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Parameterizing the FAO AquaCrop Model for Rainfed and Irrigated Field-Grown Sweet Potato

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ABSTRACT

Crop production in the Caribbean is dominated by small open field holdings that are almost totally reliant on rainfall. Sweet potato (*Ipomoea batatas* L. Lam. [Convolvulaceae]) has been identified as an important commodity to attain food and nutrition security goals of the region, particularly in light of a changing climate. The crop has high nutritional value, innate drought-tolerant properties, and can be grown with relatively low inputs. The routine use of crop models for yield optimization is largely absent in the Caribbean. In this study, an attempt was made to parameterize the FAO AquaCrop model for sweet potato for the first time. AquaCrop is a simulation model for crop water productivity, designed primarily for use in irrigation management. Parameters were developed using data from three sweet potato cultivars grown in two agroecological zones in Jamaica under rainfed and irrigated conditions. Digital photography was combined with an automated canopy estimator to track canopy development, and sample harvesting was done throughout the crop season. The overall simulation of biomass was good, with deviations of <28% for four out of six simulations, and season-long performance of the model was commendable. The simulation of yield presented more challenges, especially given the nonlinear rate of tuber development. The results, however, indicate that AquaCrop could be a useful tool for Caribbean agriculture in predicting the productivity of sweet potato under varying water availability.

Sweet potato is a dicotyledonous herbaceous trailing vine of the Convolvulaceae family that is characterized by its starchy storage roots and lobed leaves (Caribbean Agricultural Research and Development Institute, 2010). It is regarded worldwide as the sixth (fifth in developing countries) most important crop (http://cipotato.org/sweetpotato-1/) and in Jamaica is the third most widely grown root tuber (http://rada.gov.jm/?p=462). The expansion of its cultivation and use is seen as essential for the future development of Jamaica's agricultural sector (http://rada.gov.jm/?p=462) and for the food and nutrition security of the entire Caribbean region (Hutchinson, 2013) through reduced reliance on imported cereals.

Agricultural production in the Caribbean is dominated by small open field holdings that are highly reliant on rainfall with little supplemental irrigation (http://www.rlc.fao.org/).

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The rainfall climatology of the Caribbean is characterized by dry winters and wet summers (Taylor and Alfaro, 2005). The wet season is bimodal, with peaks in May to June and September to October (Chen and Taylor, 2002) separated by a brief dry period in July and August referred to as the "midsummer drought" (Magaña et al. 1999; Curtis and Gamble, 2008). During the late rainfall season (late August–November) as much as 40% of the total annual rainfall is received (Taylor et al., 2011; Climate Studies Group, Mona, 2012). There is strong year-to-year variability in annual rainfall amounts due to modulation by gradients in sea surface temperatures in and between the tropical Atlantic and Pacific (Taylor et al., 2002). Droughts are of particular concern for farmers in Jamaica and the wider Caribbean given the reliance on rainfall (Gamble et al., 2010). In this context, sweet potato assumes great importance for food and nutrition security.

The advantages of sweet potato are its adaptability to different growing conditions, its low susceptibility to natural hazards including hurricanes and other tropical systems (Caribbean Agricultural Research and Development Institute, 2010; Abdissa et al., 2011), and its innate drought-tolerant properties, including shading of the soil by its extensive canopy and an extensive and deep root system (Romero and Baigorria, 2008; Caribbean Agricultural Research and Development Institute, 2010; Stathers et al., 2013; Kunstelj et al., 2013a, 2013b).

The vulnerability of the climate-sensitive Caribbean agricultural sector is expected to be exacerbated under climate change,

Abbreviations: AWS, automatic weather station; CC, canopy cover; DAP, days after planting; WUE, water use efficiency.

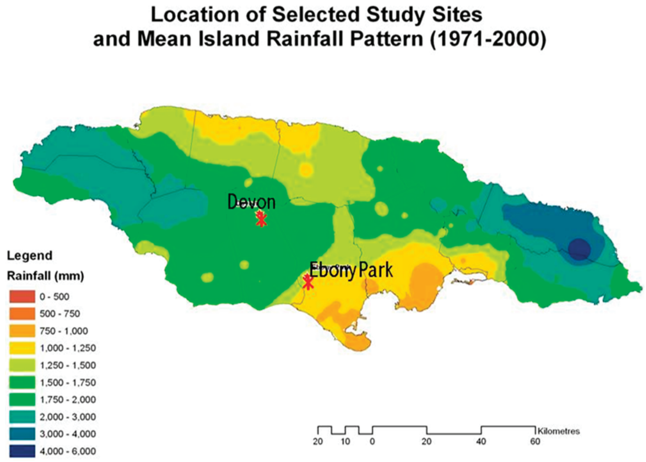

Fig. 1. Location of field test sites and mean rainfall pattern for the island of Jamaica.

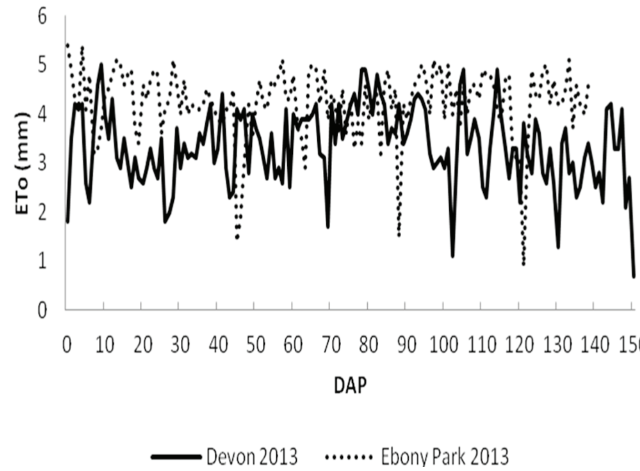

Fig. 2. Growing season reference evapotranspiration (ET_o), given in days after planting (DAP), in 2013 for Devon (solid line) and Ebony Park (dotted line), Jamaica.

and crop modeling has been identified as part of a wider adaptation strategy (Economic Commission for Latin America and the Caribbean, 2011; Hutchinson, 2013). Crop models are useful for their ability to estimate potential yields under varying environmental scenarios such as might occur under current and/or future climate change assuming optimal farm management. This, however, requires crop models that are calibrated and validated for the local conditions. With the exception of Cuba, there is little or no use of crop models in the Caribbean (Economic Commission for Latin America and the Caribbean, 2011; Hoogenboom, 2012).

The objective of this study was to parameterize the AquaCrop model for field-grown irrigated and rainfed sweet potato using its conservative parameters. AquaCrop is a crop water productivity model developed by the Land and Water Division of the FAO. The conceptual framework, underlying principles, and distinctive features of AquaCrop were documented by Steduto et al. (2009), while its structure and algorithms have been documented by Raes et al. (2009). AquaCrop simulates the yield response to water of herbaceous crops and is particularly suited to address conditions where water is a key limiting factor in crop production. It uses few input variables, which require comparatively simple methods for their determination (Steduto et al., 2008). The model uses canopy cover instead of leaf area index to monitor canopy expansion and has a good balance between simplicity and robustness, making it well suited for use in the Caribbean where agro-meteorological data are scarce.

The global applicability of AquaCrop is dependent on its being tested in a variety of locations under differing soil conditions, crops, agronomic practices, and climatic conditions (Sam-Amoah et al., 2013). For example, the calibration and evaluation of the performance of AquaCrop has been done for cotton (*Gossypium hirsutum* L.) in northern Syria (Farahani et al., 2009; García-Vila et al., 2009), for maize (*Zea mays* L.) in various locations (Heng et al., 2009; Hsiao et al., 2009), for hot pepper (*Capsicum* sp.) in south-central Ghana (Sam-Amoah et al., 2013*),* and for potato (*Solanum tuberosum* L., known as Irish potato in Jamaica) in Lima, Peru (Izzi, 2008). However, like most of the other crop models in current use, AquaCrop has not been parameterized for root crops like sweet potato or for the Caribbean region. In this study, field trials were conducted at two sites in Jamaica for the parameterization of AquaCrop over two crop seasons.

Table 1. General sweet potato site characteristics in Jamaica.

Parameter	Devon	Ebony Park
Coordinates	18°9′59.47″ N, 77°31′56.76″ W	17°56′60″ N, 77°20′60″ W
Elevation, m asl	816	67
Soil type	Chudleigh clay loam (Typic Eutrorthox)	Rhymesbury clay (Udic Chromustert)
Mean annual rainfall (1971–2000), mm	1500–1750	750–1000

Table 3. Crop season conditions at two field sites and three cropping seasons in Jamaica: at Devon on 3 Nov. 2011 to 12 Apr. 2012 and 3 May to 9 Oct. 2013 and at Ebony Park on 14 Apr. to 29 Aug. 2013.

Parameter	Devon	Ebony Park
Crop season rainfall (total), mm		
2011/2012	622	not planted
2013	645	470
Crop season irrigation (total)		
2011/2012	197	not planted
2013	44	432
Mean temperature (crop season), °C	23.2	28.2
Mean daily ET_o†, mm d^{-1}	3.5	4.2

† Reference evapotranspiration as computed by the FAO ET_o calculator.

Table 2. Description of soil characteristics at two sweet potato field sites in Jamaica.

Site	Field capacity	Permanent wilting point	Total available water	Saturated hydraulic conductivity	Curve number	pH
	%		mm m^{-1}			
Devon	39	23	160	70	75	6.34
Ebony Park	49	23	210	20	80	6.8

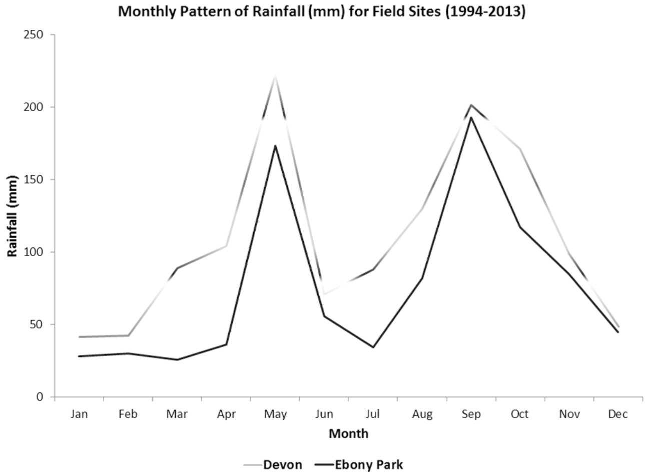

Fig. 3. Monthly pattern of rainfall for field sites (1994–2013).

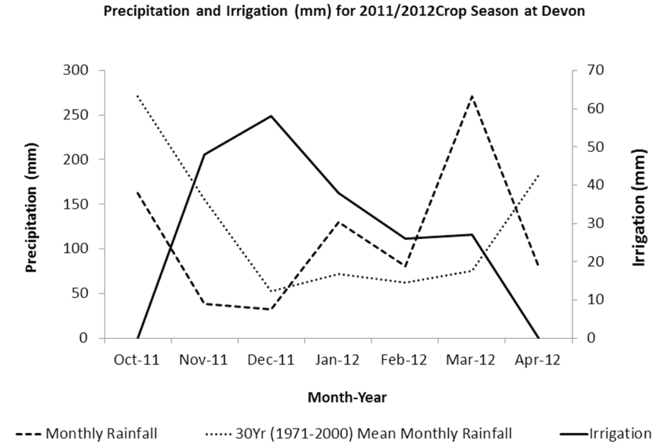

Fig. 4. Monthly precipitation and irrigation for the 2011/2012 crop season at Devon, Jamaica. During the period of drought stress in the first 59 d after planting (November–December 2011), site rainfall was 34% of the 30-yr (1971–2000) mean rainfall.

MATERIALS AND METHODS

Site Characteristics and Biometry

Parameters for the model were determined from data collected from field tests undertaken at Devon, Manchester, in 2012 and 2013 and Ebony Park, Clarendon, in 2013, located in different agroecological regions of south-central Jamaica (Fig. 1). General site characteristics are summarized in Table 1. Devon has clay loam soil with lower total available water content than the clay soil at Ebony Park. The full details of the soil characteristics are given in Table 2.

The experiment included three popularly cultivated sweet potato cultivars (Ganja, Uplifta, and Yellow Belly) and two water treatments, irrigated and rainfed. Treatments were allocated in a randomized complete block (RCB) design with five replications. At each location there were two sets of experimental RCBs, one irrigated and the other rainfed. The plots at Devon were 26 m^2 (20.7 m^2 in 2012), with larger plots at Ebony Park (53 m^2). In all cases, sweet potato slips were planted on both sides of four raised ridges at a spacing of 30.5 cm (1 ft) on the ridge. Before planting, the slips were soaked in a synthetic organophosphate pesticide (*O*,*O*-diethyl *O*-[6-methyl-2-(1-methylethyl)-4-pyrimidinyl] phosphorothioate) solution (0.5% in water) for 20 min and then drained (as recommended by the Rural Agriculture Development Authority). Treatment of the planting material was conducted to reduce the risk of infestation of the sweet potato weevil (*Cylas formicarius).*

Row spacing was 1.08 and 1.55 m for Devon and Ebony Park, respectively. Drip irrigation lines (1.27-cm diameter) were run along the length of each ridge in the irrigated plots. For planting material, potato slips of 30- to 40-cm (12–15-inch) length were obtained from vines of nursery-grown sweet potato, mainly from the apical regions. This is in keeping with recommendations for field planting in Jamaica (Fielding and Ryder, 1995; Caribbean Agricultural Research and Development Institute, 2010). The slips used as planting material developed roots and new foliage after being transplanted. There were up to 224 plants in each plot, sufficient to allow periodic destructive sampling. Fertilization was done once in each crop season at the recommended rate.

Weather Data and Irrigation

The sites are part of the network of stations maintained by the Meteorological Service, Jamaica, and have an automatic weather station (AWS) measuring multiple parameters and reporting at intervals upward from 30 min. The AWS provided the daily weather parameters needed for the climate component of the AquaCrop model in 2013. For the crop at Devon (2011/2012), data were used from an automatic weather station (at Kirkvine) located 14 km away. Variables measured included maximum and minimum temperatures, rainfall, (net) solar radiation (not available for 2011/2012), wind, and relative humidity (not available for Ebony Park). The variables (except rainfall) were used to calculate daily reference evapotranspiration (ET_o) for each site using the Penman–Monteith equation (Allen et al., 1998) and the FAO ET_o calculator (Raes, 2009). This ET_o represents an upper limit for evapotranspiration (assuming no water shortage), which is used by the AquaCrop model to simulate daily crop evapotranspiration. In 2013, the mean daily ET_o for the crop season at Ebony Park was higher than at Devon (Table 3; Fig. 2). Ebony Park had a mean crop season (2013) temperature that was 5°C warmer than Devon (Table 3).

The annual rainfall characteristic of both sites is shown in Fig. 1, and the climatological mean rainfall (1971–2000) for the sites is given in Table 1. On average, Devon (Manchester) receives nearly twice as much rainfall as Ebony Park, but both locations exhibit the characteristic bimodal rainfall pattern (Fig. 3).

Total rainfall during the 2011/2012 cropping season at Devon was 622 mm (Table 3; Fig. 4). The rainfall occurring in the first 59 d after planting (3 Nov.– 31 Dec. 2011) was 71 mm. This amount was only 34% of the 30-yr (1971–2000) mean rainfall for these months at this location (Fig. 4 and 5). As a consequence, severe drought conditions (as classified by the Meteorological Service, Jamaica) were experienced during this period. Irrigation of 197 mm was applied in this cropping season, with the highest amounts supplied during the drought period (Fig. 5). In the 2013 cropping season, rainfall was more evenly distributed and no drought was experienced. Rainfall summed to 645 mm, and this was supplemented by irrigation of only 44 mm as described below.

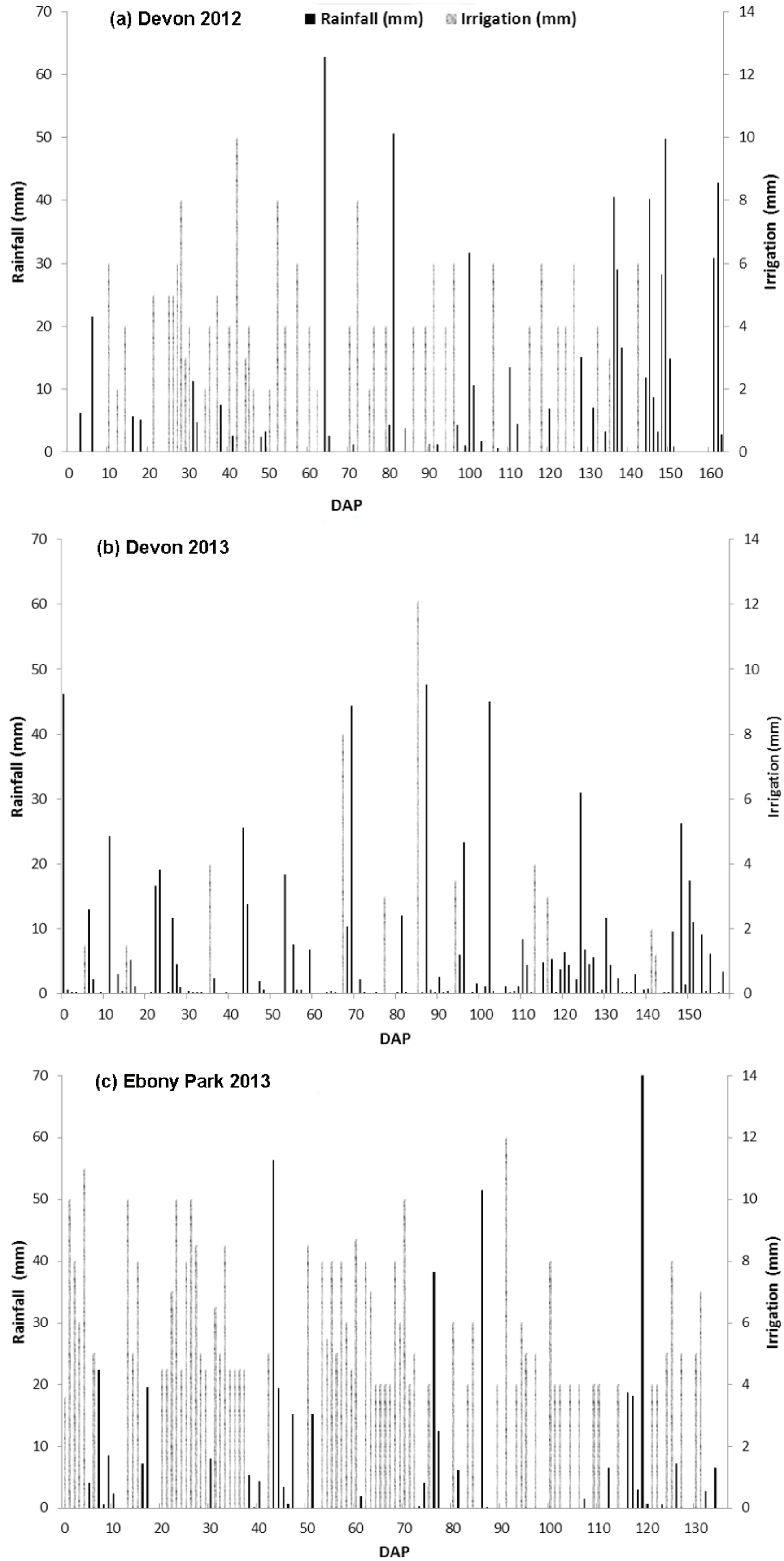

Fig. 5. Daily rainfall (black bars) and irrigation (gray bars) measured for days after planting (DAP) at (a) Devon 2011/12, (b) Devon 2013, and (c) Ebony Park 2013 in Jamaica.

Immediately after planting, when the plants were most sensitive to water stress, both irrigated and rainfed plots were watered (Fielding and Ryder, 1995; Caribbean Agricultural Research and Development Institute, 2010). Initial soil moisture was therefore at field capacity. In the first crop season at Devon, irrigation was automated by an inline timer (2-cm [3/4-inch] valve, 106 L [28 gallons] min^{-1}, battery-operated digital controller) that triggered watering of the crops four times per day. Irrigation (mean of 4.5 mm d^{-1}) was applied for a total of 43 d. In the 2013 crop season, a different irrigation schedule was used. Davis Vantage Pro Plus AWS moisture probes were used to monitor soil moisture (Davis Instruments, 2006). Irrigation was done once daily, only when a reading of 30 kPa (30 cbar) was recorded for soil moisture tension. The total number of irrigated days was 11, with a mean daily application of 4 mm. This new schedule, along with the more evenly distributed rainfall, resulted in the large difference in irrigated amounts (greater than four times more in 2012) between these two seasons.

Planting took place at Ebony Park only in 2013, and at this location the total rainfall for the crop was 470 mm with an irrigation total of 432 mm. Irrigation was done when moisture tension of 30 kPa (30 cbar) was registered on the onsite irrometer (Model R 24). The mean daily irrigation was 6 mm, and application lasted a total of 72 d.

Crop Parameters: Yield, Biomass, and Canopy Cover

Above- and belowground biomass were assessed destructively at least two times during the crop season and at final harvest. Yields were calculated from the cultivar average of four to eight plants from each plot and extrapolated to give yield per unit area in megagrams per hectare (1 Mg = 1 tonne). For the first crop at Devon in 2012, there was selective harvesting, when plants with marketable tubers were chosen for measurement of yield. Thereafter, for Devon and Ebony Park in 2013, all tubers harvested in the sample were measured without separation of marketability. Samples were dried to constant weight to obtain dry mass. Cultivar averages were determined from the mean of all five replicates as well as one cross-cultivar average calculated for each treatment. Measured values (observed) were compared with those calculated (simulated) by AquaCrop (Hsiao et al., 2011).

Canopy cover (CC) was measured every 20 to 30 d during the crop season using a combination of above-canopy digital photography and one of two software packages. The photographs were taken with a digital camera (Fujifilm 12.2 megapixels, 18× optical zoom Finepix S1800 lens). A new approach developed in the course of this research was used to estimate canopy cover (Coy et al., unpublished data, 2013). The new technique is called the Automated Canopy Estimator (ACE) and was applied at all sites. The ACE converts a digital photograph from red–green–blue (RGB) to the CIE L*a*b* color space (Wright, 1929; Guild, 1932; Commission Internationale de l'Eclairage, 1931). One major benefit of working in the CIE L*a*b* is that it is device independent and therefore a single approach can be used in the segmentation of captured images without the negative effects of differing color representations. Images are segmented based on an assessment of the bimodality of the probability distribution of the a* color values. The method was rigorously tested against ground truth segmentations of oat (*Avena sativa* L.), flax (*Linum usitatissimum* L.), rape (*Brassica napus* L.), and maize. The estimated CC values yielded high coefficients of correlation, highlighting the technique's consistency in estimation across different crop types.

In all cases, the mean CC for each cultivar was obtained from the average of the five replicates in each treatment (irrigated and rainfed separately) for use in the AquaCrop model. One mean value across all cultivars was also obtained for each treatment.

Data Analysis

Goodness of fit of the simulated results with the measured field test data was assessed on the basis of two statistical measures: the root mean square error (RMSE) and the coefficient of efficiency (E) (Nash and Sutcliffe, 1970):

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(O_i - S_i\right)^2} \qquad [1]$$

$$E = 1 - \frac{\sum_{i=1}^{N}\left(O_i - S_i\right)^2}{\sum_{i=1}^{N}\left(O_i - \bar{O}\right)^2} \qquad [2]$$

where S_i and O_i are the simulated and observed values of samples taken during the season (for biomass, canopy cover or yield) or at the end of the season (e.g., tuber yield), N is the number of observations, and $\bar{O}$ is the mean value of O_i (Heng et al., 2009).

The RMSE measures the overall mean deviation between simulated and observed values. The closer the value is to zero, the better the model performance. The coefficient of efficiency measures how the overall deviation between observed and simulated values departs from the overall deviation between observed values O_i and their mean value ($\bar{O}$) during the crop season. The values are of E are unitless and can range from $-\infty$ to 1. The closer the values are to 1, the better the model's simulation efficiency. Similar statistical analyses (comparing measured and simulated values using E and RMSE) have been used successfully by a number of other AquaCrop parameterization studies (Heng et al., 2009; Hsiao et al., 2009; Farahani et al., 2009). The deviation percentage (Hsiao et al., 2009), defined as Deviation = [(simulated − measured)/measured] ×100, was also used as a measure of how well the model performed. Plots with experimental data are presented with standard deviation bars to give an indication of the random error size.

Model Parameters

Conservative Parameters

The AquaCrop model Version 4.0 (2012) was used in the parameterization. The approach taken was to calibrate the model with the 2 yr (2011/12 and 2013) of data from Devon, Manchester. During the simulations, emphasis was placed on the progression of green canopy cover, total and belowground biomass, and to a lesser extent total reference evapotranspiration, after Hsiao et al. (2009). Conservative parameters are those that vary little among different cultivars of the same crop and so can be applied directly (unaltered) or with minimal adjustments even across different agroecological zones (Raes et al., 2009; Hsiao et al., 2009; Steduto et al., 2012*)*. Values for these parameters may be obtained from the literature or previous studies, but in the case of sweet potato there were no previous values available.

Initial (best guess) values for conservative parameters of sweet potato were therefore selected from values reported in the literature for Irish potato (calibrated for Lima, Peru) and knowledge gained of the crop. This approach, i.e., using the closest crop (Irish potato) to calibrate a totally new crop (sweet potato), was recommended by Steduto et al. (2012). Refinements to these initial values were obtained through trial and error after repeated simulations to ensure the best match of simulated to measured variables. By taking the average across cultivars, one set of conservative values was obtained and used in calendar mode for emergence date, physiological maturity, and senescence. Some differences were noted among the cultivars, especially Yellow Belly, which appeared to senescence earlier than the others. Notwithstanding, mean values were observed to give more favorable results than values for the individual cultivars.

The same set of conservative parameters was used across treatments. Once reasonable agreement was obtained with the measured values, the model was switched to the growing degree day (GDD) mode and more adjustments made to the parameters. The final set of parameters was tested against data from the crop at Ebony Park (2013). This followed the recommended approach for parameterization of AquaCrop by Steduto et al. (2012). The full set of conservative parameters is given in Table 4. In addition, the following are noted about parameter choices:

- *Canopy parameters*: Canopy cover, as determined by vine growth, varies for each of the three growth phases of sweet potato, with characteristics of the initial phase of slow vine growth and rapid growth of adventitious roots, an intermediate phase of rapid growth of vines and an increase in leaf area and storage root initiation; and the final stage of bulking of tubers but no further vine growth (Caribbean Agricultural Research and Development Institute, 2010). The size of individual leaves also varies among cultivars from small almost divided leaves for Ganja to large-lobed leaves for Uplifta. Both factors pose a challenge to estimating canopy cover parameters. The default value for a high initial canopy cover was adjusted to a best-fit value of 0.9% for the initial values for canopy cover (CC_o). The canopy growth coefficient (CGC), which determines canopy development from emergence to maximum canopy cover, was determined by the CGC estimator spreadsheet of the FAO. This was later adjusted until the best match with measured values was obtained. The measured maximum canopy value from the field tests (94%) was used, while the canopy decline coefficient (CDC, which controls the rate of canopy decline after senescence), also was adjusted until the best match was obtained.
- *Normalized water productivity*: Water productivity (WP) is measured in grams of biomass per square meter and per millimeter of cumulated water transpired (or kilograms of biomass per cubic meter of water transpired) during the

Table 4. Conservative (constant) parameters (conservative across all locations, water treatments, and cultivars) used for simulation of sweet potato at Devon and Ebony Park, Jamaica.

Parameter	Value	Units or meaning. How measured
Base temperature, °C	15	based on literature
Cutoff (upper) temperature, °C	35	based on literature
Canopy cover (CC) per seedling at 90% emergence (CC_o), %	0.9	best-fit value
Canopy growth coefficient (CGC), %	0.966	increase in CC relative to existing CC per growing degree day (GDD); adjustment to best match in calendar mode
Maximum canopy cover (CC_x), %	94	estimated by the ACE estimator (similar plant density); time to maximum canopy = 820 GDD
Crop coefficient for transpiration at CC = 100%	1.10	full canopy transpiration relative to ET_o; adjustment to best match
Decline in crop coefficient after reaching CC_x, %	0.150	decline per day due to leaf aging; adjustment to best match
Canopy decline coefficient (CDC) at senescence, %	0.798	decrease in CC relative to CC_x per GDD; adjustment to best match
Water productivity, normalized to year 2000 (WP*), g (biomass) m^{-2} mm^{-1}	20.0	function of atmospheric CO_2
Upper canopy expansion threshold (P_{upper})	0.26	fraction of total available water; above this, leaf growth is inhibited
Lower canopy expansion threshold (P_{lower})	0.66	leaf growth stops completely at this value
Canopy expansion stress coefficient curve shape	3.3	moderately convex
Upper stomatal conductance threshold (P_{upper})	0.65	above this value the stomata begin to close
Stomata stress coefficient curve shape	3.4	moderately convex
Early senescence stress coefficient (P_{upper})	0.69	above this senescence begins
Early Senescence stress coefficient curve shape	2.7	moderately convex
Reference harvest index (HI_o), %	55	suited for most cultivars
Water stress on harvest index (HI), %		
Before yield formation	8	increase in HI (moderately positive effect); water stress affecting leaf expansion
During yield formation	1.16	positive adjustment factor for HI (moderately positive); water stress affecting leaf expansion
	0.92	reducing factor for HI (slightly negative); water stress affecting stomatal closure
Aeration stress, %	–4	volume percentage below saturation that is tolerable under deficient aeration conditions (moderately tolerant to waterlogging)
GDD from 90% emergence to start of yield formation	415	could be earlier for shorter season cultivars
Length of yield formation, GDD	875	could vary slightly among cultivars

time period in which the biomass is produced (Raes et al., 2011, Steduto et al., 2012). In AquaCrop, WP is normalized for atmospheric demand and air CO_2 concentrations. Used in this way, it behaves conservatively and expresses the strong relationship between photosynthetic CO_2 assimilation or biomass production and transpiration independently of the climatic conditions. Steduto et al. (2007) suggested that the conservative nature of WP is fundamental to the robustness of the model. Water productivity for C_3 crops like sweet potato lies in the range of 15 to 20 g m^{-2} mm^{-1} (Raes et al., 2011). Using this range, the most appropriate value derived for sweet potato from the experimental data was 20.0 g m^{-2} mm^{-1}.

- *Water stress parameters and harvest index* (HI): Adjustments were made to all the default stress parameters used for Irish potato while noting the moderate sensitivity of sweet potato to water stress and the limitation to only two water treatments (irrigated vs. rainfed). The effects of water stress on the HI are categorized in two stages. Before yield formation, there is a moderately positive (8%) increase, and during yield formation there are two (sub) adjustments: (i) for leaf expansion (1.16, moderately positive) and (ii) for stomatal closure (0.92, slightly negative). The value of reference harvest index (HI_o) used was 55% based on the best fit between measured and simulated data.
- *Aeration stress*: Sweet potato is regarded as being moderately tolerant to aeration stress. For waterlogging (aeration) stress, a value of –4% of the saturated volume was used.
- *Growing degree days* (GDD): The simulations of GDD used a base of 15°C and an upper temperature of 35°C. These values were chosen based on published work on the base temperature as well the optimal range for sweet potato production (Romero and Baigorria, 2008; Ramirez, 1992; Villordon et al., 2009; Caribbean Agricultural Research and Development Institute, 2010; Stathers et al., 2013). The effect of temperature stress could not be tested because temperatures remained within the optimal range for most of the crop season in both years.

User-Specific Parameters

User-specific parameters are those that must be directly entered by the user based on accurate data and knowledge of the crop. The following considerations were made when choosing parameter values for emergence time, rooting depth, canopy senescence and physiological maturity.

- *Emergence time*: This is the time by which 90% of seedlings or new shoots have emerged from the soil. It is regarded as the starting time (first day of appearance) of the crop canopy. The emergence time was fairly uniform across the cultivars, and the mean value of 77 GDD was used.
- *Rooting depth*: Sweet potato is considered a deep-rooted crop, with the maximum effective rooting depth generally being 1 to 1.5 m (Allen et al., 1998). In this study, we found that roots exceeded these limits. The measured value of 1.6 m was used for both Devon and Ebony Park.
- *Canopy senescence and physiological maturity*: The time to senescence was taken as 1091 GDD. It was taken to be the time when yellowing was noticed in >40% of leaves. However, it was noted that late-season rainfall veiled some of the senescence, especially at Ebony Park, where significant green canopy (overlying older senescent leaves) was evident even at harvest. Physiological maturity varied slightly among the different cultivars and in general exceeded the 120 calendar days reported for local cultivars by the Caribbean Agricultural Research and Development Institute (2010). The crop season at both sites lasted in excess of 130 d, and maturity was taken as 1294 GDD.

RESULTS AND DISCUSSION

The results of the simulation are presented and discussed by location. For each cropping season, comparisons were made between the simulated and measured values of canopy cover, (total) biomass, and yield. Additionally, some results are presented for measured (by AWS) vs. simulated daily crop ET_o at Devon in 2013. In the experiment, as explained above, three cultivars were included, two high yielding (Uplifta and Ganja) and one lower yielding (Yellow Belly). Besides serving as a measure of the robustness of the model (because AquaCrop simulations pre-suppose modern high-yielding cultivars), the inclusion of Yellow Belly was to assess how its deeper roots might affect drought tolerance.

Devon, Manchester

2012 Crop Season

In the first crop season (2011/2012), AquaCrop underestimated canopy cover for both the irrigated and rainfed treatments for about 66 d after planting (DAP), though results were slightly better for the rainfed plots (Fig. 6a and 6b). However, the maximum canopy cover value for both rainfed and irrigated sweet potato (occurring at 122 DAP in the model) was

Table 5. Root mean square error (RMSE) and coefficient of efficiency (*E*) for progression of canopy cover and biomass of rainfed and irrigated sweet potato at Devon and Ebony Park, Jamaica.

		Canopy cover		Biomass		Yield	
Year	Treatment	RMSE	*E*	RMSE	*E*	RMSE	*E*
		%		Mg ha^{-1}		Mg ha^{-1}	
				Devon			
2012	irrigated	25.20	–0.59	2.81	0.74	3.68	–0.08
	rainfed	9.42	0.76	12.11	–0.69	9.44	–0.32
2013	irrigated	10.86	0.86	2.34	0.79	1.98	0.22
	rainfed	4.48	0.97	2.61	0.75	0.78	0.90
				Ebony Park			
2013	irrigated	17.25	0.29	7.37	0.39	2.57	0.64
	rainfed	16.06	0.67	1.74	0.89	3.62	–13.48

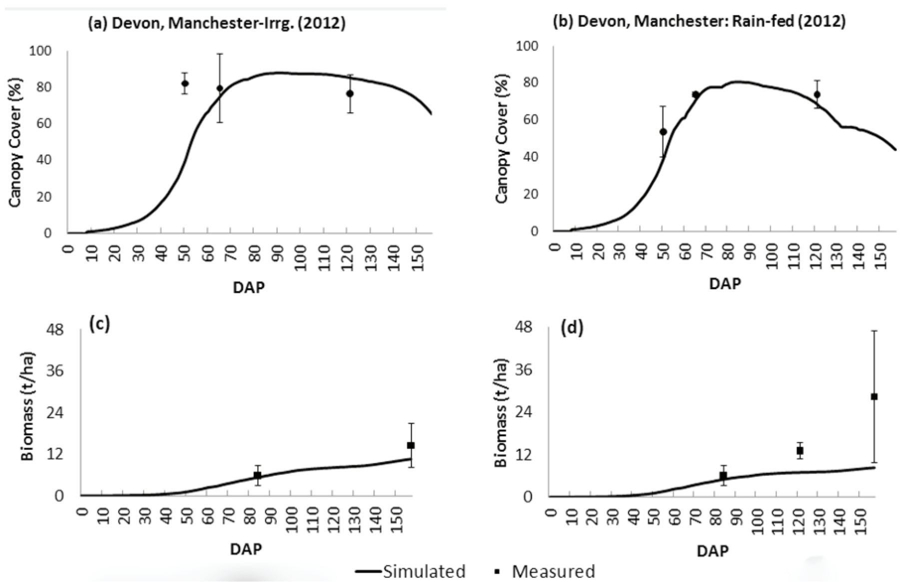

Fig. 6. Simulated (line) vs. measured canopy cover (filled circles) and biomass (filled squares) of sweet potato at days after planting (DAP) for (a,c) irrigated and (b,d) rainfed treatments at Devon, Manchester, Jamaica, in 2012. Error bars represent one standard deviation above and below the mean.

closely simulated. The large disparities between initial values resulted in large RMSE and relatively low E values (negative for the irrigated treatment), as shown in Table 5. The discrepancies might be attributable to a number of factors: the severe drought stress that was experienced in the first 60 DAP and the differential response of the cultivars to drought, which was not captured by AquaCrop. Several studies (Bourke, 1984; Martin and Carmer, 1985; Fielding and Ryder, 1995; Ku et al., 2008; Lebot, 2009) have reported that sweet potato water requirements are site and time specific. These researchers also noted that cultivars differ in their response to stress conditions including drought. AquaCrop does not simulate well under high-drought-stress conditions (Heng et al., 2009; Hsiao et al., 2009; Patel et al., 2011).

Further, the onsite weather station was inoperable during this crop season and ET_o was calculated using data from the nearest station (Kirkvine Bauxite Company), which is 14 km away. The absence of solar radiation in this data set seemingly affected the estimation of ET_o, given the known dependence of ET_o on this parameter for accurate estimates (Allen et al., 1998; Droogers and Allen, 2002; Alkaeed et al., 2006; Rahimikhoob, 2014). There was no measurement of canopy cover after the onset of senescence in this crop season, so the performance of the model during this period was not assessed for this variable.

The simulation of biomass is shown in Fig. 6c and 6d. There was good ($E = 0.74$) agreement between simulated and measured total biomass for the initial and final values for the irrigated treatment (Table 5). The irrigated sample taken at 122 DAP was inadvertently lost. Figure 6d shows a divergence between measured and simulated values of biomass in the rainfed plots as the season progressed. In general, rainfed yields were higher than those of the irrigated plants (Table 6). It appears that the low rainfall during the first third of the crop life did not adversely affect yields of the rainfed plants. On the other hand, it seems that irrigation did not benefit tuber development and possibly contributed to a reduction in yield relative to the rainfed plants. This is in agreement with observations made by Lebot (2009) in their research in Taiwan that over-irrigation tended to reduce storage root yields in areas of high rainfall, whereas a short period of drought stress appeared to stimulate root development.

While an adequate water supply through rainfall or irrigation is essential for the optimum development of storage roots, excess water can result in poor aeration. Like Lebot (2009), it was noted in this study that if sweet potato was irrigated when the total available water in the soil was depleted to about 40%, the highest yields were produced. There are exceptions, however, especially in areas where rainfall is usually low. For example, at another location in the dry southern fringe of Jamaica (Bodles, St. Catherine)

Table 6. Simulated vs. measured values of total biomass and tuber yield of rainfed and irrigated sweet potato at Devon and Ebony Park, Jamaica.

Year	Treatment	Final (total) biomass			Tuber yield		
		Measured	Simulated	Deviation	Measured	Simulated	Deviation
		Mg ha^{-1}					
		Devon					
2012	irrigated	14.5 ± 6.3†	10.6	–27.2	11.2 ± 5.7	6.3	–43.6
	rainfed	28.4 ± 18.5	8.3	–70.7	20.8 ± 14.9	5.0	–76.0
2013	irrigated	16.9 ± 5.7	13.6	–19.5	6.3 ± 4.9	7.3	16.5
	rainfed	17.8 ± 2.4	13.6	–23.6	6.7 ± 2.0	7.3	8.7
		Ebony Park					
2013	irrigated	27.8 ± 2.8	13.5	–51.4	11.0 ± 5.8	7.3	–34.0
	rainfed	14.6 ± 4.2	13.5	–7.8	2.6 ± 1.4	7.3	181.7

† Means ± standard deviations of three cultivars.

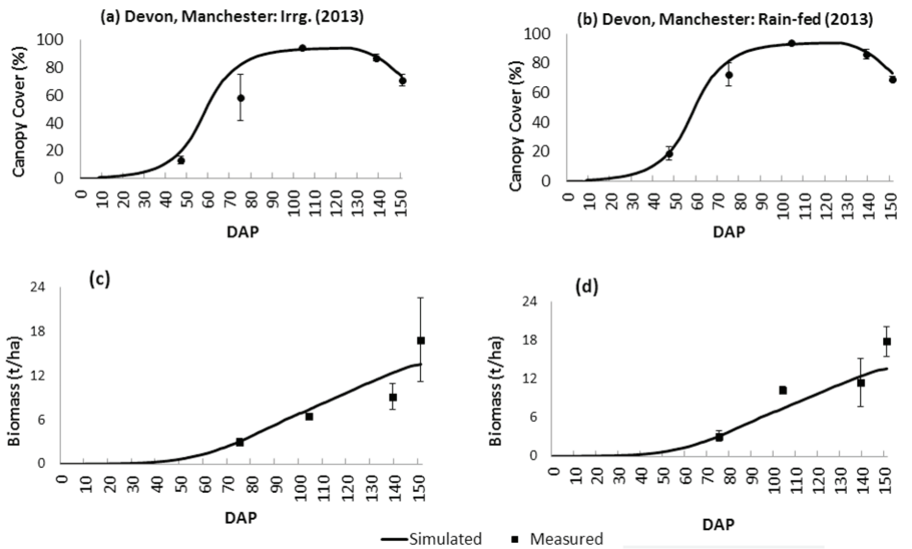

Fig. 7. Simulated (line) vs. measured canopy cover (filled circles) and biomass (filled squares) of sweet potato at days after planting (DAP) for (a,c) irrigated and (b,d) rainfed treatments at Devon, Manchester, Jamaica, in 2013. Error bars represent one standard deviation above and below the mean.

a lack of rain was experienced, and without irrigation the rainfed plants died due to severe drought stress.

There was a large deviation between the simulated and observed final yields (−43.6% for irrigated, −76.0% for rainfed) (Table 6). The lower standard deviation (14.9 for rainfed vs. 5.7 for irrigated) for the irrigated treatment suggests that irrigation reduced the variability of yield by allowing more uniform development of tubers (Table 6). The reduced variability seemingly increased the potential for making better yield predictions. The poor simulation results and large deviation in final yields is likely to have been influenced by the high yield variations occurring even within the same field trial of different cultivars, which is a known trait of sweet potato (Bourke, 1984; Martin and Carmer, 1985; Fielding and Ryder, 1995; Ku et al., 2008; Lebot 2009). Further, the demonstrated inability of AquaCrop under high-water-stress conditions noted in other studies (Heng et al., 2009; Hsiao et al., 2009; Patel et al., 2011) could also have affected the results. The lack of solar radiation data in the computation of ET_o is also noted again. The selective harvesting of plants with marketable tubers also inflated the final yields and exaggerated the disparities between measured and simulated data.

The simulated water use efficiency (WUE) and ET_o for rainfed and irrigated sweet potato was calculated at all sites using the simulated values from AquaCrop (Table 7). The WUE is a measure of how efficiently the crop is using water for yield or biomass production and can be expressed as the ratio of biomass (or yield) to evapotranspiration. Although the ET_o for the irrigated treatment was considerably higher (by 188 mm) than for the rainfed treatment, the WUE was nearly identical for both yield and biomass. This suggests that WUE can be optimized at this location without irrigation.

2013 Crop Season

Model performance for canopy cover was much improved over 2011/2012, with greater agreement between simulated and measured values for the entire crop season (Fig. 7). This is also seen in the smaller measures of RMSE (10.9 and 4.5% for irrigated and rainfed, respectively) and higher values of E (0.86 for irrigated and 0.97 for rainfed) than for the previous crop season (Table 5). The use of weather data obtained onsite and more evenly distributed rainfall seemingly improved the simulation. Data were also available for the period after senescence. Significantly, the ACE software still performed well during this period,

Table 7. Total reference evapotranspiration (ET_o) and water use efficiency (WUE) simulated by AquaCrop for rainfed and irrigated sweet potato for two sites in Jamaica. The WUE values were calculated using simulated values of biomass or yield. The ET_o data for Devon 2012 was obtained from the Kirkvine station 14 km away because the onsite automated weather station at Devon was inoperable in 2012. All other data were obtained from onsite stations.

Year	Treatment	Total ET_o	WUE: Based on biomass†	WUE: Based on yield‡
		mm	kg m^{-3}	
		Devon		
2012	irrigated	821.7 (1004.8)§	1.29	0.77
	rainfed	633.3	1.31	0.79
2013	irrigated	531.6 (560.3)	2.56	1.38
	rainfed	528.9	2.57	1.39
		Ebony Park		
2013	irrigated	414 (587.9)	3.26	1.76
	rainfed	387.6	3.48	1.88

† Final biomass/total ET_o.
‡ Final yield/total ET_o.
§ AquaCrop simulated total ET_o, with values computed by the FAO ET_o calculator given in parentheses.

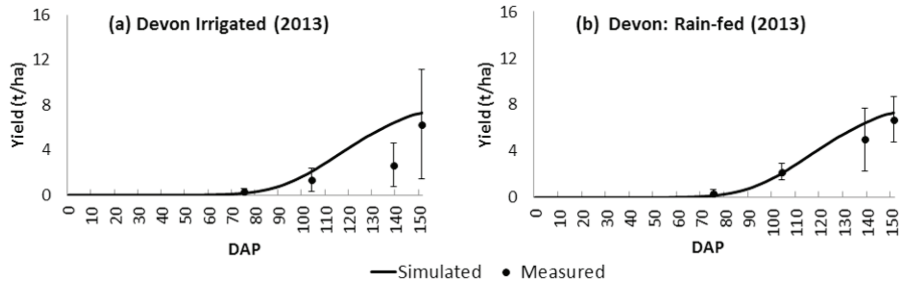

Fig. 8. Simulated (line) vs. measured (filled circles) yield of sweet potato at days after planting (DAP) for (a) irrigated and (b) rainfed treatments at Devon, Manchester, Jamaica, in 2013. Error bars represent one standard deviation above and below the mean.

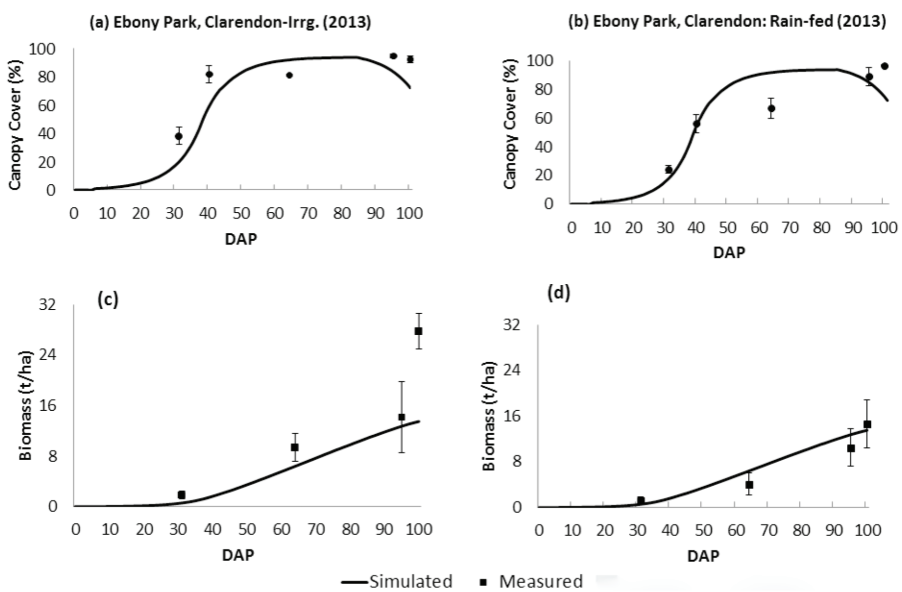

Fig. 9. Simulated (line) vs. measured canopy cover (filled circles) and biomass (filled squares) of sweet potato at days after planting (DAP) for (a,c) irrigated and (b,d) rainfed treatments at Ebony Park, Clarendon, Jamaica, in 2013. Error bars represent one standard deviation above and below the mean.

notwithstanding the dual coloration of leaves. We suggest that ACE has adequate skill to distinguish between green and senescent vegetation, which might account for the high agreement between measured and simulated values during canopy decline. The ACE software fulfills the requirement of high-quality measured data for accurate parameterization of AquaCrop noted in other studies (Hsiao et al., 2009; Steduto et al., 2012).

The accumulation of biomass was well simulated for both treatments, except at final harvest, where the model gave an underestimation of 20 to 24% (Table 6). The model was slightly more efficient in simulating biomass for irrigated sweet potato (*E* of 0.79 vs. 0.75 for rainfed). The underestimation in the final biomass was possibly due to the difference (of 7 d) between the actual harvest date and that simulated by the model. It should also be noted that the model assumes that there is no further accumulation of biomass once physiological maturity is reached. As such, if harvest does not take place on the expected date (and sometimes it is not practical to do so), there will be differences between the actual and simulated biomass. The identical simulated value for biomass and yields for rainfed and irrigated treatments was due to the small amount of irrigated water applied to the irrigated plants (equivalent to only 6.8% more total water than for rainfed plants).

The progression of yield is shown in Fig. 8. Together with the data presented in Tables 5 and 6, it is noted that the model was much more proficient at simulating rainfed yields (*E* of 0.90 vs. 0.22 for irrigated). In 2013, water was applied according to the evaporative demand of the crop as measured by the moisture probes rather than at predetermined intervals by automated irrigation as in 2011/2012. The lower yields in the 2013 season compared with those of 2011/2012 are attributed to the selective final harvesting (of marketable tubers) in 2012 and the reuse of the same plots in the 2013 season. Best practice suggests that, among other factors, crop rotation should be done to prevent the bioaccumulation of pests (arthropods and pathogens) that have a deleterious effect on yields (Caribbean Agricultural Research and Development Institute, 2010). This was, however, not possible given the space constraints at Devon. This is also in keeping with the practice adopted by farmers due to limitations in land space. Final yields for 2013 were slightly overestimated by the model, with deviations of 16.5 and 8.7% for the irrigated and rainfed treatments, respectively. However, this was a marked improvement over the simulations of the previous crop season. The non-selective, representative harvesting of tubers and accurate weather data are considered to be major contributing factors to this enhancement.

From the results for both crop seasons, it is noted that there is often correspondence between model simulations of canopy cover with biomass but not always with yield. When canopy cover is well simulated, so also is biomass. This is expected, given that the model is driven by canopy cover (Raes et al., 2009; Hsiao et al., 2009; Steduto et al., 2012). The lack of correspondence for the simulation of yield with those of CC and to a lesser extent biomass suggests the need for further investigation, particularly because sweet potato is known to have cultivar-dependent incongruence between leaf area (canopy cover) and tuber yield (Bourke, 1984; Fielding and Ryder, 1995). The inherent

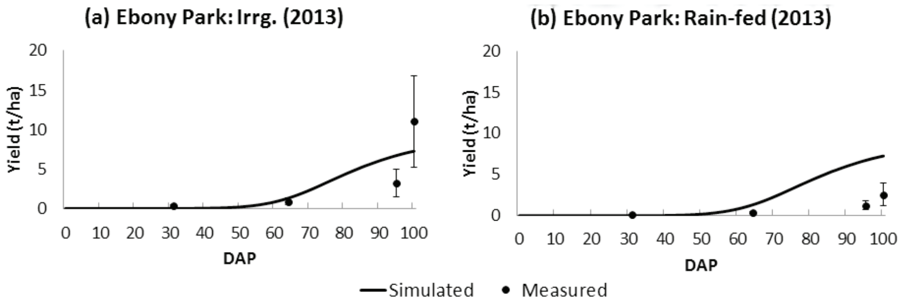

Fig. 10. Simulated (line) vs. measured (filled circles) yield of sweet potato at days after planting (DAP) for (a) irrigated and (b) rainfed treatments at Ebony Park, Clarendon, Jamaica, in 2013. Error bars represent one standard deviation above and below the mean.

differential growth rate of the canopy and tubers throughout the crop season (Caribbean Agricultural Research and Development Institute, 2010) and lower correspondence between final canopy cover and final yield present unique challenges for deriving mean model parameters for sweet potato.

There was fair agreement (RMSE = 0.79, E = 0.61) in the values of ET_o computed by the AWS and that computed by the FAO ET_o calculator (plot not shown). Notwithstanding, there were occasional deviations in some of the daily values measured by the AWS, presumably due to the differences in computation method. The seasonal totals were close: 534 mm (AWS) vs. 560 mm (FAO calculator), a difference of only 4.6%. The general correspondence is important given that many of the production areas in Jamaica do not have automatic weather stations. As such, ET_o might have to be computed by the FAO ET_o calculator, which can give reasonable estimates even with limited weather parameters. The simulated WUE values (Table 7) for yield of 1.38 (rainfed) and 1.39 (irrigated) kg m^{-3} are close to the upper range for C_3 crops like sweet potato (Sadras et al., 2007; Erickson et al., 2012). This emphasizes the important role for sweet potato cultivation in local and regional food security in light of projections for reduced water availability (Taylor et al., 2013).

Ebony Park, Clarendon (2013)

At Ebony Park, the AquaCrop simulation for canopy cover did not agree well with measured values for the irrigated crop (RMSE = 17.25, E = 0.29). However, there was a better fit for the rainfed plants (RMSE = 16.06, E = 0.67). Actual canopy development followed a slightly different pattern from that simulated by the model (Fig. 9).

The model underpredicted growth in both treatments up to 41 DAP, more so for the irrigated treatment, and then overpredicted the canopy cover for at least 30 d. However, there was better agreement as canopy closure was approached. The divergence of measured vs. simulated values in the decline phase was in part due to a heavy rainfall episode that occurred on 120 DAP. The added moisture served to stimulate further growth in the canopy, so that even at harvest a considerable portion of the canopy was still green, i.e., there was limited senescence.

There was better agreement also between simulated and measured biomass for the rainfed (E = 0.89) treatment than for the irrigated (E = 0.39) treatment. The simulated and measured rainfed biomass values were nearly identical except at the final harvest (Fig. 9c), which the model underpredicted by only 7.8%. For the irrigated plants, AquaCrop only slightly underestimated the biomass up to 96 DAP but gave a significant underprediction of 51.4% for the final measurement. The variance between the measured and simulated values at the end of the crop season was affected by the earlier maturity date of the model, which differed by 34 d from the actual harvest date. Linear interpolation between 32 and 135 DAP (R^2 = 0.98) suggested that the actual deviation could be lower (–23.8%), with improved values of RMSE (2.75) and E (0.79). The robustness of the model in reasonably estimating the biomass up until just before final harvest is notable, particularly in light of the poorly simulated canopy cover.

Overall, the model was efficient at simulating yields for the irrigated (E = 0.64) but not rainfed (E = –13.48) treatment (Fig. 10; Table 5). There was good agreement with measured yield up to 65 DAP for both rainfed and irrigated sweet potato. As the crop developed, differences between modeled and observed values increased, resulting in an underestimation of the final yield for irrigated plants of 34% and a large overestimation of 182% for rainfed plants (Fig. 8–10; Table 6). The underprediction for the irrigated treatment was influenced by the earlier maturity date in the model relative to the actual harvest date. The large disparity in the final simulated yield for rainfed sweet potato reflects the failure of these plants to form tubers. It was noted at harvest that very few tubers had formed in any cultivar under rainfed conditions at Ebony Park. Compared with the irrigated treatment, rainfed plants received only about half the total amount of water. Compared with the crop at Devon in the same season, the adverse effects of 27% less rainfall at Ebony Park was compounded by the higher evaporative demand (20% higher ET_o). Without taking into account evapotranspiration, the recommended minimum rainfall is 750 mm for sweet potato production (Caribbean Agricultural Research and Development Institute, 2010), about 60% more than that experienced by the rainfed crop at Ebony Park.

Harvest index in AquaCrop for grain crops is assumed to linearly increase from anthesis onward, after a lag phase. This type of yield development does not occur in root crops like sweet potato, which has differential growth rates throughout the season (Caribbean Agricultural Research and Development Institute, 2010), partly accounting for the disagreement between measured and simulated yields. Hsiao and Heng (2011) also noted that the model tended to underestimate biomass or yield under the lowest water supply (24% irrigation). Due to poor development of tubers in the rainfed treatment, it was difficult to accurately assess the skill of the model to simulate rainfed production at this location. The WUE at this location was higher (than at Devon) for both yield and biomass (Table 7), which further confirmed the crop's ability to successfully adapt its productivity to different environmental conditions.

CONCLUSIONS

Overall, it appears that parameterizing root and tuber crops in AquaCrop is more challenging than for other types of crops. Hsiao and Heng (2011) reported that potato (of all the crops already parameterized in AquaCrop) has the least reliable parameterization. Although significant changes were made to the *Irish* potato parameters in arriving at the current ones used for sweet potato, additional work is needed to refine the parameterization and to test other water-limited treatments, including deficit irrigation. Further data are needed from additional locations and crop seasons than the two used in this study to rigorously test the parameters derived. This testing should take into account the interactions that can take place between cultivars and their environments, location, and date of sowing (Fielding and Ryder, 1995). Additionally, more frequent sampling of biomass than could be done in this study would provide more insights into the physiological influences on the development of tubers in sweet potato and improve performance of the model during the crop life. The dynamics of belowground crops like sweet potato need to be further explored, especially the impacts of water stress on the harvest index. Other studies (Hsiao et al., 2009; Heng et al., 2009) have suggested that AquaCrop does not simulate well under high-water-stress conditions.

The good agreement between simulated and measured canopy cover (especially for the 2013 season at Devon) suggests that the ACE software can be used in the estimation of canopy cover from inexpensive digital photographs. The ACE software also appears to overcome some of the limitations faced by other techniques like the Green Crop Tracker (Liu and Pattey, 2010) that automate CC estimation, particularly as canopy closure and senescence are approached. With access to more reliable values of CC, existing relationships between CC and leaf area index can be validated or refined. Testing of the software on other crops should be undertaken.

The results presented in this study suggest that the AquaCrop model gives fairly accurate prediction of sweet potato yield and biomass under both rainfed and irrigated conditions. Canopy cover was reasonably well simulated by the model, but some divergence was noted for biomass and yield. The overall simulation of biomass was good, with deviations of <28% for four out of six simulations, and season-long performance of the model was commendable, with E values of 0.29 to 0.97 for the four crops in 2013. The simulation of yield presented more difficult challenges, especially given the differential rate of tuber development in sweet potato throughout the crop season.

The incorporation of sweet potato into AquaCrop adds a second belowground crop and the first root crop to its portfolio of crops. While further work is needed to refine the parameterization and to test the parameters across a wider combination of cultivars, climates, and soils, an important first step has been made in encouraging the use of AquaCrop as a tool for the agricultural sector in Jamaica and the wider Caribbean.

ACKNOWLEDGMENTS

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