the various organs. Crop responses to water deficits are simulated with four modifiers that are functions of fractional available soil water modulated by evaporative demand, based on the differential sensitivity to water stress of four key plant processes: canopy expansion, stomatal control of transpiration, canopy senescence, and HI. The HI can be modified negatively or positively, depending on stress level, timing and stress duration. Aqua-Crop uses a relatively small number of parameters (explicit and mostly intuitive) (Steduto *et al.*, 2009).

Estimation of ETo

The ETo was accounted with the use of ETo calculator (Version 3, January 2009; Raes *et al.*, 2009). The Penman-Monteith approach was utilized for ETo computation. This method is the most general and widely used equation for calculating daily reference ET, that is recommended by FAO (Allen *et al.*, 1998). The inputs for the calculator [maximum air temperature (Tmax),minimum air temperature (Tmin), maximum relative humidity (RHmax), minimum relative humidity (RHmin), sunshine hours (n/N) and wind speed at a height of 2 m (u2) based on long-term weather data (1979 to 2017)] were collected from Setif meteorological station.

Performance Evalution of Aquacrop

Evaluation is an important step of model verification. It involves a comparison between independent field measurements (data) and output created by the model. Different statistic indices including Average Absolute Error (AAE), root mean square error (RMSE) and agreement (D-index) were employed for comparison of simulated against observed data.

For the performance evaluation of Aqua-Crop, following notations were used:

Si = simulated value

Oi = observed value,

N = number of observations

MS = mean of simulated value,

MO = mean of observed value.

Average Absolute Error (AAE)

Absolute percentage error between simulated and observed values may be calculated using following equation (Loague and Green, 1991):

$$AAE = \frac{\sum_{i=1}^{n} |Oi - Si|}{N}$$

Root Mean Square Error (RMSE)

Root mean square error (RMSE) is calculated as follows (Loague and Green, 1991):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (Oi - Si)^2}{N}}$$

The RMSE represents a measure of the overall, or mean, deviation between observed and simulated values, that is, a synthetic indicator of the absolute model uncertainty. In fact, it takes the same units of the variable being simulated, and therefore the closer the value is to zero, the better the model simulation performance.

Index of agreement (d)

The index of agreement (d) was calculated using the Willmott (1985) equation:

$$d = 1 - \frac{\sum_{i=1}^{n}(Si - Oi)^2}{\sum_{i=1}^{n}(|Si - MO| + |Oi - MO|)^2}$$

The index of agreement is a measure of relative error in model estimates. It is a dimensionless number and ranges from 0 to 1.0, where 0 describes complete disagreement and 1.0 indicates that the estimated and observed values are identical.

Prediction error (Pe)

Model performance was evaluated using the following statistical parameter prediction error (Pe) (Nash and Sutcliffe, 1970), given by:

$$\mathrm{Pe} = \frac{(\mathrm{Si} - \mathrm{Oi})}{\mathrm{Oi}}\ x\ 100$$

Correlation coefficient (r)

The correlation coefficient is an indicator of degree of closeness between observed values and model estimated values. The observed and simulated values are found to be better correlated as the correlation coefficient approaches to 1. If observed and predicted values are completely independent i.e., they are uncorrelated then r will be zero. The correlation coefficient was estimated by the following equation:

$$\mathrm{r} = \frac{\sum_{i=1}^{n}(\mathrm{Oi} - \mathrm{MO})(\mathrm{Si} - \mathrm{MS})}{\sqrt{\sum_{i=1}^{n}(\mathrm{Oi} - \mathrm{MO})^2 \sum_{i=1}^{n}(\mathrm{Si} - \mathrm{MS})^2}}$$

Results and discussion

Quantification of the water stress

1Water stress during first stage (Sowing-Emergence)

During this stage and at all cropping seasons (2010-2016) water stress values ranged from 0.23 at fourth cropping season (2014/2015) to 0.74 at fifth cropping season (2015/2016), with a mean of 0.45 for all cropping seasons (Table 1). Leaf expansion is most sensitive to water stress (Acevedo *et al.*, 1971) and leaf growth can be drastically reduced at leaf water potentials of -0.7 to -1.2 MPa (Eastham *et al.*, 1984). Tillering is also very sensitive to water stress being almost halved if conditions are dry enough (Peterson *et al.*, 1984; Rickman *et al.*, 1983). As a result, leaf area index development is the most affected physiological process during this stage. Water deficit just before flower initiation may also decrease the number of spikelet primordia at this stage (Oosterhius and Cartwright, 1983). Water stress may affect the growth of wheat, but the effects are small when stress occurs in the early stages than when it occurs in the late vegetative phase and during grain filling (Abayomi and Wright, 1999).

Water stress during second stage (Emergence-Heading)

As shown in Table 1, water stress varied between 0.09 at third cropping season and 0.42 at fifth cropping season. This stage is therefore a period of very active plant growth. Water stress during this stage decreases spikelets per spike of fertile tillers (Hochman, 1982; Moustafa *et al.*, 1996) and causes death of the distal and basal florets of the spikes (Oosterhuis and Cartwright, 1983). It follows that mild to moderate water deficits during this period will decrease cell growth and leaf area with consequent decrease of photosynthesis per unit area due to partial stomata closure (Acevedo, 1991).

Water stress during third stage (Heading-Maturity)

During this stage and at all cropping seasons (2010-2016) water stress values ranged from 0.41 to 0.97. The highest water stress registered during fifth cropping season (2015/2016) with total mean of 0.66 (Table1). Wheat plant growth (roots, leaves, stems and ears) continues up to approximately 10 days after anthesis. Water stress may affect the growth of wheat, but the effects are small when stress occurs in the early stages than when it occurs in the late vegetative phase and during grain filling (Abayomi and Wright, 1999). Water deficit close to anthesis accelerates development (Simane *et al.*, 1993); the accumulation of soluble carbohydrates in the stem occurring between anthesis and the linear phase of grain growth is decreased (Nicholas and Turner, 1993).

The remobilization of pre-anthesis assimilates to the grain becomes very important as photosynthesis is decreased by water stress and total non-structural carbohydrates from wheat leaves and stems (particularly fructans and sucrose) significantly contribute to grain growth (Bidinger *et al.*, 1977; Richards and Townley-Smith, 1987; Kiniry, 1993; Palta *et al.*, 1994).

Water stress imposed during later stages might additionally cause a reduction in number of kernels/ear and kernel weight (Gupta *et. al.*, 2001; Dencic *et al.*, 2000).

Direct effect of water stress on GY and TKW

As shown in Fig. 1, water stress affects negatively grain yield and thousand kernels weight especially in the second (2011-2012) and fifth cropping season (2015-2016). Ashraf (1998), reported that water stress at anthesis reduces pollination and thus less number of grains are formed per spike which results in the reduction of grain yield. Moisture stress is known to reduce biomass, tillering ability, grains per spike and grain size at any stage when it occurs, due to reduction in radiation use efficiency. So, the overall effect of moisture stress depends on intensity and length of stress (Bukhat, 2005). Water stress imposed during later stages might additionally cause a reduction in number of kernels/ear and kernel weight (Gupta *et. al.,* 2001; Dencic *et al.*, 2000).

Table 1. Water stress variation depending on stages during five cropping seasons (2010-2016).

	Stages	Days	ETa	ETx	Water stress
Cropping season	Sowing-Emergence	38,75	53,38	33,43	0,37
2010/2011	Emergence-Heading	159,25	329,38	263,63	0,2
	Heading-Maturity	189,25	170,13	99,8	0,41
	Stages	Days	ETa	ETc	Water stress
Cropping season	Sowing-Emergence	38,75	46,7	25,8	0,45
2011/2012	Emergence-Heading	159,25	318,2	261,8	0,17
	Heading-Maturity	189,25	201,875	51,55	0,74
	Stages	Days	ETa	ETc	Water stress
Cropping season	Sowing-Emergence	38,75	58,78	31,08	0,47
2012/2013	Emergence-Heading	159,25	362,38	330,93	0,09
	Heading-Maturity	189,25	171,78	77,98	0,54
	Stages	Days	ETa	ETc	Water stress
Cropping season	Sowing-Emergence	38,75	47,75	36,73	0,23
2014/2015	Emergence-Heading	164,75	300,33	258,85	0,13
	Heading-Maturity	190,75	216,88	74,70	0,65
	Stages	Days	ETa	ETc	Water stress
Cropping season	Sowing-Emergence	27,75	53,75	13,65	0,74
2015/2016	Emergence-Heading	159,00	126,90	72,20	0,42
	Heading-Maturity	185,00	193,25	5,21	0,97
	Stages	Days	ETa	ETc	Water stress
Mean of five seasons	Sowing-Emergence	36,55	52,07	28,14	0,45
	Emergence-Heading	160,30	287,44	237,48	0,20
	Heading-Maturity	188,70	190,78	61,85	0,66

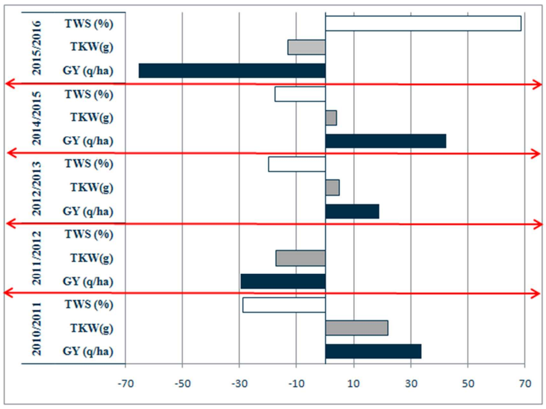


Fig. 1. Deviation from the mean values of Grain yield (GY) thousand kernels weight(TKW) and total water stress (TWS) during five cropping seasons (2010-2016).

Evaluation of the Aqua-Crop model

Grain yield (GY)

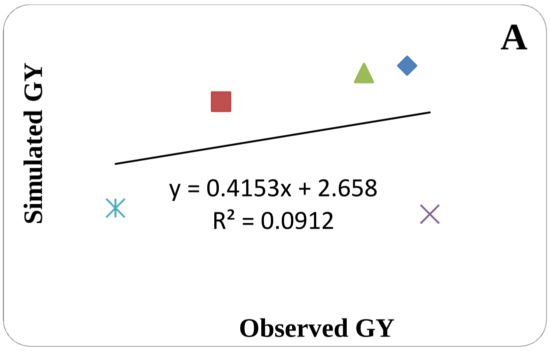
Simulation results for all seasons and all traits are presented in Table 2. Fig. 2A shows the relationship between observed and simulated grain yield for all seasons. Observed and simulated grain yield gives a correlation r = 0.30 a slope of 0.41 and a D of 0.54 (Table 2) indicating that the model explained satisfactorily the relationship between observed and modeled wheat grain yield. Araya *et al.* (2010) reported R^2 values > 0.80 when simulating barley aboveground biomass and grain yield using Aqua-Crop. The values of RMSE and AAE are 1.86 and 1.77 ton ha -1, respectively (Table 2).

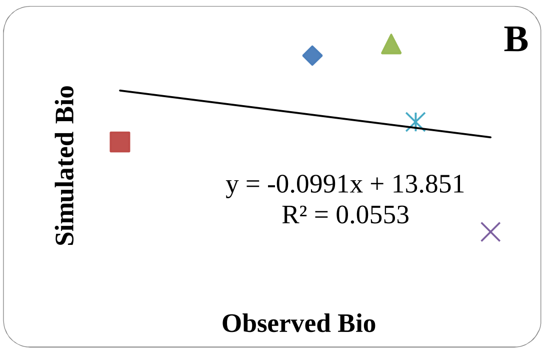
Overall the difference between the simulated and observed grain yield was 0.20 ton ha^{-1} indicating that the model overestimated the grain yield by 5.41%. Araya *et al.* (2010) used Aqua-Crop to simulate barley grain yield and reported that the simulated grain yield deviated from the observed yield with a range of 13% to 15%. Ngetich *et al.* (2012) indicated that the grain yields were slightly underestimated in the long rains season and the reverse was true for the short rains seasons. Andarzian *et al.* (2011) found that the calculated model evaluation criteria between simulated and measured yield were RMSE = 0.27 t ha^{-1}, D-index = 0.97 and R^2 = 0.95; they conclude that the Aqua-Crop model could very well predict top-weight biomass and grain yield of wheat in the central region of Iran.

Table 2. Statistical indices derived for evaluating the performance of Aqua-Crop model in predicting grain yield, biomass and harvest index.

		Observed	Simulated	AAE	RMSE	d	Pe (± %)
2010/2011	GY	5,57	6,78	1,21	1,22	0,27	21,72
	Bio	11,25	13,6	2,35	2,41	0,3	20,89
	HI	49,77	49,9	2,04	2,63	0,99	0,26
		Observed	Simulated	AAE	RMSE	d	Pe (± %)
2011/2012	GY	2,94	5,49	2,55	2,58	0,95	86,73
	Bio	7,69	12,34	4,65	4,66	0,06	60,47
	HI	38,41	44,45	6,03	8,04	0,98	15,73
		Observed	Simulated	AAE	RMSE	d	Pe (± %)
2012/2013	GY	4,96	6,52	1,57	1,85	0,43	31,45
	Bio	12,71	13,77	1,61	2,42	0,42	8,34
	HI	39,44	47,38	7,94	8,85	0,6	20,13
		Observed	Simulated	AAE	RMSE	d	Pe (± %)
2014/2015	GY	5,89	1,46	4,43	4,6	0,65	-75,21
	Bio	14,92	11,12	3,8	3,8	0,66	-25,47
	HI	39,39	13,11	26,28	26,34	0,6	-66,72
		Observed	Simulated	AAE	RMSE	d	Pe (± %)
2015/2016	GY	1,45	1,68	5,05	5,64	0,4	16,24
	Bio	13,16	12,63	7,74	8,2	0,48	-4,01
	HI	39,29	13,33	25,96	26,2	0,3	-66,07
		Observed	Simulated	AAE	RMSE	d	Pe (± %)
Over all years	GY	4,1614	4,3864	2,962	3,178	0,54	5,41
	Bio	11,946	12,6924	4,03	4,298	0,384	6,25
	HI	41,26	33,634	13,65	14,412	0,694	-18,48

AAE: Average Absolute Error, RMSE: Root Mean Square Error, d: Index of agreement and Pe: Prediction error.





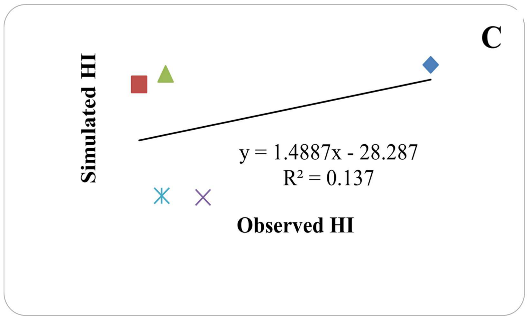


Fig. 2. Linear relationship between observed and simulated Grain yield (A), Biomass (B) and Harvest index (C) for all growing seasons.

Final above-ground biomass (Bio)

There was generally a moderate agreement between model predictions and measured biomass data with a slope of 0.1, a D of 0.38 and r of -0.23. The student s t-test showed that the simulated biomass was not signicantly different (p = 0.54) from the observed biomass with RMSE and AAE of 4.29 and 4.03 ton ha^{-1}, respectively (Table 2, Fig. 2B). These RMSE and AAE values when expressed as percent of average observed grain yield were 33.91% and 33.94%, respectively. Andarzian *et al.* (2011) mentionned that the calculated values of statistic indices of final above-ground biomass, RMSE, normalized RMSE, D-index, and R^2 were 0.6 t ha^{-1}, 4.4%, 0.97 and 0.95, respectively. Overall the difference between the simulated and observed biomass was 0.80 ton ha^{-1} indicating that the model overestimated the biomass by 6.25%, but the student s t-test showed that the simulated biomass was not significantly different from the observed biomass. Ngetich *et al.* (2012) shows a good correlation between observed and simulated of both dry final aboveground biomass and grain yields combined for maize in sub-humid and semiarid regions of central highlands of Kenya ;and there was a good fit between the simulated aboveground biomass and grain yield agreed well with their corresponding observed data for all treatments during successful seasons. Zeleke *et al.* (2011) used Aqua-Crop to simulate both total biomass and grain yield for canola (*B. napus* L.) and reported that the difference between observed and simulated values was <10%. Meanwhile, Todorovic *et al.* (2009) when assessing the ability of three models (Aqua-Crop, Crop Syst and WOFOST) to simulate sun ower growth reported that Aqua-Crop overestimated sun ower yield by 1.2%, while Crop Syst and WOFOST underestimated yield by 4.6% and 0.3%, respectively.

The authors concluded that although Aqua-Crop requires less input information compared to the other two models, it performed similarly to the other two models in modeling both total biomass and grain yield.

Harvest Index (HI)

In Aqua Crop, harvest index (HI) is simulated by a linear increase with time (Steduto *et al.*, 2009). Observed and simulated harvest index correlated well giving a slope of 1.48 and a D of 0.69 (Table 2, Fig. 2C). The student s t-test showed that the simulated harvest index was not significantly different ($p = 0.38$) from the observed harvest index with RMSE and AAE of 14.41 and 13.65%, respectively and the model underestimated the biomass by -18.48% (Table 2).

Harvest index in treatments with nearly optimal water condition (eight irrigations) increased with time and reached the reference level. But it did not increase in rainfed treatments because it was stopped by water stress. Aggarwal *et al.* (1986) found similar HI trend in wheat with irrigated treatments. The adjustment of harvest index to water stress depends on the timing and extent of water stress (Steduto *et al.*, 2009). Adjustments for pollination failure, for inhibition of stomata, for reduction in green canopy duration, for pre-flowering stress were taken into account in the simulation.

Conclusions

The results of this study proved the efficiency of the Aqua-Crop model to quantify the water stress. Total water stress during the five cropping seasons (2010-2016) ranged between 0.2 (20%) at Emergence-Heading stage to 0.66 (66%) at Heading-Maturity stage. As illustrated in Fig. 1, and during fifth cropping season (2015/2016) total water stress (68.5%) several affect grain yield and thousand kernels weight (-65.3 and -13.12% respectively).

The fourth cropping season (2014/2015) considered as the favorable season compared with the other season. Concerning the evaluation of the, Aqua-Crop model, results showed that durum wheat grain yield, Biomass and Harvest index can be simulated with relative accuracy using Aqua-Crop (v3.0). Overall, the agreement between simulated and observed wheat grain yield was satisfactory with D = 0.54, RMSE and AAE of 3.18 and 2.96 ton ha^{-1}, respectively. Regarding final above-ground biomass comparison of simulated to observed values for all growing seasons resulted in a D = 0.38, RMSE and AAE of 4.29 and 4.03 ton ha^{-1}, respectively. In addition, observed and simulated harvest index gives a D = 0.69, RMSE and AAE of 14.41 and 13.65%, respectively. Aqua-Crop's high reliability for the simulations of grain and biomass yield implies that, when properly calibrated, it can be used in developing strategies for improvement of field management decisions. As such, Aqua-Crop is recommended for applications under different agro-climatic conditions.

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