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Modelling the yield, water requirement, and water productivity of major tropical tuber crops using FAO-AquaCrop - A study over the main growing areas of India

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Abstract

A study was conducted to test and understand the reliability of the FAO-AquaCrop model for cassava and sweet potato over the major growing areas of India. This is the first study in India testing the FAO-AquaCrop model for the yield estimation of tropical tuber crops. Salem in Tamil Nadu, Thiruvananthapuram in Kerala, and West Godavari in Andhra Pradesh were selected for cassava, and Bhubaneswar in Odisha, Faizabad in Uttar Pradesh, and Kalyani in West Bengal were selected for sweet potato. The model simulations of cassava and sweet potato indicated the suitability of the FAO-AquaCrop model in estimating the crop's yield irrespective of the agro-climatological conditions with percentage error values ranging from -2.33 to 3.92% and 0.3 to 5% for cassava and sweet potato, respectively. The model also estimated gross irrigation requirements and their corresponding water productivity values. The estimated water productivity of cassava and sweet potato ranged from 3-4 kg m^{-3} and 4-8 kg m^{-3}, respectively. The water productivity of these tuber crops were higher than that of the major food grain crops and indicated their suitability in the context of water scarce conditions and ensuring food security. The information about the water requirement and crop water productivity can be used at farm level to utilize the available water resources and maximize production to ensure food security.

Keywords: Cassava, Climate change, FAO-AquaCrop, Simulations, Sweet potato, Water productivity, Water requirement.

Introduction

In the recent past, studies on the impact of climate change on major food grain crops indicate a decline in their production. This resulted in identifying alternative food crop sources, which are rich in carbohydrate and mineral nutrients. The climate-smart, tropical tuber crops are now getting much attention internationally in the context of food security and bioenergy (Tironi et al., 2017, Manners and van Ettan, 2018). Among tropical tuber crops, cassava (*Manihot esculenta* Crantz) and sweet potato (*Ipomoea batatas* Lam) are the two major crops cultivated worldwide. They are widely used in food, feed, fuel, and textile industries and are excellent sources of carbohydrate and mineral nutrients (Putpeerawit et al., 2017; Mussoline and Wilkie, 2017). The orange-fleshed sweet potato is a good source of vitamin A and can be used as a supplementary diet in the tropical and sub-tropical regions by diet diversification (Woolfe, 1992). The mineral nutritional composition of these tuber crops over rice is presented in Table 1. The comparative nutritional values over rice indicate that the tuber crops can be used as an alternative food source in the context of food security (Titus and Lawrence, 2015).

Cassava and sweet potato are generally cultivated by small farm holders on marginal lands. They are

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getting wider attention due to their nutritional content, wider adaptability to different agro-climatological conditions, and minimum input requirements for their cultivation (McCallum et al., 2017). India is the 3rd largest producer of cassava in Asia, followed by Thailand and Indonesia. However, the available literature indicated a knowledge gap in modelling studies for cassava in India (Santhosh Mithra et al., 2012). In the case of sweet potato, India ranks 2nd position in its production in Asia, followed by China. Few modelling studies for sweet potato in India were undertaken by Santhosh Mithra and Somasundaram (2008), Somasundaram and Santhosh Mithra (2008), and Santhosh Mithra et al. (2019), which aimed to estimate the crop yield without indicating crop water requirements or their water productivity. Simulating the maximum attainable crop yield under optimal water requirement conditions along with water productivity can assist field-level water management in obtaining higher yields in arid and semi-arid regions.

Table 1. Nutritional contents of cassava, sweet potato, and rice

Nutrient content in 100 g	Cassava	Sweet potato	Rice
Energy (KJ)	670	360	1528
Protein (g)	1.4	1.6	7.1
Fat (g)	0.28	0.05	0.66
Saturated fatty acids (g)	0.07	0.02	0.18
Carbohydrates (g)	38	20	80
Fiber (g)	1.8	3	1.3
Calcium (mg)	16	30	28
Iron (mg)	0.27	0.61	4.31
Magnesium (mg)	21	25	25
Phosphorus (mg)	27	47	115
Potassium (mg)	271	337	115
Vitamin C(mg)	20.6	2.4	0
Thiamin (mg)	0.09	0.08	0.58
Riboflavin (mg)	0.05	0.06	0.05
Niacin (mg)	0.85	0.56	4.19
Pantothenic acid (mg)	0.11	0.8	1.01
Vitamin B6 (mcg)	0.09	0.21	0.16
Vitamin A (IU)	13	14187	0
Vitamin E (mg)	0.19	0.26	0.11
Vitamin K (mcg)	1.9	1.8	0.1
Beta-carotene (mcg)	8	8509	0

*mcg- microgram; IU- international unit (Source: Titus and Lawrence, 2015)

FAO-AquaCrop (Steduto et al., 2009), a model developed by FAO, is widely used for various crops to estimate the crop yield for the water applied (Singh et al., 2013; Nyathi et al., 2018; Adeboye et al., 2019; Kyu and An, 2019; Pirmoradian and Davatgar, 2019; Masai et al., 2020). This model can develop optimal irrigation strategies to maximize crop yield. However, the suitability of this model for tropical tuber crops still needs to be explored in the context of food security and bioenergy productions in the changing climatic conditions. A study by Beletse et al. (2013) using the FAO-AquaCrop model for yield estimation in orange-fleshed variety of sweet potato in South Africa was one of the existing study in this area. Therefore, the present study focuses on calibrating the FAO-AquaCrop model for two major tropical tuber crops in India to estimate the yield, gross irrigation water requirement, and water productivity. Based on the available published literature, this could be the first study in India towards the application of FAO-AquaCrop model for tropical tuber crops.

Materials and Methods

Study locations, meteorological, crop and soil data

Study locations selected for the cassava crop are Salem in Tamil Nadu, Thiruvananthapuram in Kerala, and West Godavari in Andhra Pradesh. These states are the major producers of cassava in India, (Saxena et al., 2018). Bhubaneswar in Odisha, Faizabad in Uttar Pradesh, and Kalyani in West Bengal are selected as the study locations for sweet potato, and are the major sweet potato producers in India (Saxena et al., 2018). All the study locations are presented in Fig. 1.

The meteorological data (maximum and minimum temperatures, sunshine duration, relative humidity, wind speed, and rainfall) are derived from the CLIMWAT model. CLIMWAT for CROPWAT is a joint publication of the Water Development and Management Unit and the Climate Change and Bioenergy Unit of FAO. The available observations of meteorological data are also collected from the

Table 2. Soil texture and fertilizer application at the study locations

Study locations	Soil texture	Recommended fertilizer (kg ha^{-1})			Available soil nutrient at the time of planting (kg ha^{-1})		
		N	P	K	N	P	K
Thiruvananthapuram, Kerala	Clay loam	100	50	100	170	55	130
Salem, Tamil Nadu	Sandy	90	90	240	142	12	319
West Godavari, Andhra Pradesh	Sandy loam	60	60	60	276	99	199
BCKV Kalyani	Clay	75	50	75	320	18	360
NDUAT, Faizabad	Sandy loam	60	50	80	295	18	240
CTCRI RC, Bhubaneswar	Clay loam	50	20	50	310	22	390

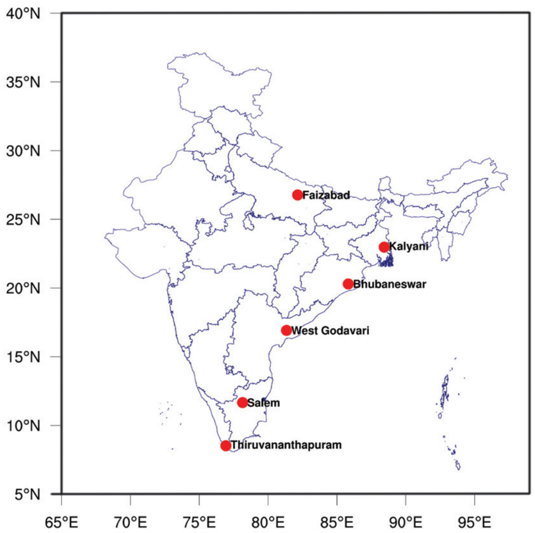

Figure 1. Study locations (red circle) of cassava and sweet potato in India

observatory located at ICAR-Central Tuber Crops Research Institute (CTCRI), Thiruvananthapuram. The climate data is selected with respect to the specific crop season and location. The required crop parameters for cassava and sweet potato, and the soil data (Table 2, Table 3 & Table 5) needed for model calibration are directly taken from the data base created as annual report of All India Coordinated Research Project on Tuber Crops, AICRP-TC (George and Sunitha, 2012-2013; George and Sunitha, 2013-2014; George et al., 2014-2015). The database of crop and soil parameters is created for future modeling studies of these crops by the ICAR-CTCRI as part of the AICRP-TC.

FAO-AquaCrop – The crop model

FAO-AquaCrop, a water-driven model developed by FAO (Steduto et al., 2009), is used in this study to estimate the yield, gross irrigation requirement, and the water productivity of two major tuber crops over the main growing areas in India. In FAO-AquaCrop model, yield is estimated in terms of biomass and harvest index (HI), i.e., in connection with biomass accumulation and transpiration (Steduto et al., 2009). The input parameters needed for this model are crop and soil data followed by monthly meteorological data such as minimum and maximum temperatures, rainfall, and reference evapotranspiration. More details about this model is described by Raes et al. (2018).

Results and Discussion

This section discusses the details of calibrated model parameters and their corresponding yield simulations of cassava and sweet potato over the selected study locations.

FAO-AquaCrop for cassava

The FAO-AquaCrop model was calibrated using the previously recorded crop and soil data from the respective study locations as part of the All India Coordinated Research Project on Tuber Crops. Crop data of one of the widely used varieties of cassava, H-226 (long duration of 10 months), developed by ICAR-CTCRI was used in this study as observations are available for this variety in all three locations. This is a hybrid crop with a plant height ranging from 1.5 to 2 m. This crop is known for its tolerance to drought and cassava mosaic disease (CMD). The

Table 3. Calibrated parameters of AquaCrop for cassava

Crop parameters	Values
Base temperature (°C)	10
Maximum temperature (°C)	40
Number of plants per hectare	12345
Days from planting to emergence	6
Days from planting to tuber initiation	50
Days from planting to maximum rooting depth	70
Shape factor	3
Days from planting to senescence	250
Days from planting to maturity/crop period	305
Crop coefficient when canopy is complete	0.80
Minimum effective rooting depth (m)	0.30
Maximum effective rooting depth (m)	1.00
Reference harvest index (HI)	85
Building up of harvest index (days)	50
Increase of HI (%)	30
Minimum growing degree days required	10
Water productivity (g m^{-2})	25
Effect of canopy cover in reducing soil evaporation in late season stage	60
Electrical conductivity (dS m^{-1}) at which the crop can no longer grow	150

calibrated model parameters are listed in Table 3, and the corresponding model simulations for yield and irrigation requirements are presented in Table 4. In the FAO-AquaCrop model, water productivity (WP, g/m²) expresses the kg of biomass per m² and per mm of cumulative transpiration water during the biomass production period (Table 3). It is the dry matter above the ground (gr or kg) produced per unit of soil area (m² or ha) and per unit of transpired water (mm). The percentage error between the observed and simulated yields indicated the model's suitability in simulating the crop's yield with error values ranging from -2.33 to 3.92%. According to Dua et al. (2014), errors up to 6% are negligible. Therefore the present calibration results recommend the reliability of FAO-AquaCrop model in simulating the yield of cassava irrespective of the agro-climatological conditions.

The simulated net irrigation and gross irrigation requirements in Table 4 indicated the seasonal water requirement to obtain the respective crop yields. The gross irrigation was estimated by assuming a field irrigation efficiency of 85%. The water requirements indicated that it depended not only on the crop but also on the soil and meteorological conditions as the water requirement changed from one study location to another for the same crop. The irrigation requirements ranged from 385 to 820 mm in the study locations. The information regarding irrigation requirements in the respective study locations can assist field-level water management and enhance water productivity.

FAO-AquaCrop for sweet potato

The local variety of sweet potato available at the

Table 5. Calibrated parameters of AquaCrop for sweet potato

Crop parameters	Values
Base temperature (°C)	8
Maximum temperature (°C)	30
Number of plants per hectare	83000
Days from planting to emergence	8/11
Days from planting to tuber initiation	32/40
Days from planting to maximum rooting depth	40
Shape factor	2
Days from planting to senescence	70/95
Days from planting to maturity/crop period	90/120
Crop coefficient when canopy is complete	1.15
Minimum effective rooting depth (m)	0.25
Maximum effective rooting depth (m)	1.00
Reference harvest index (HI)	85
Building up of harvest index (days)	30
Increase of HI (%)	10
Minimum growing degree days required	8
Water productivity (g m^{-2})	20
Effect of canopy cover in reducing soil evaporation in late season stage	70
Electrical conductivity (dS m^{-1}) at which the crop can no longer grow	10

Table 4. Model simulations for cassava

Location	Crop yield (t ha^{-1})		Error (%)	Simulated	
	Observed	Simulated		IR_n (mm)	IR_g (mm)
Thiruvananthapuram, Kerala	37.75	36.27	3.92	327	385
Salem, Tamil Nadu	38.58	38.55	0.08	697	820
West Godavari, Andhra Pradesh	37.80	38.68	-2.33	669	787

Table 6. Observed and model simulated yield of sweet potato

Location	Crop yield (t ha^{-1})		Error (%)	Simulated	
	Observed	Simulated		IR_n (mm)	IR_g (mm)
Bhubaneswar, Odisha	12.80	12.16	5.0	170	200
Faizabad, UP	16.66	16.19	2.8	126	148
Kalyani, WB	16.51	16.46	0.3	171	209

respective study locations was used in this study to calibrate the crop model. The duration of crop varieties was 90 days at Bhubaneswar, and 120 days at Faizabad and Kalyani, respectively. The calibrated crop parameters are listed in Table 5. The crop model's simulations are presented in Table 6. The calculated percentage error ranging from 0.3 to 5% indicates the suitability of FAO-AquaCrop model in simulating the yield of sweet potato.

The gross irrigation requirements are also presented in Table 6. The assumption during each irrigation is to irrigate the crop when 65% (Savva and Frenken, 2002) of the readily available soil moisture (RAW) got depleted and then bring back the soil moisture to field capacity (FC). The irrigation requirement for sweet potato ranged from 148 to 209 mm in the three study locations.

Water productivity of cassava and sweet potato

The estimated water productivity of cassava and sweet potato using the FAO-AquaCrop model is presented in Figs. 2 & 3. Water productivity is the crop production per unit amount of water used (Molden, 1997), and this measures the biophysical gain from the unit of water consumed in crop

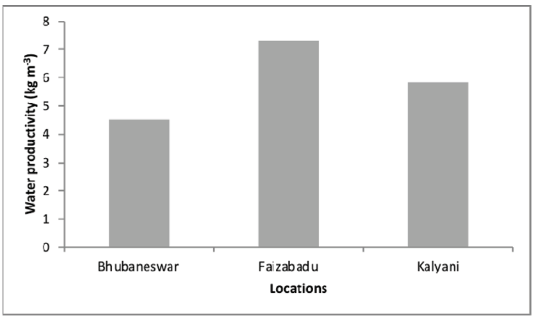

Figure 2. Water productivity of cassava estimated by FAO-AquaCrop model

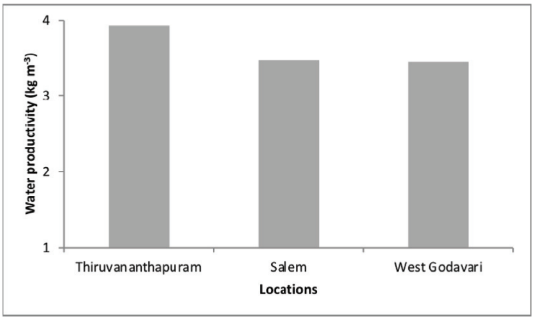

Figure 3. Water productivity of sweet potato estimated by FAO-AquaCrop model

production. The water productivity of cassava from the model output ranged between 3 and 4 kg m^{-3} and the same for sweet potato was between 4 to 8 kg m^{-3} in all the study locations. The highest water productivity was observed in Thiruvananthapuram and Faizabad in the case of cassava and sweet potato, respectively. The water productivity can be further improved by avoiding various field losses of water.

Information regarding the water productivity of these crops can assist the water managers in optimizing the use of available water resources, maximizing the crop production, designing new irrigation systems in a sustainable manner, and developing appropriate tools to increase crop water productivity. This also avoids the competition for water among all the other field crops, and enhances food security. However, field studies are needed to verify the model estimates of irrigation water requirements as well as crop water productivity.

The model simulations of cassava and sweet potato indicated the model's reliability in estimating the yield irrespective of the agro-climatological conditions of the study locations. The model also estimated the irrigation requirement for the crops during the cropping season, and it indicated the water requirement changed from one location to another depending on the soil and meteorological parameters. The derived water productivity of cassava and sweet potato in this study compared to rice: 0.5 to 1.1 kg m^{-3}, wheat: 0.6-1.9 kg m^{-3}, maize: 1.2-2.3 kg m^{-3} (http://www.fao.org/3/y4525e/y4525e06.htm), showed the suitability of tropical tuber crops as future insurance crop in the context of water scarcity and food security. As an outcome of this study, the decision managers can estimate the crop's yield and irrigation water requirement of tuber crops using the FAO-AquaCrop model. They can transmit this information into the field level to maximize crop production, and wisely utilize the available water source among other crops in the context of climate change and food security. However, more studies are needed to analyze the climate change impact on yield and irrigation water requirement of these tuber crops using the FAO-AquaCrop model over the major growing areas of India.

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