Performance of AquaCrop Model in Simulating Tuber Yield of Potato (Solanum tuberosum L.) under Various Water Availability Conditions in Mekelle Area, Northern Ethiopia

Yibrah Gebremedhin[1] Araya Berhe[2] Amsalu Nebiyu[3]
1.Tigray Agricultural Research Institute, Alamata Agricultural Research Center, P.O.Box 54, Alamata, Ethiopia
2.Mekelle University, Department of Crop and Horticultural Sciences, P. O. Box 3057, Mekelle, Ethiopia
3.Jimma University College of Agriculture and Veterinary Medicine, P. O. Box 307, Jimma, Ethiopia
*Corresponding Author Email: yibrah99@yahoo.com

Abstract
Potato is sensitive to high temperature and moisture deficits which could be one of the major reason for low potato production in Ethiopia. The objective of this study was to validate and apply AquaCrop model for devising better water management strategies for optimal potato production in the region based on experimental data conducted at Mekelle areas (Mekelle University (MU) and Mekelle Agricultural Research Center (MARC)) during the cropping season in 2012; There were three treatments of water: Full Supplementary (FSI), Deficit Irrigation (DI) and Rainfed (RF) laid out in RCBD with three replications. AquaCrop model was calibrated and validated to simulate the observed WUE, growth and yield of potato. Results of the statistical parameters showed that AquaCrop model was able to accurately simulate the final dry tuber yield (E=0.96 and NRMSE=3.49%), water use efficiency (E=0.33 and NRMSE=13.8%), and total biomass (E=0.72 and NRMSE=7%) at MU site. Similarly, the model was able to simulate final tuber yield (E=0.84 and NRMSE=8%) and WUE(E=0.49 and NRMSE=1.58%) at MARC. Whereas, biomass yield was not accurately simulated by the model (E=-1.81 and NRMSE=27.1%) for MARC site. Thus, AquaCrop model could be used for planning and predicting irrigation management purposes.
Keywords: AquaCrop model, Calibration, Validation, Simulation

1.Introduction

Potato (*Solanum tuberosum* L.) belongs to the genus Solanum (Correll, 1962) and is a major world food crop and by far the most important vegetable crop in terms of quantities produced and consumed worldwide (FAO, 2005). The crop was introduced to Ethiopia around 1858 by Schimper, a German botanist (Berga *et al*., 1994).It is one of the tuber crops grown in Ethiopia by approximately one million farmers (CSA, 2008/2009). Potato is regarded a high-potential food security crop because of its ability to provide a high yield of high-quality product per unit input with a shorter crop cycle (mostly < 120 days) than major cereal crops like maize (Adane *et al*., 2010). In volume of world crop production, potato ranks fourth following wheat, maize, and rice and among the root and tuber crops potato ranks top followed by cassava, sweet potato and yams in that order (FAO, 2008).

Ethiopia is endowed with suitable climatic and edaphic conditions for potato production. However, the national average yield is about 7- 8 tons/ha, which is very low as compared to the world's average production of 15 tons per hectare (FAO, 2011). One of the problems for the low yield of potato production are like drought and flood, pests and diseases, soil erosion, shift in rainfall pattern and decline in available water are the major ones (Deressa, 2007). Potato crop faced challenges from changing seasonal rainfall patterns due to its sensitivity to soil water deficits (FAO, 2012). Variability in precipitation in the region has been manifested with extended dry spell, erratic and highly variable in space and time (WFP, 2009). The climate is mainly semi-arid and for most of the region the major rainy season (locally called *kiremt*) lasts for 2 to 3 months, between mid- June and mid-September. The annual rainfall of the study area is uni-modal with about 80% of the precipitation falling in a two and half month's period during summer (NMSA, 2001).Due to this reason, there is a need to improve the water use efficiency for potato production to obtain more crop per drop with declining irrigation resources and the uncertainty in temporal and spatial distribution of rainfall. Farmers in the area are finding difficulty in how use the limited irrigation water resource to tackle the shortage of rainfall and dry spell in the length of growing period of potato.

Among many, one of the mechanisms/ strategies to stabilize and improve productivity of rainfed Potato is to increase crop productivity per unit of water and application of supplementary irrigation to fill the gaps by dry spells (FAO, 1990). The development of crop growth models has increased understanding of the link between production factors and crop productivity Hoogenboom (2000). However, validated crop models are needed to evaluate alternative water productivity strategies in such dry land areas. Taking into account its user friendliness, its application in crop water productivity and water management strategies and other agronomic management scenarios, AquaCrop model was found to be the most suitable crop model for this study.

Objective

The general objective of this study was to evaluate Performance of AquaCrop model in simulating tuber yield of Potato under various water availability in the study area.

The specific objectives were:

- To calibrate and validate AquaCrop model for simulating potato tuber yield and biomass under various water management
- To develop optimal water management strategies

2. Materials and Methods

2.1 Description of the Study Area

The experiment was conducted during the cropping season in 2012 at Mekelle area which is found 780 kilometers north of the capital, Addis Ababa. The experiment was caried out at two sites: Mekelle agricultural research center (MARC) (at a latitude and longitude of 13°29′N and 39°28′E, respectively and with an elevation of 2070 m.a.s.l) and Mekelle University (MU) sites (at a longitude and latitude of $39^0$6' E and $13^0$3'N and with an eleveation of 2112 m a s l). The soil type at Mekelle University is cambisol soil with sandy clay loam texture whereas at MARC, the soil type is vertisol soil with clay texture.The annual rainfall and daily maximum and minimum temperature for Mekelle University experimental site is 545 mm, 25.3 ^{0}C and 12.5 ^{0}C, respectively (MU, 2012). Whereas, the annual rainfall and daily maximum and minimum temperature for Mekelle Agricultural Research Center experimental site is 527 mm, 26.11^{0}C, and 11.7 ^{o}C, respectively (MARC, 2012).

2.2 Experimental Material

Jalene Potato variety was used as planting material. Jalene variety was released by Holleta Agricultural Research center in 2002. The variety is early maturing (90-120 days) and suited for areas having an altitude of 1600-2800 m.a.s.l and rainfall 750-1000mm (EARO, 2004). Seed tuber was obtained from Alage farmers based seed system supported by International Potato Center (CIP) and Tigray Agricultural Research Institute. Seed tubers having 3-4 sprouts and medium sized tubers were selected for planting.Planting date was on 17 and 18 July, 2013 at Mekelle University and Mekelle Agricultural Research center, respectively.

2.3 Experimental Design and Treatments

The experiment was laid out in RCBD design replicated three times. Seed tubers were planted at 15 cm depth with a spacing of 0.75m*0.30m between rows and plants in a plot size of 6cm*9 cm each having 8 rows respectively. There were three water treatments: Rainfed (RF), Deficit Irrigation (DI) and Full Supplementary irrigation (FSI). Crop water requirement and irrigation scheduling were calculated using CROPWAT software version 8.0. Fixed frequency and fixed amount of irrigation was applied.

Full supplemental irrigation: The application of irrigation water depending on the crop water requirement starting from the cessation of rainfall to end of the growing season (tuber initiation, tuber bulking and tuber maturation). Irrigation was applied manually using a plastic pipe directly into the plants.

Deficit irrigation: Four irrigation at four days interval applied after cessation of rainfall. Rainfed cessation coincided with tuber initiation (55 days after planting).

2.4 Crop Management

Land preparation, planting date, weeding, fertilizer application and method, earthling up/heap and other agronomic practices of the crop were carried out as per the recommendation of the Ethiopian Agricultural Research Organization (EARO, 2004).165 kg Urea and 195 kg/ha DAP (Di Ammonium phosphate) were applied as side dressing between plants in the row respectively. Urea was applied in split form (half at planting and the other half at flowering). MZ 63.5% WP was used to control late blight at the rate of 2.5 kg per hectare.

AquaCrop Model Description

AquaCrop model is a water-driven model that requires a relatively low number of parameters and input data to simulate the yield response to water of most of the major field and vegetable crops cultivated worldwide (Steduto *et al*., 2003). One important application of AquaCrop would be to compare the attainable against actual yields in a field, farm, or a region, to identify the constraints limiting crop production and water productivity (bench marking tool) (Raes *et al*, 2009).

The unique features that distinguishes AquaCrop from other crop models is its focus on water, the use of ground canopy cover instead of leaf area index, and the use of water productivity values normalized for atmospheric evaporative demand and of carbon dioxide concentration that confer the model an extended extrapolation capacity to diverse locations and seasons, including canopy development, stomata conductance, canopy senescence and harvest index are used as the key physiological responses to water stress (Steduto *et al*., 2009).

2.5 Data Collection

2.5.1 Crop data

Crop data that include days to emergence, maximum canopy cover, canopy senescence, maximum rooting depth, tuber initiation and days to maturity, plant height and dry biomass were measured.

Table 1. Crop data measurements and detail descriptions

Crop data measurement	Details descriptions
Emergence date	Number of days from planting up to 50% of the plants emerged
Time to reach maximum canopy cover	The time required to reach maximum canopy cover
Time to reach canopy senescence	The time at which senescence of leaves starts
Time to reach maximum rooting depth	Determined after measuring root length at a series of times
Tuber initiation date	the date when swollen portion at the top of the stolen was seen
Days to maturity	Number of days from planting to the stage when majority of the plants in a plot has changed the color from green to yellow
Plant height(m)	was measured at every 10 days interval from five tagged plants
Canopy Cover	Overhead digital camera was used to capture the canopy cover. Then the captured picture was analyzed using image analyzer software
Dry biomass (t/ha)	dry biomass of the stem, leaves, root, stolen and tuber were recorded; and dry weight was recorded after air-drying the fresh samples and further oven drying at 65^0C for 72 hours at every 10 days interval (Mulubrhan, 2004)
Harvest index	was determined as the ratio of dry weight of tubers to the total dry biomass weight. This was taken at harvest
Root length (m)	five randomly selected main roots was measured at every 10 days interval
Total dry tuber yield (t/ha)	data was taken from two middle rows from plot area of 4.5m by 1.50m

Sampling techniques of biomass and tuber yield

Three plants were uprooted randomly every 10 days interval from the rows excluding the border and middle two rows the middle two rows were reserved for final tuber harvest whereas the border rows were left for protection). The plants were removed without damaging the roots. Then, the fresh biomass was separated into roots, leaves, stems, tubers and stolen. Dry weight was measured after oven dried at 65 C^O for 72 hours. Fresh and dry mass of each part were weighed and recorded.

2.5.2 Climate data

Climate data that includes temperature (Tmax and Tmin), relative humidity, rainfall, and wind speed and sun shine hours of 15 years were obtained from the respective site. Reference evapotranspiration (ETo) was calculated using Cropwat software version 8.0 based on Penman Montheith approach (Allen *et al.,* 1998). The seasonal temperature, rainfall and reference evapotranspiration were entered into AquaCrop model.

CO_2 concentration: Atmospheric CO2 concentration, according to the program default files (AquaCrop considers 369.47 pp as reference level, which is the average of the atmospheric concentration of CO2 in 2000 at Mauna Loa observatory, Hawaii).

2.5.3 Soil data

The soil physical characteristics such as field capacity, permanent wilting point, bulk density and textural classes of the experimental sites were analyzed at Mekelle soil laboratory.

2.5.4 Irrigation amount and scheduling

Crop water requirement and irrigation schedule was determined using Cropwat software (Version 8.0) based on climatic, soil and crop data inputs. The following parameters were used to run CropWat software (Allen et al., 1998):

$ETc = Kc.\ ET_O$---Eq(1)

Where: Kc = Crop coefficient, ETo = reference evapotranspiration

Net irrigation requirement = ETc – effective rainfall

Gross irrigation requirement = Net irrigation req/application efficiency

Irrigation water was conveyed into the plant directly using plastic pipe hence the application efficiency was 90%.

2.5.5 Water Use Efficiency (WUE)

WUE is a useful indicator for quantifying the impact of irrigation scheduling decisions with regard to water management. In crop production system, WUE is used to define the relationship between crop production and the amount of water used in crop production, expressed as crop production per unit volume of water (Raes *et al*., 2009). In this study, WUE refers to the ratio between the final dry tuber yields (Y) and cumulative crop evapotranspiration (ET). ET was obtained from the output of AquaCrop.

WUE ($kg.m^{-3}$) = Yield (kg)/(∑ET) (m^3)---Eq (2)

2.6 AquaCrop Model Calibration and Validation Procedures
To calibrate the AquaCrop model (version 4.0) for potato, independent observations data sets of field experiments in 2012 were used. In the calibration process certain observed crop characteristics (time to emergence, time to attain maximum canopy cover, time to flowering, and senescence and physiological maturity (in calendar days) for non-water stress conditions (FSI treatments) at MU were used. After the calibration process, the model was validated using separate data sets (from rainfed, deficit and full irrigation treatments) measured at both MARC and MU sites.
Table 2. Experimental and agronomic information used in AquaCrop model calibration

Agronomy Data	Treatments by location					
	Full Irrigation		Deficit irrigation		Rainfed	
	MU	MARC	MU	MARC	MU	MARC
Planting density, plants /m^2	4.44	4.44	4.44	4.44	4.44	4.44
Sowing date	18/7/2012	19/7/2012	18/7/2012	19/7/2012	18/7/2012	19/7/2012
Days to Emergence	10	10	10	10	10	10
Days to maturity	91	100	91	100	91	100
WP*, g m-2	20	20	20	20	20	20
Seasonal rainfall, mm	382.6	357.4	382.6	357.4	382.6	357.4
Supplementary Irrigation, mm	216.6	220	110.2	82.5	-	-
Average ET_0 (mm/day)	3.8	4.6	3.8	4.6	3.8	4.6
Max rooting depth(m)	0.60	0.60	0.60	0.60	0.60	0.60

2.7 Performance Evaluation of AquaCrop Model
Validation of Aquacrop model for biomass (B), yield (Y) and water use efficiency (WUE) were done by comparing simulated outputs against the observed data collected from the field using the following statistical techniques

Root Mean Square Error (RMSE)
Root mean square error (RMSE) was calculated according to Loague and Green (1991):

$$RMSE=\sqrt{\frac{(Oi-Si)^2}{N}} \text{--} Eq(3)$$

The RMSE represents a measure of the overall mean deviation between observed and simulated values, that is, a synthetic indicator of the absolute model uncertainty. The closer the value is to zero, the better the model simulation performance. Where, S_i = simulated value
O_i= observed value, N = number of observations $\bar{O_i}$ =mean of O_i and
$\bar{S_i}$ =mean of Si
Normalized RMSE gives a measure (%) of the relative difference of simulated versus observed data. The normalized RMSE expressed in percent Eq (5), was calculated according to Loague
and Green (1991).

$$NRMSE=\left(\sqrt{\frac{(Oi-Si)^2}{N}}\right)x\ \frac{100}{M} \text{--} Eq(4)$$

The simulation is considered excellent with a normalized RMSE is less than 10%, good if the normalized RMSE is greater than 10% and less than 20%, fair if normalized RMSE is greater than 20 and less than 30%, and poor if the normalized RMSE is greater than 30% .M is the mean of the observed variable.

Coefficient of Efficiency (E)
Coefficient of efficiency, E (Nash and Sutcliffe, 1970) was calculated using Equation 5.

$$E=1-\frac{\sum_{i=1}^{N}(Oi-Si)^2}{\sum_{i=1}^{N}(Oi-\bar{Oi})^2} \text{--} Eq(5)$$

The coefficient of efficiency (E) expresses how much the overall deviation between observed and simulated values departs from the overall deviation between observed values (O_i) and their mean value (O_i). The added value of this statistical indicator (E) as compared to RMSE is in its ability to capture how well the model performs over the whole simulation span. E expresses an efficiency of the model performance, that is, the smaller the departure from (O_i – $\bar{O}$), the higher the performing efficiency of the model. The E is unit less and may assume values ranging from –∞ to +1, with better model simulation efficiency when values are closer to +1.

Correlation coefficient (R^2)
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 CC will be zero (Loague and Green, 1991).The correlation coefficient was estimated by the Equation 6.

$$R^2 = \frac{\sum_{i=1}^{N}((Oi - \bar{O}i)(Si - \bar{S}i))}{\sqrt{\sum_{i=1}^{N}(Oi - \bar{O}i)^2 \sum_{i=1}^{N}(Si - \bar{S}i)^2}} \quad \text{------ Eq(6)}$$

2.8 Running of the model

After all fundamental parameters were fulfilled, simulation results were obtained based on the equation (Steduto et al., 2007) : $B=WP*\sum Tr$ *--Eq(7)*

Where, B-Biomass, WP-Water productivity and Tr- Transpiration and;
The harvestable portion (yield) is then determined via the harvest index (HI) Eq (8):
Y = B • HI --Eq(8)
Where, Y-Yield, and HI-Harvest Index

3. Results and Discussion
3.1 Performance of AquaCrop in simulating Dry Tuber Yield of potato
Performance of AquaCrop model in simulating dry tuber yield was evaluated using different statistical parameters. AquaCrop model adequately simulated the tuber yield at MU as indicated by high model efficiency (0.96) and low NRMSE (3.49%) (Table 3). This finding was in agreement with Neelam et al. (2010) who reported the good simulation performance of the model in simulating potato tuber yield with E (0.63), RMSE (0.202 t/ha) and R^2 (0.877).

Table 3. Statistical evaluation of observed and simulated dry tuber yield of potato at MU and MARC (t/ha)

TRT	MU		MARC	
	OBS	SIM	OBS	SIM
FSI	-	-	12.73	11.518
DI	9.94	9.545	11.54	10.722
RF	6.54	6.844	7.69	7.545
	Statistical Parameters			
E	0.96		0.84	
R^2	0.99		0.99	
RMSE	0.29		0.85	
NRMSE(%)	3.49		8.0	

*OBS=Observed, SIM=Simulated ,(-)=Data used for calibration

At MARC, the statistical parameters showed that dry tuber yield were well simulated as indicated by lower NRMSE (8.0%) and high model efficiency (E:0.84) (Table 3).There was good correlation between simulated and observed tuber yield (R2 =0.99). This result was in agreement with M.Bitri et al. (2014) who reported potato tuber yield was adequately simulated by the model with the performance evaluation of RMSE (0.27 t/ ha), normalized RMSE(5%), E(0.97) and R^2 (0.95). In both locations, simulation results had the similar trend. The highest simulated yield were obtained from using full irrigated (11.518) at MARC and (9.582 ton/ha) at MU. While lowest tuber yield were obtained from rainfed (7.545) at MARC and (6.853 ton/ha) at MU respectively.

Table 4. Statistical evaluation of observed and simulated sequential total dry biomass (t/ha) at MU and MARC

TRT	MU		MARC	
	OBS	SIM	OBS	SIM
FSI	-	-	17.61	12.2
DI	12.26	10.98	15.39	11.6
RF	8.84	8.75	11.76	9.43
Statistical Parameters				
E	0.72		-1.81	
R^2	0.99		0.97	
RMSE	0.74		4.05	
NRMSE(%)	7.02		27.11	

3.2 Performance of AquaCrop in simulating Total dry biomass of potato at MU and MARC

AquaCrop model was able to simulate the total dry biomass yield as indicated by high model Efficiency E (0.72), low NRMSE (7.0%) and high correlation (R^2=0.99) at MU (Table 4). M.Berti et al.(2014) who also explained, the model predicted biomass values at harvest quite well with the calculated values of statistic indices, RMSE, normalized RMSE, E, and R^2 were 0.6 t/ ha,, 4.4%, 0.97 and 0.95, respectively.

On the other hand at MARC, total dry biomass yield was not adequately simulated by AquaCrop. This might be due to the manner which the model simulate crop growth or error in measured data.However, NRMSE showed good to satisfactory simulation performance efficiency.The high coefficients of determination showed better correlation (0.97) (Table 4).Accordingly, the results of this study showed that the AquaCrop model was able to adequately simulate the potato dry tuber yield at both locations and total biomass at MU.

3.3 Water Use Efficiency (WUE)

At MU, AquaCrop showed good prediction of WUE with E 0.33 and NRMSE 13.81%. Similarly at MARC, AquaCrop was able to adequately simulate WUE with (E=0.49 and NRMSE=1.58) (Table 5).

Table 5. Statistical evaluation of observed and simulated Water Use Efficiency at MU and MARC (Kg/m3)

TRT	MU		MARC	
	OBS	SIM	OBS	SIM
FSI	-	-	3.03	2.74
DI	3.83	3.08	2.93	2.72
RF	2.52	2.64	2.37	2.32
Statistical Parameters				
E	0.33		0.49	
R2	0.99		0.99	
RMSE	0.44		0.04	
NRMSE (%)	13.81		1.58	

3.4 Irrigation Schedule Strategies

Irrigation application strategies (in both timing and frequency) based on model simulation could be used as means of evaluating crop water productivity for a given farm. As indicated in Table 6, simulation results for the different irrigation treatments showed that highest tuber yield were obtained under full supplementary irrigation (eight irrigation), six irrigation (for early and late application) and four times irrigation (early). Whereas, lower yields were observed under late irrigation application Deficit irrigation treatment (four irrigation) applied early had slightly lower yield as compared with the full irrigated (0.31% t/ha). However, the last four irrigation applications had a yield loss of about 14.85% and 14.41% when compared with full supplemented and deficit (four early applications). This indicates the critical stage in potato production for water stress was the tuberization. Depending on the time of irrigation, yield reduction ranging between 0.31% (deficit irrigation (4E) and 40% (Rainfed) was simulated.

This finding was in agreement with Costa et al.(1997) who reported that water stress imposed during tuberization severely hindered plant physiological processes and penalized tuber yield. Similarly, Steyn *et.al*.(2007) verified that treatments imposed with water stress during initiation of during tuber initiation had the lowest tuber yield as compared with other stress stages.

Simulation results of total biomass under different irrigation strategies showed that highest biomass were obtained under full irrigation (eight irrigation), six (both early an late) and four irrigation (4). Four irrigation when applied after the cessation of rain showed 0.27% yield loss when compared with full irrigation whereas late application with four irrigation resulted in 12.5% yield loss.

Table 6. Application of AquaCrop model for determining alternative irrigation strategies in potato fields at MU

TRT	Appln. (DAP)	Freq	B(t/ha)	Yd(%)	Y(t/ha)	D/ce (%)
I1	RF	-----	8.75	25.8	6.84	40.1
I2	60-64	2 (E)	10.18	8.2	8.59	11.5
I3	60-72	4 (E)	10.98	0.3	9.55	0.3
I4	60-80	6 (E)	11.01	0	9.58	0
I5	60-88	8 (FSI)	11.01	0	9.58	0
I6	84-88	2 (L)	8.9	23.7	7.12	34.6
I7	76-88	4 (L)	9.79	12.5	8.34	14.9
I8	68-88	6 (L)	10.93	0.73	9.58	0

*Note. E=Stands for early irrigation application L=Stands for late irrigation application FSI=Full Supplementary Irrigation

Similarly, the highest yield and biomass yield were obtained by six and eight irrigation (both early and late), and full supplemented. Whereas, lowest yield and biomass were obtained by rainfed treatment followed by two irrigation, especially late application(Table 7). The highest biomass and yield loss by rainfed was 29.37% and 52.58% as compared with full supplemented. Four to six early irrigation applications after cessation of rainfall seems enough to obtain good yield and biomass atMU. However, at MARC, application of six to eight irrigation (early and late) after cessation of rainfall could be effective method in the study area. This might be due to the difference mainly in soil type.

Table 7.Application of AquaCrop model for determining alternative irrigation strategies in potato fields at MARC

Trt	Appln. (DAP)	Freq	B(t/ha)	D/ce (%)	Y(t/ha)	D/ce (%)
I1	RF	----	9.43	29.4	7.55	52.6
I2	60-64	2(E)	10.72	13.8	9.8	17.6
I3	60-72	4(E)	11.6	5.2	10.72	7.5
I4	60-80	6(E)	12.25	-0.4	11.54	-0.2
I5	60-88	8(E)	12.28	-0.7	11.59	-0.6
I6	60-96	10(FSI)	12.2	0	11.52	0
I7	92-96	2(L)	9.52	28.2	7.99	44.2
I8	84-96	4(L)	10.29	18.6	9.59	20.1
I9	76-96	6(L)	11.34	7.6	10.84	6.3
I10	68-96	8(L)	12.28	-0.65	11.76	-2.04

4. Summary and Conclusion

The finding on performance evaluation of AquaCrop model showed that the model had well simulated tuber yield, total biomass and WUE at both sites except total biomass at MARC. Alternative irrigation application showed that four to six early irrigation applications after cessation of rainfall seems enough to obtain good yield and biomass at MU. However, at MARC, application of six to eight irrigation after cessation of rainfall could be effective method after cessation of rainfall. Finding the most critical stage of physiological water stress of the crop to be supplied with deficit irrigation seems preferable method, and then, the additional water used in full supplementary irrigation should be saved and invested in additional land productivity.

However, further research on other agronomic practices like appropriate planting date combined with the onset, cessation of the rains and the seasonal dry spells, and optimum fertility level should be studied. It is also advisable to include the effect of weeds, disease and pests incidence on the crop's yield.

Conflict of Interests

The author(s) have not declared conflict of interests

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