Calibration and validation of AquaCrop for deficit and full irrigation of tomato

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Abstract: The objective of this study was to calibrate and test AquaCrop for tomato (*Lycopersicon esculentum*) grown under deficit and full irrigation. Two field experiments were carried out in the tropical humid coastal savanna zone in Mfantseman district of the Central Region of Ghana. Data from the first experiment were used to calibrate the model while data obtained from the second experiment were used to validate the model. The calibrated AquaCrop model concentrated on its performance to predict crop yield and seasonal crop water requirement (ET_c). Four treatments were investigated: T1 (no irrigation after plant establishment), T2 (50% ET_c restoration), T3 (100% ET_c restoration up to beginning of flowering, then 50% ET_c restoration) and T4 (100% ET_c restoration). The results revealed that AquaCrop was able to simulate the yield of tomato for T2-T4 with the exception of Treatment T1 which was simulated with the highest deviation of 45.1%. On the other hand, the model was able to simulate the seasonal water requirements to an appreciable degree in both experiments. It must be pointed out that the calibration of AquaCrop suffered from a lack of data on the progress of crop canopy cover which is a very important parameter used in developing the model.

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1 Introduction

An FAO analysis[1] of 93 developing countries expects increase of agricultural production over the period 1998-2030 by 49% in rain fed and by 81% in irrigated regions. Therefore, much of the additional food production is expected to come from irrigated land, three quarter of which is located in the developing countries. In the developing countries, the irrigated area in 1998 has nearly doubled than that in 1962. FAO estimates that the irrigated area in the selected 93 developing countries will only grow by 23% over the 1998-2030 periods. However, the effective harvested irrigated area (considering the increase in cropping intensity) is expected to increase by 34%. It is estimated that between 16 950 km^3 and 18 600 km^3 of water is consumed annually in global food production[2]. Out of this, 35% is green water consumed under rain-fed crop production, 10% blue water consumed under irrigated crop lands and 55% green water consumed by pastures[3]. Holding the current rates of agricultural water use

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efficiency constant, an estimated additional amount of 5700 km^3 of fresh water will be required annually to meet the estimated food demand in 2050[4]. The relationship between crop production and evapotranspiration, called crop water production function, is important to engineers, agronomists, water resource planners as well as economists. This importance is currently accentuated due to competition among users, declining groundwater reserves, various legal institutions and degradation in water quality. Simulation models that quantify the effects of water on yield at the farm level can be valuable tools in water and irrigation management. Modeling tools that support management decisions with regard to efficient water use in crop production are essential. AquaCrop is a new decision support tool useful in modeling and devising strategies for efficient management of crop-water productivity at farm level. To make AquaCrop globally applicable, it must be tested in different locations with different soil conditions, crops, agronomic practices and climatic conditions. Calibration and performance evaluation has been done for cotton by Farahani et al.[5] and Garcia-Vila et al.[6], for maize by Heng et al.[7] and Hsiao et al.[8] and also for hot pepper by Sam-Amoah[9]. Given the economic importance of tomato in Ghana, it was felt that AquaCrop could be used to study the crop's response to different water application levels. Ultimately, this would lead to a better understanding of how to improve the yield of tomato through the adoption of optimal water management practices. The primary objective of this work was to calibrate and test AquaCrop for tomato grown under deficit and full irrigation in a tropical humid coastal savanna zone in Mfantseman district of the Central Region of Ghana.

2 Materials and methods

2.1 Location and climatic condition of project site

The study, which also consisted of field experiments, was carried out on a farmer's farm located at Nsanfo, in the Mfantseman district of the Central Region of Ghana, from 11th of January 2014 to 14th of November, 2014. Nsanfo, the ecological zone within which the experiments were carried out is in the coastal savannah zone. Two distinct seasons are experience in a year. The major rainy seasons occurs between March and July with its maximum in June, while the minor wet season starts in September and ends around November. The mean annual rainfall is 940 mm; there is a dry spell from December to February. Generally, temperatures are uniformly high throughout the year, with a mean annual minimum temperature of about 26°C[10]. The coolest month is August and highest temperatures are recorded in March. The relative humidity of the area lies between 90% and 100% in the mornings and nights but falls to around 70% in the afternoons. These values are, however considerably in the dry season. In all, two field experiments were carried out (11th January - 25th May, 2014 and 1st July - 14th November, 2014) (Table 1). Both experiments were conducted under a rain shelter and involved the growing of tomato in buckets filled with sandy loam soil using an irrigation interval of three days with different irrigation treatments. The data from the first experiment were used to calibrate the model whilst those obtained from the second experiment was used to validate it.

Table 1 Duration and dates of the various growth stages for both experiments

Growth stage	Duration /d	1st Experiment	2nd Experiment
Initial	14	11/01/14 - 25/01/14	01/07/14 - 15/07/14
Development	36	26/01/14 – 03/03/14	16/07/14 – 21/08/14
Mid-season	61	04/04/14 - 04/05/14	22/08/14 - 24/10/14
Late season	20	05/05/14 – 25/05/14	25/10/14 – 14/11/14

2.2 Soil and vegetation of project site

The soil of the experimental site was a sandy loam. It consist of brown to grey poorly drained, fine textured soil developed on an old alluvium on nearly flat valley bottoms. The site has a vegetation of mainly coasted thicket climax and forbs regrowth. Characteristically, the soil is neutral to slightly acid in reaction (pH 6.5) and has a medium nutrient status. It has medium internal drainage, medium run-off and moderate permeability.

2.3 Experimental design

In all, two field experiments were conducted. The first one involved the growing of tomato in plastic buckets filled with sandy loam soil using three days irrigation interval. The results obtained were used to calibrate the AquaCrop model and this was done between January and May, 2014. The second experiment, similar to the first one, provided results used in validating the AquaCrop model and this was carried out between July and November, 2014.

The Randomized Complete Block Design (RCBD) was used with four irrigation treatments: T1 (no irrigation after plant establishment), T2 (50% ET_c restoration), T3 (100% ET_c restoration up to beginning of flowering, then 50% ET_c restoration) and T4 (100% ET_c restoration) and three replications (R1, R2 and R3). There were five plants per treatment under each replication with plant spacing of 1.0 m. The experiments were carried out under a rain shelter.

Figure 1 Bucket with transplanted seedlings to tomato under rain shelter

2.4 Calculation of crop water requirement (ET_c) and crop coefficient (K_c)

Crop water requirement and crop coefficient were determined as follows:

$$ET_c = ET_0 \times K_c \quad (1)$$

$$K_c = \frac{ET_c}{ET_o} \quad (2)$$

$$ET_o = E_{pan} \times K_{pan} \quad (3)$$

$$ET_c\,(3\text{ d}) = \text{Loss in weight of buckets} \quad (4)$$

$$ET_c \text{ for a growth stage} = \text{Summation of } ET_c \text{ for the number of irrigation days} \quad (5)$$

where, ET_c is crop evapotranspiration or crop water requirement, mm/d; K_c is crop factor; ET_o is reference crop evapotranspiration, mm/d; K_{pan} is pan coefficient (0.80); E_{pan} is pan evapotranspiration, mm/d.

2.5 A brief description of AquaCrop

Aqua Crop is a menu driven program with a well-developed user interface. Menus (Windows) are the interface between the user and the program. Multiple graphs and schematic displays in the menus help the user to discern the consequences of input changes and to analyze the simulation results. From the main menu, the user has access to a whole set of menus where input data is displayed and can be updated. Input data consist of climate data, crop, management and soil characteristics that define the environment in which the crop will develop[8]. Before one simulates, the simulation period and the initial conditions at the start of the simulation must be entered. When running a simulation, the user can track changes in the soil water content and the corresponding changes in the crop development, soil evaporation, transpiration, evapotranspiration rate, biomass production and yield. Simulation results are stored in output files and the data can be retrieved in spread sheet format for further processing and analysis. Program settings allow the user to alter default settings and also reset to their default values again.

AquaCrop, developed by FAO simulates attainable yields of the major herbaceous crops in response to water. Compared to other models, AquaCrop has a significantly smaller number of parameters and attempts to strike a balance between simplicity, accuracy and robustness. Root zone water content is simulated by keeping track of incoming and outgoing water fluxes. Instead of leaf area index, AquaCrop uses canopy ground cover. Canopy expansion, stomatal conductance, canopy senescence and harvest index are the key physiological processes which respond to water stress. Low and high temperature stresses on pollination and harvestable yield are considered, as cold temperature stress on biomass production. Evapotranspiration is simulated separately as crop transpiration and soil evaporation and the daily transpiration is used to calculate the biomass gain via the normalized biomass water productivity. The normalization is for atmospheric evaporative demand and carbon dioxide concentration, to make the model applicable to diverse locations and seasons, including future climate scenarios. AquaCrop accommodates fertility levels and water management systems, including rainfed, supplemental, deficit and full irrigation. Simulations are routinely in thermal time, but can be carried out in calendar time. Future versions will incorporate salt balance and capillary raise. AquaCrop is aimed at users in extension services, consulting firms, governmental agencies, NGOs, farmers associations and irrigation districts, as well as economists and policy analysts in need of crop models for planning and assessing water needs and use of projects and regions. Steduto et al.[11] have described the conceptual framework, underlying principles and distinctive components and features of AquaCrop (Figure 2). The structural details and algorithms of AquaCrop have also been reported by Raes et al.[12]

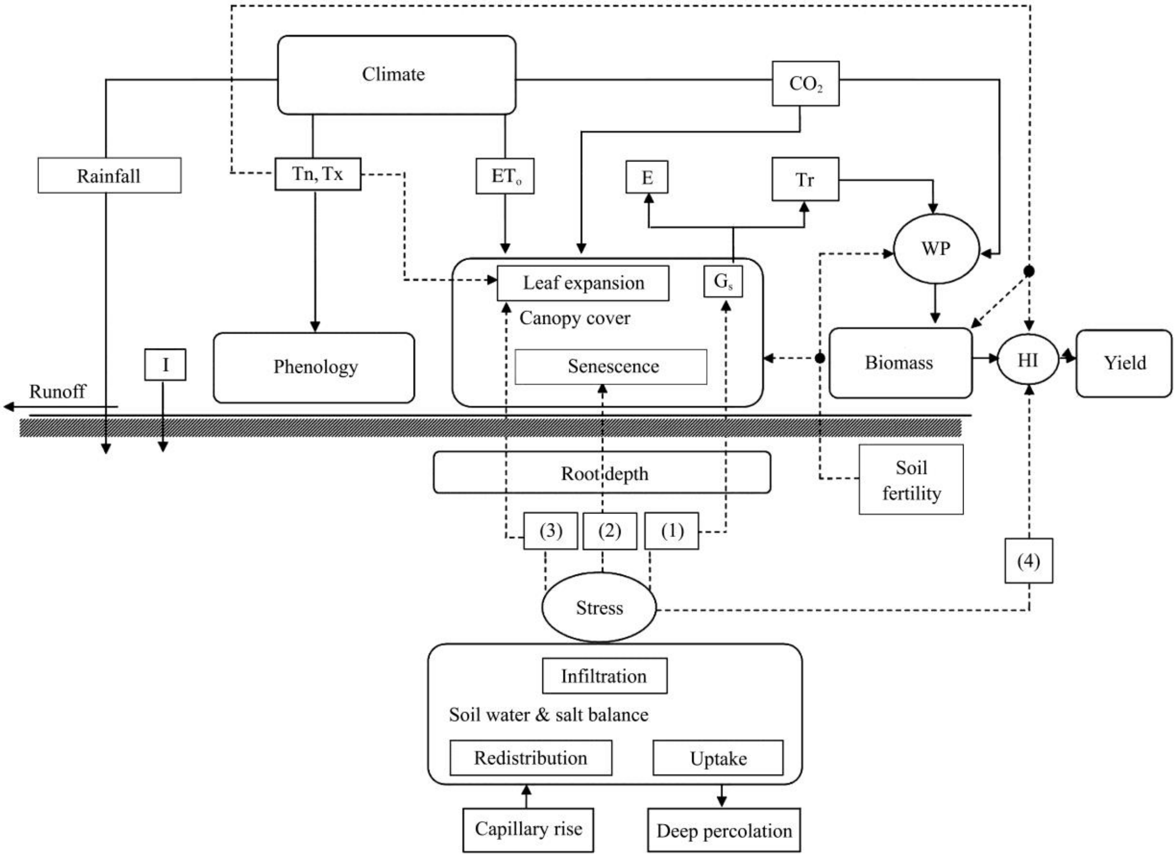

Figure 2 Flowchart of AquaCrop indicating the main components of soil-plant-atmosphere continuum[11]

2.6 Creating input files

2.6.1 Climate file

Creating a climate file consists of selecting or creating a Temperature file, ET_o file, Rain file and CO_2 file. When creating these files, the user has to specify the type of data (daily, 10-daily or monthly data), the time range and the data. Existing climatic data can also be pasted in an ET_o, Rain or Temperature file as long as the structure of the file is respected. Temperature and rainfall data covering the period of the experiments were obtained from thermometers and a rain gauge situated at the farm where the experiments were conducted. A US Class A evaporation pan was used to estimate the daily reference evapotranspiration (ET_o) over the growth season by using the equation:

$$ET_o = K_p \times E_{pan} \tag{6}$$

where, K_p is pan co-efficient; E_{pan} is pan evaporation, mm/d.

As the experiments were conducted under a rain shelter, the Rain file contained only zero values even though there were rainfall events over the seasons. The default CO_2 file supplied with AquaCrop was used.

2.6.2 Crop file

When creating a crop file, the user selects the type of crop (fruit/grain producing crops, leafy vegetable crop, roots and tubers of forage crops) and specifies a few parameters. With the help of this information AquaCrop generates the complete set of required crop parameters. The parameters are displayed and the values can be adjusted in the crop characteristics menu. Four growth stages of the tomato plant were considered namely: the initial stage (excluding seedlings at the nursery), the development stage (period of rapid growth of the crop, also known as vegetative stage), the mid-season stage (flowering and fruiting stage), and the late season stage (full maturity and ripening of fruits) were considered for the two experiments conducted.

2.6.3 Irrigation schedule

When creating an irrigation schedule the user specifies the time and the application depth of the irrigation events. In both experiments, a three-day irrigation interval schedule was adopted, and the volume of water to be applied on each three-day interval was derived from the computed loss in weight of each bucket with plant over the last three days. The equivalent in volume basis was found and applied to the plants according to the various treatments. Irrigation days for both experiments amounted to 43 days out of the 131 days of the growing period. Irrigation files were created for each of the treatments in the two experiments.

2.6.4 Soil file

When creating a soil file, the user has to specify only a few characteristics (soil type, depth of soil, etc). With the aid of this information, AquaCrop generates the complete set of soil parameters. The parameters and values can be adjusted in the soil profile characteristics menu. The texture of the soil was sandy loam.

2.7 Aqua crop model parameterization

Some crop parameters were assumed to be conservative (i.e., their values do not change) while the user-specific parameters were estimated from the first experiment (Tables 2 and 3).

Table 2 Conservative parameters of AquaCrop used in simulation

Description	Units/Meaning	Value
Base temperature	°C	10
Upper temperature	°C	30
Soil H_2O depletion factor, canopy expansion	Upper threshold (p-exp)	0.25
Soil H_2O depletion factor, canopy expansion	Lower threshold (p-exp)	0.55
Coefficient of positive impact on HI	Vegetative growth	10
Coefficient of negative impact on HI	Stomatal closure	8
Allowable maximum increase of specified HI	%	15
H_2O productivity normalized for *ET*o and CO_2	gm^{-3} (WP)	17
H_2O productivity normalized for *ET*o & CO_2 during yield formation	gm^{-3} (WP)	100

Note: HI, harvest index; WP, water productivity.

Table 3 User-specific parameters used in simulation

Parameter	Unit	Measured or Calibrated
Soil surface covered by an individual seedling at (90%) recover	cm^2/plant	5
Number of plants per hectare	hm^{-2}	60 000
Time from transplanting to recover	d	7
Maximum canopy cover, *CCx*	%	55
Time from transplanting to start senescence	d	100
Time from transplanting to maturity, i.e. length of crop cycle	d	131
Time from transplanting to flowering	d	91
Length of flowering stage	d	11
Maximum effective rooting depth	m	0.80
Time from sowing to maximum rooting depth	d	80
Reference Harvest Index (HIO)	%	50
Water productivity (WP)	gm^{-3}	17
Soil texture		Sandy loam

Note: *CCx*, Canopy cover of tomato.

3 Results and discussion

The calibrated AquaCrop model concentrated on its performance to predict crop yield and seasonal crop water requirement (ET_c). As a summary of the outcome of the simulations, the simulated fruit yield and the seasonal ET_c of the different irrigation treatments were compared with the measured values for the first and second experiments in Tables 4 and 5.

Table 4 Comparison between simulated and measured values of yield and seasonal ET_c of tomato for various treatments (Experiment 1 - Calibration)

Treatments	Yield/t hm^{-2}			Seasonal ET_c/mm		
	Measured	Simulated	Deviation/%	Measured	Simulated	Deviation/%
T_1	0.27	0.35	30.0	26.60	30.10	13.2
T_2	2.43	2.88	18.5	184.7	204.3	10.6
T_3	3.11	3.62	16.4	219.4	236.5	7.8
T_4	5.74	6.11	6.44	325.0	344.0	5.8

Table 5 Comparison between simulated and measured values of yield and seasonal ET_c of tomato for various treatments (Experiment 2 - Validation)

Treatments	Yield/t·hm^{-2}			Seasonal ET_c/mm		
	Measured	Simulated	Deviation /%	Measured	Simulated	Deviation/%
T_1	0.71	1.03	45.1	30.40	34.80	14.4
T_2	2.68	2.91	8.60	268.0	299.3	11.7
T_3	3.53	3.80	7.60	293.3	306.1	4.4
T_4	6.82	7.18	5.30	385.4	397.6	3.1

Considering both the calibrated and validated results for the yield of tomato, the deviations range from 5% to 45% indicating that AquaCrop was could not simulate the yield of tomato as was expected. The deviations were higher for T1 in both experiments where there was no irrigation after plant establishment. However AquaCrop predicted good results for yield in T4 in both experiments where there was 100% ET_c restoration.

Considering the calibrated results indicated in Tables 4 and 5 for the seasonal crop water requirement, the deviations ranged from 3.1% to 14.4%, indicating that AquaCrop was able to simulate the seasonal water requirements relatively accurately. This is in agreement with the observation made by Sam-Amoah et al.[9] who also used AquaCrop to simulate the yield of hot pepper. Considering the validation experiment (Table 5), it can be seen that T4 was quite accurately simulated by AquaCrop as the deviation recorded was only 3.1%. The deviation for T3 was relatively better than T2 and T1. As in the calibration experiment, the seasonal water requirement was quite accurately simulated with the deviations ranging from 5.8% to 13.2%.

4 Conclusions

From the two simulations, it can be concluded that generally,

1) AquaCrop was not able to simulate the yield of tomato for most of the treatments especially with treatment T1 which was simulated with the highest deviation of 45.1%.

2) On the other hand, the model was able to simulate the seasonal water requirements to an appreciable degree in both experiments.

3) It must be pointed out that the calibration of AquaCrop suffered from a lack of data on the progress of crop canopy cover which is a very important parameter used in developing the model.

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