



CALIBRATION AND VALIDATION OF AQUACROP MODEL FOR TOMATO CROP UNDER FULL AND DEFICIT IRRIGATION

A. I. Arab¹, M. K. Othman¹, O. J. Mudiare², A. A. Ramalan² and U. D. Idris³

¹National Agricultural Extension and Research Liaison Services (NAERLS), Ahmadu Bello University, P.M.B. 1067, Zaria, Nigeria

²Department of Agricultural and Bio-resource Engineering, Ahmadu Bello University, Zaria, Nigeria

³Samaru College of Agriculture, Division of Agricultural Colleges, Ahmadu Bello University, Zaria, Nigeria

*Corresponding author's email address: adamuarab72@gmail.com

ARTICLE INFORMATION

Submitted 4 March, 2022
Revised 30 June, 2022
Accepted 1 May, 2023

Keywords:

Calibration
Validation
AquaCrop
Deficit
Irrigation

ABSTRACT

This study reported herein was conducted at the Institute for Agricultural Research (IAR) irrigation site, Kadawa, Kano State, Nigeria during the 2016/17 and 2018/19 irrigation seasons (The 2017/18 trial failed due to emergency repairs that led to shut-down of the main channel from Tiga dam for four weeks). The main aim of the research is to use field data to calibrate and validate AquaCrop model to simulate tomato yield and water responses in Northern Nigeria. AquaCrop model was calibrated and validated using the 2016/17 and 2018/19 season field trial data respectively. The evaluated results indicated that the model was able to simulate tomato fruit and biomass yield, seasonal crop water use and fruit water productivity at harvest satisfactorily in full ETc and water stress condition. Also, AquaCrop model was able to simulate fruit yield and biomass yield along the crop growth stages with sufficient accuracy but fails to simulate Canopy cover (CC) accurately during the initial stage as indicated by normalized root mean square error (NRMSE), Nash-Sutcliffe model efficiency (EF), Willmott's index of agreement (d) and coefficient of residual mass (CRM) values of 88%, 0.75, 0.89 and -0.88 respectively. However, the model was able to simulate CC relatively well during the development and middle stages with a tendency of over-predicting CC by about 2% in development stage and under-predicting CC by about 11% during the middle stage. Furthermore, the AquaCrop model was found to be simple, robust, require minimal input data and accurate in simulating soil water balance, fruit and biomass yield of tomato. Therefore, it is recommended for used in evaluation of irrigation scheduling and water management strategies that will improve crop water productivity of tomato crop in Northern Nigeria.

© 2023 Faculty of Engineering, University of Maiduguri, Nigeria. All rights reserved.

1.0 Introduction

In order to provide a more precise evaluation of water management strategy, a long-term study and analysis is necessary which also allows for a comparison between different strategies in terms of water scheduling. Such study and analysis would provide a baseline for developing various irrigation scheduling strategies that will be employ to improve crop water productivity. Also, the development and certification guidelines for optimal irrigation scheduling and water requirements requires extensive direct field experiments (Bazza, 1999).

Direct field experiment is very expensive, laborious and time consuming and often apart from subjected to uncontrolled condition such as weather, diseases, it is also practically difficult to set-up field trial in remote areas. Igbadun et al. (2006) stated that it is practically difficult to analyse

long-term effect and large impact scenarios on the field thus the cheap and efficient way to carry out an evaluation of the impacts of irrigation scheduling practices is through the use of empirical production functions or computer-based simulation models.

The complexity of assessing crop yield responses to water deficit using direct field experiments led to the advent of empirical production functions as the most practical option to assess crop yield response to water. Among the empirical function approaches, is the equations developed by Doorenbos and Kassam (1979) to determine the yield response to water of field, vegetables and tree crops. Scientific and experimental progresses in crop- water relations from 1979 to date, gave rise to the development and application of computer models to simulate crop yield response to water. More advanced computer-based simulation models that are based on different irrigation strategies and for specific edapho-climatic conditions such as CERES, Subtor-POTATO, EPIC, ALMANAC, CropSyst, TOMGRO and CROPGRO are now available. Such models require advanced skills for their calibration and need a great number of parameters for the simulation process. Also, the scientific approach of these models does not recommend their use by farmers and technicians, therefore, scientists, graduate students and advanced users in highly commercial farming represent the typical users of these models. In an attempt to achieve a new model that is less complex with accuracy, simplicity and robustness, the FAO developed AquaCrop model which focuses on yield response to water.

In order to come-up with a comprehensive recommendation on the irrigation scheduling strategies to adopt for furrow irrigated tomato under water stress, and the corresponding soil water balance of a given field, calibration and validation of a computer-based crop simulation models such as AquaCrop, to predict crop yield and water responses is necessary. The calibrated and validated model could be used as a decision support system tool for tomato growers and managers of irrigable areas to take optimal water management decision that will improve yield and crop water productivity. Also, Raes *et al.* (2010) stated that the goodness of fit for the calibrated parameters values provided in the AquaCrop manual was low for tomato and further stated that the model parameters were not calibrated for water stress conditions. Therefore calibration and validation of AquaCrop model will contribute toward improving the reliability of the conservative parameters included in the AquaCrop manual for tomato crop.

2. Materials and Methods

2.1 Evolution of AquaCrop Model

The tremendous complexity of crop responses to water deficits has led to the advent of empirical functions as the most practical tool to assess crop responses to water, among which, is the Equation 1 developed by Doorenbos and Kassam (1979) to assess yield response to water of field, vegetable and tree crops.

$$\left(1 - \frac{Y}{Y_x}\right) = K_y \left(1 - \frac{ET}{ET_x}\right) \quad (1)$$

Where: Y_x and Y are the maximum and actual yield, ET_x and ET the maximum and actual evapotranspiration, and K_y the proportionality factor between relative yield decline and relative reduction in evapotranspiration.

Scientific and experimental progresses in crop-water relations led to the development of AquaCrop model which evolved from Equation 1. The AquaCrop model differs from most models due to its accuracy, simplicity and robustness. Details of the conceptual framework, underlying principles, and distinctive components and features of AquaCrop are described by Steduto et al. (2009), while the structural details and algorithms are presented by Raes et al. (2009). Calibration and performance evaluation for several crops are reported by Farahani et al. (2009); Garcia-Vila et al. (2009); Heng et al. (2009); Hsiao et al. (2009).

2.2 Study Area

The field experiments used in calibrating and validating the AquaCrop model were conducted at the irrigation site of the Institute for Agricultural Research, (IAR) Irrigation Research Farm at Kadawa (Latitude $11^{\circ}38'41''$ N, Longitude $8^{\circ}25'51''$ E and 490m above sea level), northern Nigeria, during the 2016/17 and 2018/19 irrigation seasons respectively (The 2017/18 trial failed due to emergency repairs that led to the shut-down of the main channel from Tiga dam for four weeks). The area lies within the Kano River Irrigation project (KRIP), Sudan savannah zone of Nigeria, and has a surface irrigation facility. The meteorological data for 2016/17 and 2018/19 irrigation season were obtained from the International Institute for Tropical Agriculture (IITA) meteorological station (Kadawa).

2.3 Experimental Design

The experiment consists of nine irrigation regimes (treatments) distributed in a randomized complete block design (RCBD) with three replications and furrow irrigation method was employed for water application. The treatments were based on water application regulated at selected crop growth stages. On each replication, there were nine experimental treatments. Each treatment has 2.25 m x 94 m plot size consisting of three (3) well levelled-ridges and two (2) furrows. The furrow spacing and length is 0.75 m and 94 m respectively. The description of experimental treatment is shown in Table 1.

2.4 Determination of Soil Characteristics

Undisturbed soil samples were taken from the experimental site at six different depths (0 – 15, 15 – 30, 30 – 45, 45 – 60, 60 – 75 and 75 – 90 cm) and subjected to a standard laboratory method for determination of basic soil characteristics.

Table I: Description of Experimental Treatment

Treatment	Crop growth stages				Treatment description
	Initial	Dev.	Middle	Late	
T1	100%	100%	100%	100%	Irrigating 100% of ET _c in all stages.
T2	100%	50%	100%	100%	Irrigating 50% of ET _c during development stage and 100% at the remaining stages.
T3	100%	100%	50%	100%	Irrigating 50% of ET _c during middle stage and 100% at the remaining stages.
T4	100%	100%	100%	50%	Irrigating 50% during late stage and 100% at the remaining stages.
T5	100%	75%	100%	100%	Irrigating 75% of ET _c during development stage and 100% of ET _c at the remaining stages.
T6	100%	100%	75%	100%	Irrigating 75% of ET _c during middle stage and 100% of ET _c at the remaining stages.
T7	100%	100%	100%	75%	Irrigating 75% of ET _c during late stage and 100% of ET _c at the remaining stages.
T8	100%	50%	50%	50%	Irrigating 100% during the initial stage and 50% of ET _c at the remaining stages.
T9	100%	75%	75%	75%	Irrigating 100% during the initial stage and 76% of ET _c at the remaining stages.

2.5 Field Operations and Measurements

2.5.1 Determination of crop water requirement

The potential evapo-transpiration was computed using ET_o – Calculator (FAO Penman Monteith equation), Version 3.2 (FAO, 2012) for the duration of the irrigation season using meteorological data for the past 15 years and the crop evapotranspiration was calculated using Equation 2.

2.5.2 Irrigation

Furrow irrigation method was employed for water application. Water was applied to the furrow through the use of spiles. The discharge into the furrows through the spiles was calibrated by direct method to be 1.4litres/sec. The irrigation interval of seven (7) days was adopted because that is the predominant farmers practice in the study area. Water applied was based on the daily reference evapotranspiration computed from 15 years of climatic data (1999 – 2014) for the study location using ET_o – Calculator (FAO Penman Monteith equation), Version 3.2 (FAO, 2012). The depth of water applied per irrigation was calculated by summing the crop evapotranspiration (Equation 2) computed from the reference evapotranspiration ET_o – Calculator and the crop coefficient (K_c) for the duration of the irrigation interval.

$$ET_c = ET_o \times K_c \quad (2)$$

where:

ET_c = crop evapotranspiration, mm/day

ET_o = reference evapotranspiration, mm/day

K_c = crop coefficient

2.5.3 Soil moisture measurement

Soil moisture content measurement was carried out throughout the growing seasons with the use of Theta-probe (Type: ML2x) and Moisture Meter (HH2, DELTA-T DEVICES).

The actual crop evapotranspiration was calculated from the measured soil moisture content data obtained with Theta-Probe and moisture meter device using Equation 3, as outlined by Michael (1978).

$$ET_a = \sum_{i=1}^n \left[\frac{M_1 - M_2}{100} \right] D_i \times B_i \quad (3)$$

where :

ET_a = actual crop evapotranspiration (mm)

M_1 = gravimetric moisture content (g/g) at first sampling in the i th layer;

M_2 = gravimetric moisture content (g/g) at second sampling in the i th layer;

D_i = depth of i th layer (mm)

B_i = apparent specific gravity of the i th soil layer

n = number of layers within the soil profile

2.5.4 Determination of canopy cover

Green canopy cover was measured during the initial, development and middle crop growth stages of 2016/17 and 2018/19 field trials to obtain canopy cover development data. The Canopy cover was derived from pictures of the canopy taken overhead with a digital camera at around mid-day. The soil surface area covered by the green canopy was then measured from the pictures using IMAGE J software package. The Per cent canopy cover (CC) was then calculated using Equation 4.

$$\text{Canopy cover} = \frac{\text{soil surface area covered by the green canopy}}{\text{unit ground surface area}} \times 100\% \quad (4)$$

2.5.5 Determination of fruit yield and dry above ground biomass

Samples of the above ground biomass during the initial, development and middle crop growth stages were harvested from 0.75m² area of each treatment and dried and weighed to obtain biomass production data. Final Tomato fruits yield and above ground biomass was obtained from five (5) tagged plants in the centre ridge of each treatment measuring 1.35m² area (i.e. 1.8 x 0.75m). Tomato fruits harvested from the tagged plants (1.35m²) of each treatment were weighed fresh and after drying. Each treatment has an area of 1.8m x 0.75m which constitutes the net plot for final yield assessment.

2.6 Input Data for AquaCrop Model

The input data used for running of the AquaCrop model were: weather, soil, crop and irrigation scheduling (timing and depth of water applied). Five weather input variables used to run the AquaCrop model during the simulation were: daily maximum and minimum air temperatures,

daily rainfall, the mean annual carbon dioxide concentration in the bulk atmosphere from 1902 to 2099 and daily average evaporative demand of the atmosphere expressed as reference evapotranspiration (ET_o) for 15 years calculated with the use of ET_o calculator software (version 3.5). The rainfall input was not use as there was no rainfall event during the period of the two trials. The soil input variables is presented in Table 2; while the irrigation scheduling input data for 2016/17 and 2018/19 seasons were as shown in Tables 3 and 4 respectively.

2.7 Calibration and Validation of AquaCrop Model (5.0 Version)

Calibration of the AquaCrop model was accomplished by using the generated data from the field experiments during the 2016/17 irrigation season as model input and then simulating the model to predict the output viz, the yield, canopy cover, biomass and water balance. Subsequently, the predicted output values were compared with the observed values of the experimental plot. The difference between the model predicted output and the measured experimental output was minimized in each case by iteration process in which one specific input variable was chosen as the reference variable at a time and adjusting only those parameters that were known to influence the reference variable the most. The process was repeated successively to arrive at the closest match between the model simulated and observed experimental values for each treatment combinations. Finally, the observed experimental parameters that produced the best result in line with the measured output values were selected and used for the model calibration. The observed data generated during the 2018/19 season field trial was used to validate the model performance. Calibrated AquaCrop model was simulated with the input data of the experimental trial during the year 2018/19 to predict the fruit yield, biomass and water productivity. The criteria used in the model validation are statistical test and graphical plots of simulated and measured output.

2.8 Performance Evaluation of AquaCrop

Model performance evaluation was carried using graphical plots and statistical indicators. The statistical indicators that were used to evaluate the performance of AquaCrop model are: RMSE (root mean square error), NRMSE (normalized root mean square error), R2 (coefficient of determination), EF (Nash-Sutcliffe model efficiency coefficient), and d (Willmott index of agreement).

3. Results and Discussion

3.1 Soil Characteristics and Irrigation Scheduling

The soil characteristics of the study area that was used as soil input data for running the AquaCrop model was presented in Table 2 while the irrigation scheduling (timing and depth of water applied) for 2016/17 and 2018/19 field trial were presented in Table 3 and 4, respectively.

Table 2: Soil Characteristics at IAR Irrigation Farm, Kadawa

Depth	BD	Soil water content			Particle distribution (corrected to 20°C)			Textural class ^a	Soil PH	Soil EC	K _{sat}	TAW
		SAT	FC	PWP	Clay	Silt	Sand					
Cm	g/cm ³	%vol	% vol	% vol	%	%	%		Ratio	ds/m	mm/day	mm/m
0 – 15	1.56	41	22	10	10	34	56	Sandy loam	6.80	0.050	1,200	120
15 – 30	1.56	41	22	10	16	32	52	Sandy loam	6.87	0.065	1,200	120
30 – 45	1.56	41	22	10	16	32	52	Sandy loam	6.97	0.043	1,200	120
45 – 60	1.56	41	22	10	18	30	52	Sandy loam	6.95	0.035	1,200	120
60 – 75	1.42	46	31	15	18	32	50	Loam	6.95	0.065	500	160
75 – 90	1.42	46	31	15	16	34	50	Loam	6.88	0.040	500	160

^a Textural classification based on USDA; BD – Bulk density; FC – Field capacity; PWP – Permanent wilting point; EC – Electrical conductivity; K_{sat} – Saturated hydraulic conductivity; SAT – Volumetric soil water content at saturation; TAW – Total available water.

Table 3: Depth of Water Applied during 2016/17 Season

Treatments	Growth Stages				Seasonal Water applied (mm)
	Initial (0 – 28 DAT)	Development (29 – 60 DAT)	Middle (61 – 100 DAT)	Late (101 – 127 DAT)	
T1 (I ₁₀₀ D ₁₀₀ M ₁₀₀ L ₁₀₀)	115	98	212	129	554
T2 (I ₁₀₀ D ₅₀ M ₁₀₀ L ₁₀₀)	115	50	212	129	506
T3 (I ₁₀₀ D ₁₀₀ M ₅₀ L ₁₀₀)	115	98	107	129	449
T4 (I ₁₀₀ D ₁₀₀ M ₁₀₀ L ₅₀)	115	98	212	65	490
T5 (I ₁₀₀ D ₇₅ M ₁₀₀ L ₁₀₀)	115	73	212	129	529
T6 (I ₁₀₀ D ₁₀₀ M ₇₅ L ₁₀₀)	115	98	160	129	502
T7 (I ₁₀₀ D ₁₀₀ M ₁₀₀ L ₇₅)	115	98	212	98	523
T8 (I ₁₀₀ D ₅₀ M ₅₀ L ₅₀)	115	50	107	65	337
T9 (I ₁₀₀ D ₇₅ M ₇₅ L ₇₅)	115	73	160	98	446

DAT: Days after transplanting

Table 4: Depth of Water Applied during 2018/19 Season

Treatments	Growth Stages				Seasonal Water applied (mm)
	Initial (0 – 30 DAT)	Development (31 – 62 DAT)	Middle (63 – 102 DAT)	Late (103 – 129 DAT)	
T1 (I ₁₀₀ D ₁₀₀ M ₁₀₀ L ₁₀₀)	76	122	247	133	578
T2 (I ₁₀₀ D ₅₀ M ₁₀₀ L ₁₀₀)	76	62	247	133	518
T3 (I ₁₀₀ D ₁₀₀ M ₅₀ L ₁₀₀)	76	122	125	133	456
T4 (I ₁₀₀ D ₁₀₀ M ₁₀₀ L ₅₀)	76	122	247	67	512
T5 (I ₁₀₀ D ₇₅ M ₁₀₀ L ₁₀₀)	76	92	247	133	548
T6 (I ₁₀₀ D ₁₀₀ M ₇₅ L ₁₀₀)	76	122	186	133	517
T7 (I ₁₀₀ D ₁₀₀ M ₁₀₀ L ₇₅)	76	122	247	101	546
T8 (I ₁₀₀ D ₅₀ M ₅₀ L ₅₀)	76	62	125	67	330
T9 (I ₁₀₀ D ₇₅ M ₇₅ L ₇₅)	76	92	186	101	455

3.2 Calibrated Tomato Input Parameters for AquaCrop

The crop simulation input parameters used for AquaCrop model calibration are as shown in Table 5. During the calibration process the conservative parameters were adapted from the report of Raes *et al* (2010), these parameters are generally assumed to be applicable to a wide range of conditions and not specific for a given crop cultivar (Table 5). The time from transplant-to-transplant recovery, flowering, maximum canopy cover, maximum rooting depth, senescence and maturity as obtained from the field were 4, 32, 60, 52, 100 and 127 days, respectively (Table 5). The following model output were recorded: Length of flowering stage and length of building of harvest index, 56 and 89 days, respectively. The maximum and minimum effective rooting depth was set at 0.65 and 0.30 m, respectively. The water productivity (normalized for ETo and CO₂) adopted was 17.0 g/m² while the reference harvest index was set at 55% and the soil was set as sandy loam with initial soil moisture condition as wet dry.

Table 5: Tomato input parameters for AquaCrop Model calibration

Year used for calibration			2016/17	
	Description of Input parameter	Units	Value	Type
I. Crop phenology	Base temperature (T_{base})	°C	8.0	Conservative ¹
	Upper temperature (T_{Upper})	°C	28.0	Conservative ¹
	Canopy cover per seedling at 90% emergence (CC_0)	cm ² /plant	5	Conservative ²
	Number of plants per hectare	No	29,630 ^a	Management ³
	Time from sowing to emergence/transplant to recovery	days	4 ^a	Management ³
	Canopy growth coefficient (CGC)	%/day	14.5	Conservative ¹
	Maximum canopy cover (CC_x)	%	80 ^a	Management ³
	Time from transplant to start senescence	days	100 ^a	Cultivar ⁴
	Canopy decline coefficient (CDC)	%/day	8.0	Conservative ¹
	Time from sowing/transplant to maturity	days	127 ^a	Cultivar ⁴
	Time from sowing/transplant to flowering	days	32 ^a	Cultivar ⁴
	Length of flowering stage	days	56 ^a	Cultivar ⁴
	Minimum effective rooting depth (Z_0)	m	0.30	Management ³
	m	0.65	Management ³	
	-	1.5	Conservative ¹	

Year used for calibration		2016/17		
	Description of Input parameter	Units	Value	Type
	Maximum effective rooting depth (Z_x)	Days	52 ^a	Cultivar ⁴
	Shape factor describing root zone expansion	Days	60 ^a	
	Time from transplant to maximum rooting depth			
	Time from transplant to maximum canopy cover			
2. Crop	Crop coefficient at full canopy but prior to senescence (K_{cb_x})	%/day	1.10	Conservative ¹
Transpiration	Crop decline coefficient due to ageing, nitrogen deficiency, (K_c)	mm/day	0.15	Conservative ¹
	Effect of canopy cover on reducing soil evaporation in late stage		60	Conservative ¹
3. Biomass and yield	Water productivity normalized for ET_0 and CO_2 (WP)	g/m^2	17.0	Conservative ¹
		g/m^2	2.8	Conservative ¹
	Water productivity normalized for ET_0 and CO_2 during yield formation (as %WP* before yield formation)	%	55	Cultivar ⁴
		days	89	Cultivar ⁴
		%	15	Conservative ¹
	Reference harvest index (HI_0)			
	Building of harvest index			
	Allowable maximum increase of specified HI			
4. Soil Water Stresses	Depletion threshold for canopy expansion - Upper threshold ($P_{exp, Upper}$)	-	0.25	Conservative ¹
	Depletion threshold for canopy expansion - Lower threshold ($P_{exp, Lower}$)	-	0.55	Conservative ¹
	Depletion threshold for stomatal control - Upper threshold (P_{sto})	-	0.50	Conservative ¹
		-	0.70	Conservative ¹
	Depletion threshold for canopy senescence - Upper threshold (P_{sen})	-	0.90	Conservative ¹
	Depletion threshold for failure of pollination - Upper threshold (P_{pol})	-	3.0	Conservative ¹
		-	3.0	Conservative ¹
	Shape factor for water stress coefficient for canopy expansion	-	3.0	Conservative ¹
		$^{\circ}C$	8.0	Conservative ¹
	Shape factor for water stress coefficient for stomatal control	$^{\circ}C$	40	Conservative
	Shape factor for water stress coefficient for canopy senescence			
	Minimum air temperature below which pollination starts to fail			
	Maximum air temperature above which pollination starts to fail			

¹Conservative generally applicable; ²Conservative for a given species; ³Dependent on environment and/or management; ⁴Cultivar specific; a = data obtained from field

3.3 AquaCrop Model Calibration

Calibration results of dry fruit yield, biomass yield and seasonal evapotranspiration is presented in Table 6 while Figure 1 presents the relationship between the simulated dry fruit yield during model calibration. The simulated dry fruit yield ranged from 2.479 t/ha to 5.496 t/ha (Table 5). The simulated fruit and biomass yield and seasonal evapotranspiration of the different treatment

were compared with the measured values for the calibration trial (2016/17 irrigation season). The maximum and minimum dry fruit yield prediction error per cent of 17.7% and 1.9% were recorded in T8 (I₁₀₀D₅₀M₅₀L₅₀) and T3 (I₁₀₀D₁₀₀M₅₀L₁₀₀) respectively. The prediction error reported here is in agreement with what was reported by Darko *et al.*, (2016) that a maximum and minimum prediction error of 18.5% and 6.4% were recorded in treatment of “50% deficit level throughout the growth stages” and full irrigation treatment respectively. The simulated and measured fruit yield correlated well with R² value of 0.88 indicating that the model explained 88% of the relationship between measured and simulated tomato fruit yield. Student T-test was carried out to evaluate the difference between measured and simulated fruit yield. The result indicates that the difference between measured and simulated fruit yield was not significant at 5% probability level with $t_{tab} = 2.306$, while $t_{cal} = 1.503$.

Table 6: Calibration Results of Dry-fruit Yield, Biomass Yield and Seasonal Evapotranspiration

Treatment	Dry fruit yield (t/ha)			Total Biomass yield (t/ha)			Crop water use (mm)		
	Sim.	Mea.	Pe	Sim.	Mea.	Pe	Sim.	Mea.	Pe
T1 (I ₁₀₀ D ₁₀₀ M ₁₀₀ L ₁₀₀)	5.496	5.387	2.0	9.966	9.753	2.2	528.9	517.5a	2.2
T2 (I ₁₀₀ D ₅₀ M ₁₀₀ L ₁₀₀)	4.621	4.530	2.0	8.223	7.417	10.9	476.8	472.1e	1.0
T3 (I ₁₀₀ D ₁₀₀ M ₅₀ L ₁₀₀)	3.793	3.722	1.9	7.208	7.698	-6.4	419.7	424.3g	-1.1
T4 (I ₁₀₀ D ₁₀₀ M ₁₀₀ L ₅₀)	5.050	4.951	2.0	9.313	8.588	8.4	495.6	486.2d	1.9
T5 (I ₁₀₀ D ₇₅ M ₁₀₀ L ₁₀₀)	5.127	5.026	2.0	9.191	8.777	4.7	502.5	515.4b	-2.5
T6 (I ₁₀₀ D ₁₀₀ M ₇₅ L ₁₀₀)	4.724	4.333	9.0	8.758	8.377	4.5	476.2	486.3d	-2.1
T7 (I ₁₀₀ D ₁₀₀ M ₁₀₀ L ₇₅)	5.304	5.127	3.5	9.675	9.225	4.9	512.6	506.5c	1.2
T8 (I ₁₀₀ D ₅₀ M ₅₀ L ₅₀)	2.479	3.012	-17.7	4.683	5.462	-14.3	343.6	336.4h	2.1
T9 (I ₁₀₀ D ₇₅ M ₇₅ L ₇₅)	4.182	4.099	2.0	7.721	7.272	6.2	439.7	445.8f	-1.4

Sim- simulated; Mea- measured; Pe – Prediction error Per cent

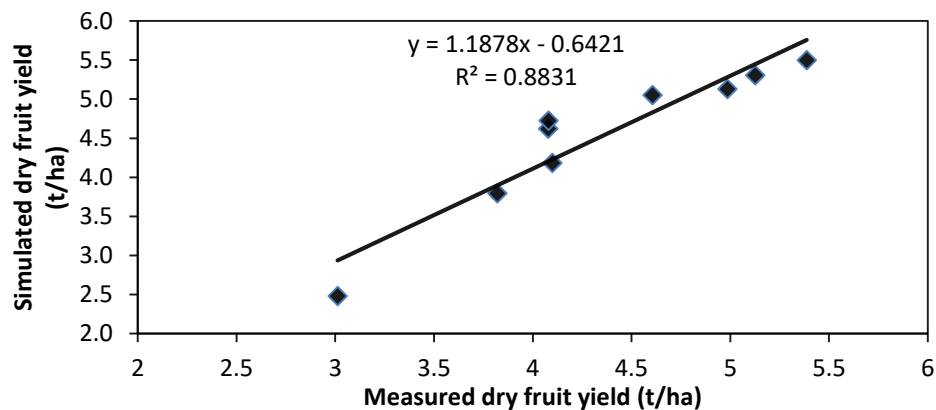


Figure 1: Comparison of simulated and measured dry fruit yield during calibration

The comparison between simulated and measured Total biomass yield during calibration is presented in Figure 2. A good fit was achieved between the measured and simulated total biomass yield with R² value of 0.92. The result of the student t – test, $t_{tab} = 2.306$, while $t_{cal} = 1.243$

indicates no any significant difference between measured and simulated total biomass yield at 5% probability level.

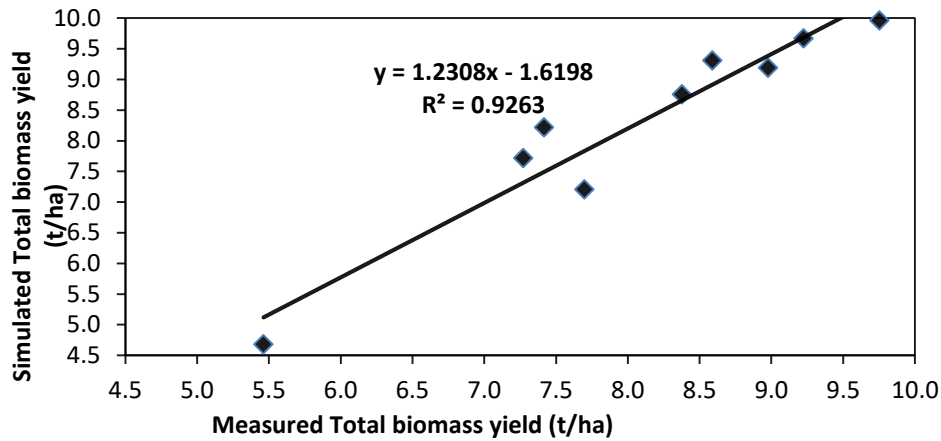


Figure 2: Comparison between simulated and measured Total biomass yield during calibration

The R^2 values obtained for fruit and biomass (0.88 and 0.92 respectively) is in agreement with Rinaldi *et al.* (2011) who reported an averages R^2 value of 0.84 and 0.96 for fruit and total biomass yield respectively for a three (3) years experimental data in Mediterranean region; and Kale and Wadatkar (2017) who obtained R^2 value of 0.87 and 0.95 for fruit and total biomass yield in India.

The comparison between measured and simulated seasonal crop water use during calibration is presented in Figure 3. The simulated values varied from 344 to 529 mm while the field measured values varied from 336 to 518 mm as shown in Table 5. Student T-test result ($t_{\text{tab}} = 2.306$, $t_{\text{cal}} = 0.188$) for the comparison between field measured and simulated values of the seasonal evapotranspiration indicated that the difference was not significant at 5% probability level. Furthermore, the simulated and measured seasonal evapotranspiration correlated well giving R^2 value of 0.97 indicating that the model explained 97% of the relationship.

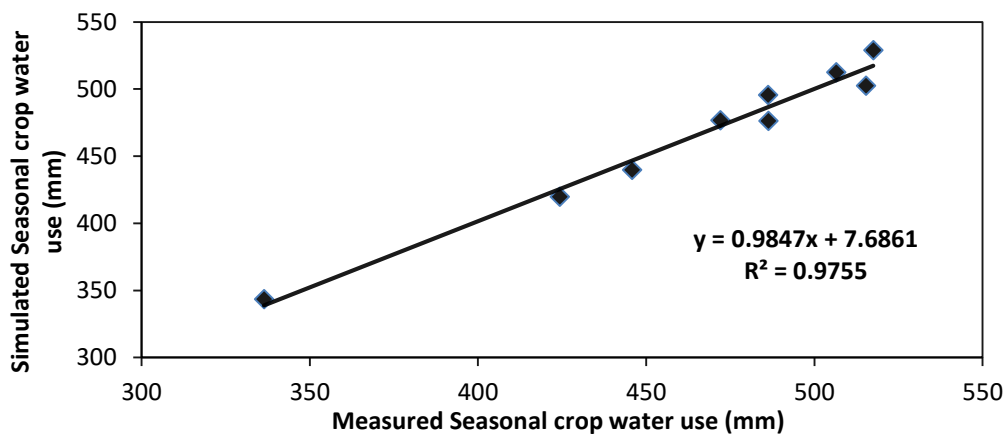


Figure 3: Comparison between simulated and measured seasonal crop water use during calibration

The result of the statistical indicators used in evaluating the performance of the AquaCrop model for the final calibration test is presented in Table 7. The coefficient of determination (R^2) for fruit yield, total biomass yield and crop water use were 0.88, 0.92 and 0.97 respectively. Their values are above 0.8 which are considered as good. The root mean square error (RMSE) obtained were 0.37 t/ha, 0.54t/ha and 8.54 mm for fruit, total biomass and crop water use respectively. They are close to 0 which is good since the range is from 0 to positive infinity (in which the former indicates 'good' and the latter 'poor' model performance). The normalized root mean square error (NRMSE) for fruit, total biomass and crop water use were 8.3, 6.5 and 1.8% respectively which are considered very good since the values are less than 10%. The Nash-Sutcliffe model efficiency (EF) is 0.99 for all the three parameters (fruit, total biomass and crop water use) which is greater than 0.8 and considered as very good, indicating that there is a perfect match between measured and simulated. The Willmott's index of agreement (d) recorded for fruit. Total biomass and crop water use is 0.99 which indicate a good agreement between measured and model-simulated. Since all the five statistical indices used for the model evaluation are positive, it implies that the AquaCrop model can be used for simulating yield and water balance. The coefficient of residual mass (CRM) indicates that the model has the tendency to over predict fruit, total biomass at harvest and seasonal crop water use by 4%, 3% and 0.1% respectively.

Table 7: Statistical indices of the comparison between simulated and measured dry fruit and dry biomass yield at harvest and seasonal crop water use during calibration (2016/17 season)

Statistical performance indices	Dry fruit yield (DFY)	Total Dry biomass yield (TBY)	Crop water use
R^2	0.88	0.92	0.97
RMSE*	0.37	0.54	8.54
NRMSE (%)	8.3	6.5	1.8
EF	0.99	0.99	0.99
d (Willmott's index of agreement)	0.99	0.99	0.99
CRM	0.04	0.03	0.001

*unit of RMSE for Fruit and Biomass yield is t/ha; Crop water use is mm

The simulated and field measured crop water productivity with respect to dry fruit is presented in Table 8 while the statistical model performance indicators are presented in Table 9. The crop water productivity reflects the water utilization efficiencies, the rate at which the water supplied is converted to harvestable produce. It gives a quantitative measurement of dry fruit produced per cubic meter of water used in evapotranspiration. The per cent error between measured and simulated crop water productivity varied from 0 to 17.5%. The statistical indices used for the model evaluation was considered as a good performance, which indicates that the model is capable in predicting crop water productivity. The CRM shows that the model has a tendency to under-predict crop water productivity by 6%.

Table 8: Comparison of simulated and measured crop water productivity (dry fruit) during model calibration

Treatments	CWP (kg/m ³)		
	Sim.	Mea.	Pe
T1(I ₁₀₀ D ₁₀₀ M ₁₀₀ L ₁₀₀)	1.04	1.04	0.0
T2(I ₁₀₀ D ₅₀ M ₁₀₀ L ₁₀₀)	0.76	0.86	11.6
T3(I ₁₀₀ D ₁₀₀ M ₅₀ L ₁₀₀)	0.90	0.90	0.0
T4(I ₁₀₀ D ₁₀₀ M ₁₀₀ L ₅₀)	1.00	0.95	5.3
T5(I ₁₀₀ D ₇₅ M ₁₀₀ L ₁₀₀)	0.80	0.97	17.5
T6(I ₁₀₀ D ₁₀₀ M ₇₅ L ₁₀₀)	0.84	0.84	0.0
T7(I ₁₀₀ D ₁₀₀ M ₁₀₀ L ₇₅)	0.96	1.01	5.0
T8(I ₁₀₀ D ₅₀ M ₅₀ L ₅₀)	0.85	0.90	5.6
T9(I ₁₀₀ D ₇₅ M ₇₅ L ₇₅)	0.76	0.92	17.4

Table 9: Statistical indices of the comparison between simulated and measured dry fruit yield water productivity at harvest during calibration (2016/17 season)

Statistical performance indices	Dry fruit water productivity
RMSE*	0.09
NRMSE (%)	10.2
EF	0.98
d (Willmott's index of agreement)	0.99
CRM	-0.06

*unit of RMSE for Fruit yield is kg/m³

3.4 AquaCrop Model validation

The observed data generated during the 2018/19 season field trial was used to validate the model performance. Calibrated AquaCrop model was simulated with the input data of the experimental trial during the year 2018/19 to predict the dry fruit yield, biomass and water productivity. As a summary of the outcome of the simulations, the simulated dry fruit yield, total biomass yield and seasonal crop water use of the different irrigation treatments were compared with the measured values generated during the 2018/19 field trial and the results is presented in Table 10 while Figure 4, 5 and 6 shows the relationship between the simulated dry fruit yield, total biomass yield and seasonal crop water use, respectively, during model validation.

Table 10: Validation results of Dry fruit yield, Biomass yield and Seasonal Evapotranspiration

Treatment	Dry fruit yield (t/ha)			Total Biomass yield (t/ha)			Crop water use (mm)		
	Sim.	Mea.	Pe	Sim.	Mea.	Pe	Sim.	Mea.	Pe
T1 (I ₁₀₀ D ₁₀₀ M ₁₀₀ L ₁₀₀)	5.542	5.534	0.1	10.041	9.989	0.5	561.2	563.1	-0.3
T2 (I ₁₀₀ D ₅₀ M ₁₀₀ L ₁₀₀)	4.677	4.134	13.1	8.388	7.582	10.6	500.3	480.4	4.1
T3 (I ₁₀₀ D ₁₀₀ M ₅₀ L ₁₀₀)	4.094	4.121	-0.7	7.584	8.074	6.1	453.2	451.8	0.3
T4 (I ₁₀₀ D ₁₀₀ M ₁₀₀ L ₅₀)	5.321	4.878	9.1	9.691	8.966	8.1	540.0	501.3	7.7
T5 (I ₁₀₀ D ₇₅ M ₁₀₀ L ₁₀₀)	5.296	5.154	2.8	9.544	9.345	2.1	541.4	543.5	-0.4
T6 (I ₁₀₀ D ₁₀₀ M ₇₅ L ₁₀₀)	4.911	4.267	15.1	8.981	8.796	2.1	514.1	502.1	2.4
T7 (I ₁₀₀ D ₁₀₀ M ₁₀₀ L ₇₅)	5.472	5.295	3.3	9.928	9.723	2.1	554.5	539.4	2.8
T8 (I ₁₀₀ D ₅₀ M ₅₀ L ₅₀)	2.972	3.134	-5.2	5.516	5.577	1.1	372.6	326.6	14.1
T9 (I ₁₀₀ D ₇₅ M ₇₅ L ₇₅)	4.453	4.369	1.9	8.126	7.963	2.0	478.6	451.2	6.1

The simulated fruit yield varied from 2.972 to 5.542 t/ha while the biomass yield varied from 5.516 to 10.041 t/ha (Table 10). The result of student t-test indicates that the difference between measured and simulated fruit yield was not significant at 5% probability level with $t_{tab} = 2.306$, while $t_{cal} = 2.235$. Similarly, the result of the student t – test, $t_{tab} = 2.306$, while $t_{cal} = 1.529$ indicates no any significant difference between measured and simulated total biomass yield at 5% probability level. The fruit yield prediction error range from 0.1 to 15.1% and that of biomass yield range from 1.1 to 10.6% indicating that the model was able to simulate yield of tomato as expected. For the seasonal crop water use, the prediction error ranged from 0.3 to 14.1% indicating that AquaCrop model was able to simulate the seasonal crop water use relatively accurately. The prediction error reported herein is in agreement with Darko et al. (2016) who obtained prediction error ranging from 3.1 to 14.4% for seasonal crop water use.

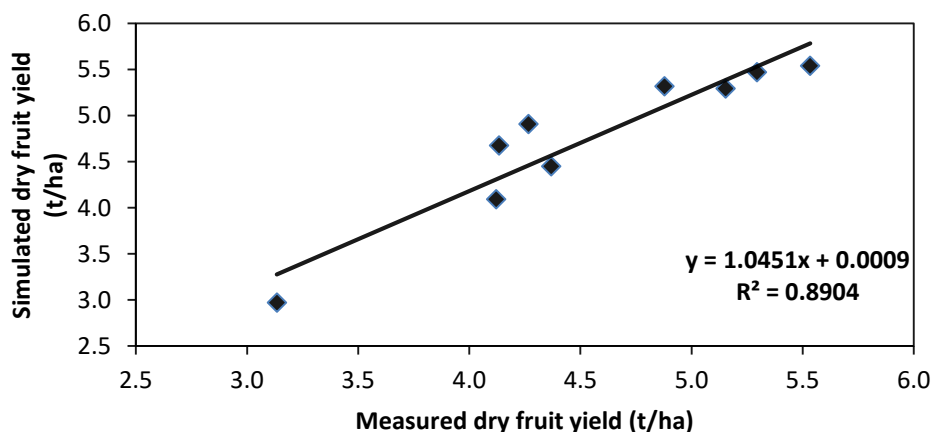


Figure 4: Comparison of simulated and measured dry fruit yield during validation

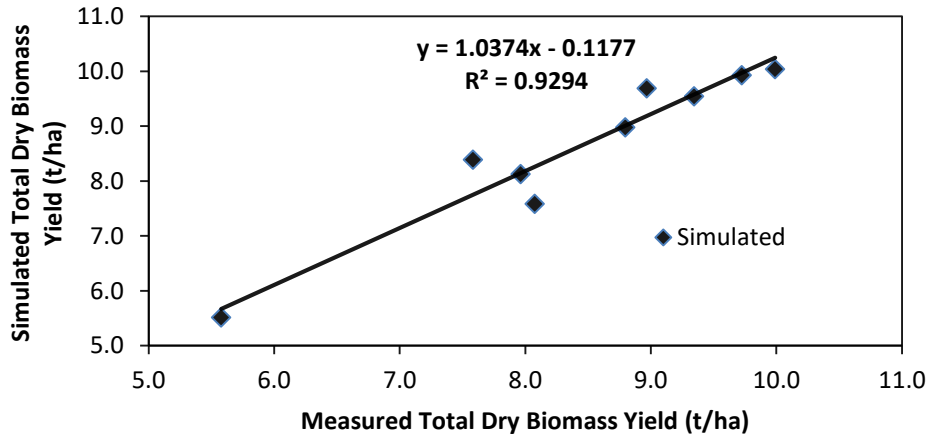


Figure 5: Comparison between simulated and measured Total biomass yield during validation

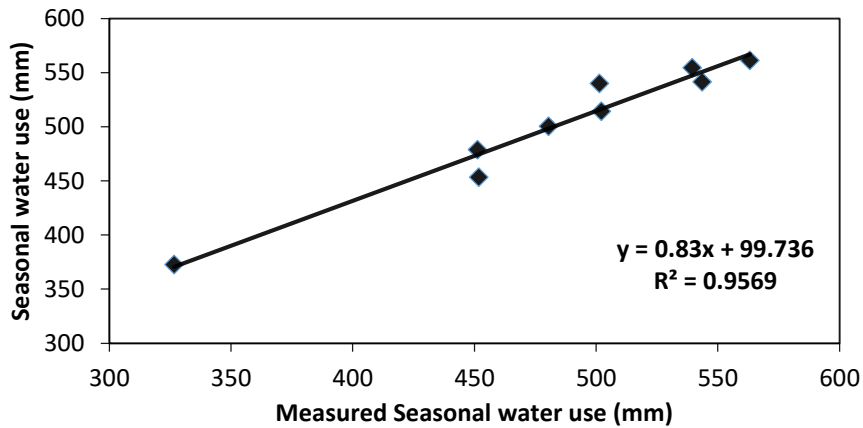


Figure 6: Comparison between Simulated and Measured seasonal water use during validation

The statistical indices for the model validation are presented in Table II. The R^2 values for fruit yield, biomass yield and seasonal crop water use were 0.89, 0.92 and 0.96 respectively which are considered good since the values are above 0.8. The RMSE obtained for fruit yield (0.33 t/ha), biomass yield (0.42 t/ha) and seasonal crop water use (23.9 mm) are closer to 0 than positive infinity and are considered as good. Furthermore, the NRMSE values for fruit, biomass and seasonal crop water use were 7.0, 4.8 and 4.8% respectively are less than 10% and are rated as very good. The Nash-Sutcliffe model efficiency (EF) and Willmott's index of agreement (d) for dry fruit, biomass and seasonal crop water use is 0.99 which indicates a perfect agreement between measured and model simulated values. The CRM indicates that the model has the tendency to over-predict fruit yield and seasonal crop water use by 4% and biomass yield by 2%. However, Student T-test result ($t_{tab} = 2.306$, $t_{cal} = 2.999$) for the comparison between field measured and simulated values of the seasonal evapotranspiration indicated that the difference was significant at 5% probability level but the other indices for model performance evaluation indicated a perfect agreement. The comparison between field measured and model simulated

crop water productivity for dry fruit yield during validation is presented in Table 12 while Table 13 shows the statistical performance indicators. The prediction error ranged from 0 to 16.7%. The statistical indices used for the model evaluation RMSE (0.07 kg/m³); NRMSE (7.7%); EF (0.99); and d (0.99), were considered as a good performance indicating that the model is capable in predicting crop water productivity. The CRM shows that the model has a tendency to over-predict crop water productivity by 1%.

Table 11: Statistical indices of the comparison between simulated and measured dry fruit and dry biomass yield at harvest and seasonal crop water use during validation (2018/19 season)

Statistical performance indices	Dry fruit yield (DFY)	Total Dry biomass yield (TBY)	Crop water use
R ²	0.89	0.92	0.96
RMSE*	0.33	0.42	23.9
NRMSE (%)	7.0	4.8	4.8
EF	0.99	0.99	0.99
d (Willmott's index of agreement)	0.99	0.99	0.99
CRM	0.04	0.02	0.04

*unit of RMSE for Fruit and Biomass yield is t/ha; Crop water use is mm

Table 12: Comparison of simulated and measured crop water productivity (dry fruit) during model validation

Treatments	CWP (kg/m ³)		
	Sim.	Mea.	Pe (%)
T1(I ₁₀₀ D ₁₀₀ M ₁₀₀ L ₁₀₀)	0.99	0.98	1.00
T2(I ₁₀₀ D ₅₀ M ₁₀₀ L ₁₀₀)	0.94	0.86	9.30
T3(I ₁₀₀ D ₁₀₀ M ₅₀ L ₁₀₀)	0.91	0.91	0.00
T4(I ₁₀₀ D ₁₀₀ M ₁₀₀ L ₅₀)	0.99	0.97	2.10
T5(I ₁₀₀ D ₇₅ M ₁₀₀ L ₁₀₀)	0.98	0.95	3.20
T6(I ₁₀₀ D ₁₀₀ M ₇₅ L ₁₀₀)	0.96	0.85	12.9
T7(I ₁₀₀ D ₁₀₀ M ₁₀₀ L ₇₅)	0.99	0.98	1.00
T8(I ₁₀₀ D ₅₀ M ₅₀ L ₅₀)	0.80	0.96	16.7
T9(I ₁₀₀ D ₇₅ M ₇₅ L ₇₅)	0.93	0.97	4.10

Table 13: Statistical indices of the comparison between simulated and measured dry fruit yield water productivity at harvest during validation (2018/19 season)

Statistical performance indices	Dry fruit water productivity
RMSE*	0.07
NRMSE (%)	7.70
EF	0.99
d (Willmott's index of agreement)	0.99
CRM	0.01

*Unit of RMSE for Fruit yield is kg/m³

3.3 Model Simulation along Crop Growth Stages

3.3.1 Canopy cover simulation

The simulated canopy cover (CC) for the crop growth stages is presented in Table 14. The simulated canopy cover was at par to the measured values during the initial stage with a prediction error of 48% for treatment T6 and 47% for the remaining treatments. However, the simulated CC were closer to the measured values during the development and middle stage except for T2 (I₁₀₀D₅₀M₁₀₀L₁₀₀) and T5 (I₁₀₀D₇₅M₁₀₀L₁₀₀) which recorded 23% and 15% prediction error respectively during the middle stage. One common observation with regards to these two treatments (T2 and T5) was that the deficit was imposed in the development stage while in the middle stage (where the highest prediction errors were recorded) the treatments received full irrigation. Perhaps, this suggest that the model is insensitive to detecting sudden change in water applied after transition from 50 and 25% deficit in development stage to full irrigation in the middle stage. Table 15 shows the statistical indices for the comparison between simulated and measured CC for the growth stages. The AquaCrop model fails to simulate CC accurately during the initial stage as indicated by normalized root mean square error (NRMSE), Nash-Sutcliffe model efficiency (EF) and Willmott's index of agreement (d) values of 88%, 0.75 and 0.89 respectively. The coefficient of residual mass (CRM) value of -0.88 obtained during the initial stage indicates that the model has the tendency of under-predicting canopy cover by about 88%. However, the model was able to simulate CC relatively well during the development and middle stages (as indicated in Table 3.10) with a tendency of over-predicting CC by about 2% in development stage and under-predicting CC by about 11% during the middle stage.

Table 14: Comparison between measured and simulated canopy cover during initial, development and middle crop growth stages

Treatments	Initial Stage (%) (0 – 28 DAT)			Development Stage (%) (29 – 60 DAT)			Middle Stage (%) (61 – 100 DAT)		
	Sim	Mea	Pe	Sim	Mea	Pe	Sim	Mea	Pe
	T1(I ₁₀₀ D ₁₀₀ M ₁₀₀ L ₁₀₀)	4.0	7.5	47	57.3	58.6	2	73.2	79.8
T2(I ₁₀₀ D ₅₀ M ₁₀₀ L ₁₀₀)	4.0	7.5	47	58.6	56.6	4	59.1	76.8	23
T3(I ₁₀₀ D ₁₀₀ M ₅₀ L ₁₀₀)	4.0	7.5	47	60.1	58.6	3	73.3	79.8	8
T4(I ₁₀₀ D ₁₀₀ M ₁₀₀ L ₅₀)	4.0	7.5	47	60.1	58.6	3	73.3	79.8	8
T5(I ₁₀₀ D ₇₅ M ₁₀₀ L ₁₀₀)	4.0	7.5	47	59.9	58.6	2	68.2	79.8	15
T6(I ₁₀₀ D ₁₀₀ M ₇₅ L ₁₀₀)	4.0	7.7	48	60.1	58.6	3	73.3	79.8	8
T7(I ₁₀₀ D ₁₀₀ M ₁₀₀ L ₇₅)	4.0	7.5	47	60.1	58.6	3	73.3	79.8	8
T8(I ₁₀₀ D ₅₀ M ₅₀ L ₅₀)	4.0	7.5	47	58.6	58.6	0	59.5	65.9	10
T9(I ₁₀₀ D ₇₅ M ₇₅ L ₇₅)	4.0	7.5	47	59.9	58.6	2	68.2	65.9	3

Table 15: Statistical indices of the comparison between simulated and measured canopy cover during initial, development and middle crop growth stages

Statistical performance indices	Initial Stage	Dev. Stage	Middle Stage
	(%) (0 – 28 DAT)	(%) (29 – 60 DAT)	(%) (61 – 100 DAT)
RMSE (t/ha)	3.52	1.42	8.86
NRMSE (%)	88.1	2.4	12.8
EF	0.75	0.99	0.98
d (Willmott’s index of agreement)	0.89	0.99	0.99
CRM	-0.88	0.02	-0.12

3.3.2 Above-ground biomass simulation

Above ground biomass refers to a conglomeration of stems, leaves, flowers, etc., and is derived from the amount of water transpired by means of crop water productivity after normalization for CO₂ and ETo. Table 16 shows the simulated and measured above ground biomass production during initial, development and middle stage for tomato while Table 17 presents the statistical indices for the comparison of model simulated and measured above ground biomass for the crop growth stages. The simulated above ground biomass are relatively closer to the measured values during the three growth stages with a prediction error of 0 to 7%, 0 to 37% and 1 to 33% during the initial, development and middle stage respectively. The CRM values of -0.05, 0.17 and 0.13 obtained for initial, development and middle stage respectively indicates the tendency of the model to under-predict the above ground biomass by 5% in the initial stage and over-predict above ground biomass by 17% and 13% during the development and middle stage respectively.

Table 16: Comparison between measured and simulated above ground biomass during initial, development and middle crop growth stages

Treatments	Initial Stage (t/ha)			Development Stage (t/ha)			Middle Stage (t/ha)		
	Sim	Mea	Pe	Sim	Mea	Pe	Sim	Mea	Pe
T1(I ₁₀₀ D ₁₀₀ M ₁₀₀ L ₁₀₀)	0.094	0.101	7	1.410	1.105	28	4.131	4.153	1
T2(I ₁₀₀ D ₅₀ M ₁₀₀ L ₁₀₀)	0.094	0.101	7	1.535	1.123	37	3.254	3.205	2
T3(I ₁₀₀ D ₁₀₀ M ₅₀ L ₁₀₀)	0.094	0.101	7	1.544	1.123	37	4.216	3.205	32
T4(I ₁₀₀ D ₁₀₀ M ₁₀₀ L ₅₀)	0.094	0.101	7	1.544	1.123	37	4.257	3.205	33
T5(I ₁₀₀ D ₇₅ M ₁₀₀ L ₁₀₀)	0.094	0.101	7	1.542	1.123	37	3.836	3.205	20
T6(I ₁₀₀ D ₁₀₀ M ₇₅ L ₁₀₀)	0.094	0.094	0	1.544	1.544	0	4.252	3.963	7
T7(I ₁₀₀ D ₁₀₀ M ₁₀₀ L ₇₅)	0.094	0.101	7	1.544	1.123	37	4.257	3.205	33
T8(I ₁₀₀ D ₅₀ M ₅₀ L ₅₀)	0.094	0.094	0	1.535	1.545	1	3.181	3.317	4
T9(I ₁₀₀ D ₇₅ M ₇₅ L ₇₅)	0.094	0.094	0	1.542	1.545	0	3.805	3.317	15

Table 17: Statistical indices of the comparison between simulated and measured above ground biomass during initial, development and middle crop growth stages

Statistical performance indices	Initial Stage (%)	Development Stage (%)	Middle Stage (%)
RMSE (t/ha)	0.01	0.33	0.66
NRMSE (%)	6.1	21.5	17.0
EF	0.99	0.93	0.95
d (Willmott's index of agreement)	0.99	0.98	0.99
CRM	-0.05	0.17	0.13

4. Conclusion

From the study reported herein, it can be concluded that:

1. The evaluation of the model using calibration and validation trials data set indicated that the model was able to simulate tomato fruit and biomass yield, seasonal crop water use and fruit water productivity at harvest satisfactorily in full ETc and water stress condition.
2. AquaCrop model was able to simulate fruit yield and biomass yield along the crop growth stages with sufficient accuracy but fails to simulate CC accurately during the initial stage as indicated by normalized root mean square error (NRMSE), model efficiency (EF) and Willmott's index of agreement (d) values of 88%, 0.75 and 0.89 respectively and the coefficient of residual mass (CRM) value of -0.88.
3. AquaCrop model is simple, robust, require minimal input data and found to be accurate in simulating soil water balance, fruit and biomass yield of Tomato. Therefore, it is recommended for used in evaluation of irrigation scheduling and water management strategies that will improve crop water productivity of tomato crop in Northern Nigeria.

Acknowledgments

This research is part of the project entitled "Simulation of Soil Water Balance, Response to Water Stress and Yield of Furrow Irrigated Tomato Using AquaCrop Model", funded by the Tertiary Educational Trust Fund (TET-Fund) of Nigeria under the Institutional Based Research (IBR) funding Scheme. We thank both TET-Fund and Management of Ahmadu Bello University for providing the fund and support for the conduct of the field experiments.

References

Bazza, M. 1999. Improving irrigation management. (Kirda, C., Moutonnet, P., Hera, C and Nielsen, DR. (eds)). Crop yield response to deficit irrigation, Dordrecht, The Netherlands, Kluwer Academic Publishers.

Darko, RO., Yan, HF., Liu, JP. and Abbey, A. 2016. Calibration and validation of AquaCrop for deficit and full irrigation of tomato. *Int. Journal of Agricultural and Biological Engineering*, 9(3): 104 – 110. DOI: 10.3965/j.ijabe.20160903.1812

Doorenbos, J. and Kassam, AH. 1979. Yield response to water. Irrigation and Drainage Paper no. 33. FAO, Rome.

FAO. 2012. ETo Calculator. Land and Water Digital Media Series No. 36, FAO, Rome, Italy. Website: <http://www.fao.org/nr/water/ETo.html>.

Farahani, HJ., Izzi, G. and Oweis, TY. 2009. Parameterization and evaluation of the AquaCrop model for full and deficit irrigated cotton. *Agronomy Journal*, 101: 469–476.

García-Vila, M., Fereres, E., Mateos, L., Orgaz, F. and Steduto, P. 2009. Deficit irrigation optimization of cotton with AquaCrop. *Agronomy Journal*, 36: 21–31.

Heng, L. K., Hsiao, T., Evett, S., Howell, T. and Steduto, P. 2009: Validating the FAO AquaCrop model for irrigated and water deficient field maize. *Agronomy Journal*, 101: 488 – 498

Hsiao, TC., Heng, L., Steduto, P., Rojas-Lara, B., Raes, D. and Fereres, E. 2009. AquaCrop – the FAO crop model to simulate yield responses to water: III. Parameterization and testing for maize. *Agronomy Journal*, 101: 448 – 459

Igbadun, HE., Mahoo, HF., Tarimo, AKPR. and Salim, BA., 2006: Crop water productivity of an irrigated maize crop in Mkoji sub-catchment of the Great Ruaha River Basin, Tanzania. *Agricultural Water Management*, 85: 141–150.

Kale, MU. and Wadatkari, SB. 2017. Application of soft computing technique to simulate yield of irrigated tomato. *International Journal of Pure and Applied Research in Engineering and Technology*, (2): 386 – 393. Available online at: <http://www.ijpret.com>.

Michael, AM. 1978. Irrigation Theory and Principles. Vikas Publishing House, PVT. Ltd. New Delhi, India.

Raes, D., Steduto, P., Hsiao, TC. and Fereres, E. 2009. AquaCrop—The FAO crop model for predicting yield response to water: II. Main algorithms and soft ware description. *Agronomy Journal*, 101:438–447

Raes, D., Steduto, P., Theodore, C., Hsiao, TC. and Fereres, E. 2010: Reference Manual, Annexes. Annex I. Crop parameters – AquaCrop, 34 – 38.

Steduto, P., Hsiao, T C., Raes, D. and Fereres, E. 2009. AquaCrop – the FAO crop model to simulate yield response to water: I. Concepts and underlying principles. *Agronomy Journal*, 101. 426 – 437