Agricultural and Forest Meteorology 281 (2020) 107850

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Calibration and evaluation of aquacrop for groundnut (*Arachis hypogaea*) under water deficit conditions

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ARTICLE INFO

Keywords:
Arid and semi-arid environments
Crop modelling
Evapotranspiration
Water regimes
Yield

ABSTRACT

Groundnut (*Arachis hypogaea* L.) is an important grain legume in the arid and semi-arid tropics. AquaCrop model (V5.0) was calibrated and tested for its ability to simulate canopy cover (CC), biomass, yield and evapotranspiration (ET) of groundnut under water deficit conditions. Controlled environment and field trials were conducted during the 2015/16 and 2016/17 seasons across three environments in South Africa (Ukulinga, Fountainhill and Umbumbulu). The model was calibrated using data from a controlled environment and field trials from Ukulinga under optimum irrigation, deficit irrigation and rainfed conditions for 2015/16 summer season. The model was tested using data collected from Fountainhill and Umbumbulu during 2016/17. Model calibration showed that AquaCrop simulated CC and cumulative biomass well. The model overestimated ET by 21 – 38%. The model performed well in simulating CC and cumulative biomass during testing at Fountainhill and Umbumbulu. Overall the model showed potential for simulating yield and ET of groundnut under water deficit conditions. There is a need to further test the model under different soils and climates.

1. Introduction

Groundnut (*Arachis hypogaea* L.) is an important grain legume in the arid and semi-arid regions (Chibarabada et al., 2017). It is popular for its multiple uses where it can be consumed as a snack or processed to peanut butter or cooking oil. Groundnut has also been associated with high nitrogen fixation making it a strategic crop for sustainable intensification. Currently, groundnut has shown suitability to arid and semi-arid environments but has also shown instability across environments and seasons (Sahay and Sarma, 2005; Mekontchou et al., 2006; Nawaz et al., 2009). In these regions, water remains one of the limiting factors to crop production. There are gaps on how groundnut adapts to different environments and to varying water availability. For successful production of groundnut in arid and semi-arid regions, there is a need for information on its adaptability to these regions. This requires investments in time and resources on research, which are often limited in these regions. Crop growth models have been developed partly to answer research questions, thus, limiting time and resources spent on carrying out field experiments under various environments and management (Dourago-Neto et al., 1998; Rauff and Bello, 2015).

Crop growth models mimic growth and development of crops under different conditions using empirical and mathematical relationships (Dourago-Neto et al., 1998; Rauff and Bello, 2015). They are useful decision support tools (Boote et al., 1996), making them valuable tools in agriculture. Groundnut has been modelled successfully in Decision Support System for Agrotechnology Transfer (DSSAT) (Jones et al., 2003) and Agricultural Production Systems sIMulator (APSIM) (Robertson et al., 2002) models. While these models were successful in simulating yield under different management conditions (Bhatia et al., 2008; Yadav et al., 2012), their wider use has been limited by their complexity. They require a relatively large number of input parameters, of which some are challenging to obtain under field conditions, especially in cases where resources are constrained (Corbeels et al., 2016; Jones et al., 2017). This confines their application to research applications where resources, instrumentation and expertise are available. Considering complexity, the FAO developed a simple yet capable of maintaining accuracy and robustness model – AquaCrop (Raes et al., 2009; Steduto et al., 2009). AquaCrop requires relatively fewer number of input parameters that are relatively intuitive. It is an engineering type model that is not only targeted for scientists but end users such as students, farmers and policy makers (Steduto et al., 2009). This makes it a useful model for answering research questions where resources are constrained.

AquaCrop is a yield response to water model and can be used to simulate yield and water productivity under different agro ecologies and management practices (Raes et al., 2009; Steduto et al., 2009).

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https://doi.org/10.1016/j.agrformet.2019.107850
Received 2 March 2018; Received in revised form 11 November 2019; Accepted 17 November 2019

AquaCrop has been successfully parameterised for several crops including, but not limited to, wheat (*Triticum aestivum*) (Andarzian et al., 2011), maize (*Zea mays*) (Heng et al., 2009) sorghum (*sorghum bicolor*) (Araya et al., 2016) and cotton (*Gossypium spp*.) (Farahani et al., 2009). Thus far, a few grain legume crops such as soybean (*Glycine max*) (Adeboye et al., 2017), bambara groundnut (*Vigna subterranea*) (Karunaratne et al., 2011; Mabhaudhi et al., 2014) and pea (*Pisum sativum*) (Paredes and Torres, 2017) have been calibrated and tested for AquaCrop. For these crops, AquaCrop was able to predict yield under different production scenarios (Karunaratne et al., 2011; Mabhaudhi et al., 2014, Paredes and Torres, 2017; Adeboye et al., 2017). AquaCrop was successfully applied to assess the impact of sowing dates and irrigation strategies on yield and water use of pea (Paredes and Torres, 2017). AquaCrop has the potential to be useful decision support tool for production of grain legumes in arid and semi-arid regions. This is currently limited as only a few grain legumes (soybean, bambara groundnut and pea) have been calibrated and validated for AquaCrop.

There is need to calibrate and test AquaCrop for more grain legume crops. Groundnut is among the major grain legumes produced by subsistence and commercial farmers in the arid and semi-arid regions (Chibarabada et al., 2017). Currently, AquaCrop has not been calibrated and validated for groundnut. Availability of a well–calibrated model, is an initial step to increased application of AquaCrop to answer research questions on adaptability of groundnut to varying water availability and environmental conditions. The aim of the study was to calibrate and test the performance of AquaCrop model for groundnut under varying water regimes and environments under water deficit conditions. The specific objectives were to (i) calibrate AquaCrop for groundnut (ii) evaluate its ability to simulate CC, biomass, yield and evapotranspiration (ET) of groundnut for varying soils and climates.

2. Material and methods

2.1. AquaCrop model

The FAO's AquaCrop model is an engineering type, water–driven and canopy level model (Raes et al., 2009; Steduto et al., 2009) that builds on previous work related to yield response to water (Doorenbos and Kassam, 1979). It simulates yield response to water availability. Yield is simulated using four phases which are; crop development, crop transpiration, biomass production and yield formation (Steduto et al., 2009; Vanuytrecht et al., 2014). AquaCrop is a canopy level model because it simulates crop development through the canopy's expansion, aging, conductance and senescence. When simulating crop development, AquaCrop describes the green canopy, which is above ground as well as development of root zone (below ground). To describe stresses on canopy expansion, AquaCrop uses stress coefficients (Ks) where; Ks is 1 when water stress is non-existent (above upper threshold) and Ks is 0 when water stress completely stops canopy expansion (below lower threshold) (Steduto et al., 2009; Vanuytrecht et al., 2014). In AquaCrop, CC is proportional to transpiration.

The same pathway for transpiration is used for CO_2 intake by the plant, which is then converted to carbohydrates through photosynthesis - hence transpiration is proportional to biomass production (Steduto et al., 2009; Vanuytrecht et al., 2014). The relationship between biomass produced and water consumed by a given species is linear for a given climatic condition, hence AquaCrop uses a normalised crop water productivity function [above ground dry matter produced per unit land area or per unit of water transpired (mm)] in the simulation of biomass. This relationship is the core of AquaCrop and is where the description 'water–driven' emanates from. The equation for the simulation of biomass is therefore (Steduto et al., 2009; Vanuytrecht et al., 2014);

$$B = WP \times \sum T_r, \tag{1}$$

where:

B = Above ground biomass (kg m^{-2}),
WP = Normalised water productivity (kg m^{-2}), and
T_r = Crop transpiration (mm).

To calculate the yield, AquaCrop uses the harvest index (HI), taking into consideration the adjustments in HI due to stress at the start of the yield formation, during flowering and during yield formation (Steduto et al., 2009; Vanuytrecht et al., 2014). Therefore;

$$Y = f_{HI} \times HIo \times B, \tag{2}$$

where:

Y = yield (kg m^2),
f_{HI} = multiplier which considers the stresses that adjust the HI from its reference value,
HIo = Reference HI (%), and
B = Total above ground biomass (kg m^2).

To run simulations, AquaCrop requires inputs of climate data, crop characteristics, soil characteristics and description of management practices.

2.2. Study areas

Field trials were conducted at three sites (Fountainhill Estate, Ukulinga Research Farm and Umbumbulu Rural District), in KwaZulu-Natal, South Africa. Ukulinga Research Farm [29°37′S; 30°16′E; 750 m above sea level (m.a.s.l.)] was the on-station research trial, while Umbumbulu (29°59′S; 30°42′E; 593 m.a.s.l.) and Fountainhill Estate (29°25′S; 30°34′E; 1020 m.a.s.l.) were on-farm research trials. Average annual rainfall at Ukulinga is 694 mm which is received mainly during the summer months (mid-October to mid-February). During the summer months, average maximum temperatures are between 26 °C and 28 °C while minimum temperatures can be as low as 10 °C. Fountainhill Estate is classified as a subtropical highland climate with average annual rainfall of 905 mm while Umbumbulu is located in a moist coastal hinterland region with the climate being sub-tropical popular for rainfall throughout the year. Umbumbulu is humid with annual rainfall between 900 to 1 200 mm. Further details on observed climate characteristics can be obtained in Chibarabada et al. (2018).

A pot trial was conducted in a growth tunnel at the University of KwaZulu-Natal's Controlled Environment Facility, Pietermaritzburg, South Africa (29°37′S; 30°23′E; 750 m.a.s.l.). The environment in the growth tunnel is semi-controlled with temperatures ranging from ~18/33 °C (day/night) and relative humidity (60 – 80%), which is a warm subtropical climate (Modi, 2007).

2.3. Experimental design

2.3.1. Field trials

Experiments were conducted during the 2015/16 and 2016/17 summer seasons. At Ukulinga Research Farm, the experimental design was a split-plot design. The water treatments [optimum irrigation (OI), deficit irrigation (DI) and rainfed (RF)] were the main plots. Irrigation was applied through a sprinkler system with a distribution uniformity of ≈ 85%. The sprinkler nozzles had a throw distance (radius) of 8 m. The distance between the water treatments was 12 m to avoid sprinkler overspray. The sprinkler irrigation system had an approximate application rate of 7 – 8 mm•hr^{-1}. This was regularly measured and used to estimate irrigation run time. The actual amount of irrigation after each irrigation event was measured using rain gauges randomly placed in the experimental plots. Irrigation scheduling was based on management allowable depletion (MAD). Management allowable depletion was the maximum amount of total available water (TAW) allowed to be depleted from the root zone before irrigation occurs. In the OI treatment, MAD was 20% TAW. This was based on the Alberta Irrigation Management Manual (2016), recommended management allowable depletion (MAD) for grain legumes. The approach to DI was to apply irrigation (MAD: 20% TAW) at the growth stages that were most sensitive to water stress (Geerts and Raes, 2009). The most water stress sensitive growth stages of the grain legume crop species were the flowering and pod-filling stages (Ahmed and Suliman, 2010; Vurayai et al., 2011). Soil water content (SWC) were measured using a PR2/6 profile probe connected to an HH2 handheld moisture meter (Delta–T, UK). The sensors of the PR2/6 profile probe are positioned to measure volumetric water content at 6 depths (0.10, 0.20, 0.30, 0.40, 0.60 and 1.00 m along the probe). Further details on irrigation management and SWC can be found in Chibarabada et al. (2019). All the water treatments were fully irrigated up to the point where 90% of the sown seed had emerged to ensure establishment of all trials and enough plants for destructive sampling and measurements of CC. In the rainfed trial, irrigation was withdrawn after crop establishment and the trial relied entirely on rainfall thereafter.

At Umbumbulu and Fountainhill, the trials were entirely rainfed. Plant population was 88 889 plants ha^{-1}. Individual plot size at all the sites was 17.85 m^2. Trials from Ukulinga during the 2015/16 were used to calibrate the model while trials at all the sites during 2016/17 were used for model evaluation (Table 1). Planting dates for all the trials are given in Table 1. Details of field experimental designs and layouts are provided in supplementary Fig. 1 and Chibarabada et al. (2018). Details of how the trials were managed are described in Chibarabada et al. (2018).

2.3.2. Controlled environment

A pot trial was conducted during 2015/16 summer season for the purposes of determining some parameters needed to calibrate the model (Table 1). The pot trial was conducted in a growth tunnel at the University of KwaZulu-Natal's Controlled Environment Facility, Pietermaritzburg, South Africa (29°37′12″S; 30°23′49″E). The environment in the growth tunnel is semi-controlled with temperatures ranging from ~18/33 °C (day/night) and relative humidity (60 – 80%), which is a warm subtropical climate (Modi, 2007). The pots were 20 litre round pots with a surface area of 706 cm^2. Three seeds were planted per pot. The experimental design included three water treatments [80, 60 and 30% of field capacity (FC)] with three replications (3 × 3 = 9 pots). The three water treatments [80, 60 and 30% (FC)] represented no water stress, mild water stress and severe water stress, respectively. This was based on previous studies that used the same treatments to impose water stress in pot trials. In addition to the nine pots, nine other pots, (three replications × three water treatments) were added to monitor soil evaporation from the pots. Soil evaporation was deducted from the total evapotranspiration of the pots to determine crop transpiration. Twenty-seven pots (three water treatments × nine intervals) were also added to allow for destructive sampling on all three plants to determine plant mass fortnightly. This allowed for correction of plant mass when determining irrigation through gravimetric measurements.

Water was applied based on gravimetric water content (1 g = 1 mℓ) every two days by weighing trays to determine the amount of water used by the plants and then refilling the trays to their corresponding field capacities. Water added at each irrigation event was recorded in order to determine water use at the end of the experiment (Bittelli, 2011). Soil water content was measured before an irrigation event, weekly from the time of planting up to harvest using a ML-2x Theta probe connected to an HH2 handheld moisture meter (Delta-T, UK).

2.3.2.1. *Determination of water use (ET)*

The amount of water used (ET) to establish seedlings across the different watering regimes was converted from mℓ to m^3 using the conversion;

$$1000\,\text{ml}=0.001\,\text{m}^3 \tag{3}$$

This was then converted to depth (mm) using conversion factors described by Allen et al. (1998) where;

$$1\,\text{mm day}^{-1}=10\,\text{m}^3\text{ha}^{-1}\text{day}^{-1} \tag{4}$$

Determination of ET was through a soil water balance (Allen et al., 1998)

$$ET=I + R - D - Ro \pm \Delta SWC \tag{5}$$

where, I = Irrigation (mm); R is rainfall (mm); ΔSWC is changes in soil water content (mm); D is drainage (mm); and Ro is runoff (mm). For pot trials, the equation was modified to exclude E, R, D and Runoff.

To determine the evaporation component (movement of water from the soil surface to the air), a modified soil water balance was conducted for the empty pots where;

$$E_s = I \pm \Delta SWC \tag{6}$$

where E_s = evaporation (mm); I = irrigation (mm) and ΔSWC is changes in soil water content (mm).

Thereafter, evaporation was deducted from measured ET, to obtain transpiration (T_r). The soil water balance was therefore modified to;

$$T_r=I - - E_s \pm \Delta SWC \tag{7}$$

where: T_r = transpiration (mm) = water use =, I = irrigation (mm), E_s = Evaporation, and ΔSWC = changes in soil water content (mm).

2.3.2.2. *Determination of water productivity*

Water Productivity was calculated as;

$$WP= B\,/T_r \tag{8}$$

where: WP is water productivity, B is the biomass (g/m^2) and T_r is the actual transpiration (mm).

Table 1
Summary of experimental design, planting dates and data sets used for calibration and testing of the model.

Season	Site	Water treatment	Planting date	Calibration	Testing
2015/16	Ukulinga	[a]OI	17 November 2015	✓	
		[b]DI*	17 November 2015	✓	
		Rainfed*	17 November 2015	✓	
2015/16	Pot trial	80% [c]FC	20 December 2015	✓	
		60% [c]FC*	20 December 2015	✓	
		30% [c]FC*	20 December 2015	✓	
2016/17	Fountainhill	Rainfed*	14 December 2016		✓
	Umbumbulu	Rainfed*	30 November 2016		✓

[a] OI = Optimum irrigation;.
[b] DI = Deficit irrigation;.
[c] FC = Field capacity;.
* Trials established for water deficit conditions.

2.4. Model inputs

2.4.1. Climate data

For Ukulinga, daily climate data was obtained from an automatic weather station (AWS) that is located at the Research Farm. The AWS is part of the Agricultural Research Council – Institute for Soil, Climate and Water network of weather stations. For Fountainhill and Umbumbulu, daily climate data was obtained from the South African Sugar Association (SASA) weather web portal (http://portal.sasa.org.za/weatherweb). For all sites, a default file of the mean annual CO_2 concentration measured at the Mauna Loa Observatory in Hawaii that is provided by AquaCrop was used.

2.4.2. Crop parameters

The initial values for the conservative parameters were selected from a relatively similar grain legume (bambara groundnut) that has been calibrated and validated for AquaCrop (Mabhaudhi et al., 2014). Additionally, bambara groundnut has similar growth habit and occupies similar ecological niche as groundnut. These values were then adjusted during calibration using data collected from the OI treatment at Ukulinga during the 2015/16 season and the pot trials. For parameters not measured during the experiments such as maximum effective rooting depth and water extraction pattern, values from the template crop file and AquaCrop defaults were used, respectively.

The crop file (.CRO) was created using data collected from Ukulinga during 2015/16 and pot trials. Crop parameters from the OI treatment were used to calibrate the model as they represent the crops' potential under no stress (Table 2). Data from the DI and rainfed irrigation treatments were used to determine crop response to water stress. In cases where data from field trials was inadequate to determine crop responses to water stress, data from pot trials were used. Transpiration could not be determined under field conditions; hence WP was determined from the pot trial (Table 2). Parameters not considered were biomass production affected by soil salinity and fertility stress. Crop phenology was observed in calendar days and thereafter converted to thermal time (GDD) in AquaCrop.

2.4.3. Soil parameters

Soil files (.SOL) for each site (Ukulinga, Umbumbulu and Fountainhill) were created using site specific soil data (Table 3). There was no groundwater file (.GWT) created.

2.4.4. Irrigation and field management

Irrigation was applied through a sprinkler system with a distribution uniformity of 85% and 100% soil surface wetting. Three separate irrigation files (.IRR) for the fully irrigated, deficit and rainfed trial were created. For the field management file (.MAN), soil fertility was non-limiting, there was no mulching and soil bunds and there were no practices to prevent surface runoff.

2.4.5. Observations

Above ground biomass was determined following the protocol by United States Department of Agriculture – Natural Resource Conservation Services (USDA-NRCS). To determine accumulation of above ground biomass, destructive sampling was randomly conducted on six plants every fortnight and plants were oven dried at 80 °C until there were no changes in mass observed. Leaf area index (LAI), which is the one–sided green leaf area per unit ground surface area occupied by the plant, was routinely measured using the LAI-2200C Plant Canopy Analyzer (LICOR, USA). Leaf area index values were then converted to CC using the formula by Mabhaudhi et al. (2014). Observed CC data and above ground biomass were used to create field observation files (.OBS) for each water treatment and experimental site.

Crop ET was calculated under field conditions as the residual of a modified soil water balance (Allen et al., 1998);

$$ET = ER + I \pm \Delta SWC, \tag{9}$$

where;

ET = evapotranspiration,

ER = Effective rainfall (mm) is monthly effective rainfall that is stored in the root zone after subtracting the amount of rainfall lost to runoff and deep percolation [United States Department of Agriculture – Soil Conservation Services (USDA-SCS, 1967)],

I = irrigation (mm), and

ΔSWC = changes in soil water content (mm) measured using a PR2/6 soil moisture probe (Delta T, UK).

At harvest, six plants were harvested randomly from each plot and air dried until constant mass was reached for determination of total biomass and yield.

2.5. Simulation procedure

AquaCrop version 5.0 (FAO, 2015) was used. The model was run in thermal time (growing degree days). Simulation periods were linked to the growing cycle (day one after sowing to maturity; planting dates are given in Table 1). At Ukulinga, during 2015/16 initial soil water content was at field capacity within 24 h following a rainfall event and irrigation was applied soon after planting. During 2016/17 initial soil water content was 50% of TAW at Ukulinga, 42% of TAW at Umbumbulu and 55% of TAW at Fountainhill.

2.6. Model evaluation statistics

To evaluate model performance, statistical indicators used were correlation of determination (R^2), root mean square error (RMSE), normalised root mean square error ($NRMSE_{cv}$), Nash-Sutcliffe model efficiency coefficient (EF) and Willmott's index of agreement (D-index) (FAO, 2015). For R^2, values > 0.90 were considered as very good, while values between 0.70 and 0.90 were considered good. Values between 0.50 and 0.70 were considered moderately good, while values less than 0.50 were considered poor. Root mean square error ranges from 0 to positive infinity, and expressed in the units of the studied variable. A RMSE approaching 0 indicates good model performance. Normalised RMSE on the other hand gives an indication of the relative difference between simulated and observed values. It is expressed as a% with < 10% being very good and > 25% being poor. The Nash-Sutcliffe EF model determines the relative magnitude of the residual variance compared to the variance of the observations (FAO, 2015). An EF of 1 indicates a perfect match between the model and the observations. An EF of 0 means that the model predictions are as accurate as the average of the observed data. A negative EF implies that the mean of the observations gives a better prediction than the model. In this study, EF less than 0.4 was considered poor (FAO, 2015). The D-index ranges between 0 and 1, with 0 indicating no agreement and 1 indicating a perfect agreement between simulated and observed data. D-index was acceptable when it was above 0.64 (FAO, 2015). Overall model performance was considered good when at least any 3 of the 5 model evaluation indicators were good to very good.

The final biomass, ET and yield differences were computed as percentage relative differences obtained using the formula;

$$[(\text{Simulated} - \text{Observed})/\text{Observed}] \times 100. \tag{10}$$

Relative differences of ± 10% were considered accurate (Farahani et al., 2009; Steduto et al., 2009) while differences of ± 20% were acceptable.

3. Results and discussion

3.1. Calibration

Model evaluation indicators showed that there was a good match

Table 2
Selected crop parameters and values used for the calibration of groundnut in AquaCrop.

Parameter	Determination	Unit	Value
Planting method		–	Direct sowing
Plant population	Plant population based on intra-row spacing of 0.75 m and inter-row spacing of 0.15 m	Plants hectare^{-1}	88 889
Seedling size	Obtained under controlled environment where the mean initial seedling leaf area per plant was measured at 90% emergence on five randomly selected plants using the LI-3100C Leaf Area Meter (LICOR, USA).	cm^2	3
Initial canopy cover (CCo)	Model derived	%	0.27
Time to emergence	Time to emergence was determined as the number of days from planting to when 90% of the plants had > 20 mm hypocotyl protrusion.	Growing Degree days	127
CCx	Consistent maximum canopy observed.	%	68
Time to maximum canopy cover (CCx)	Measured with the LAI-2200C Plant Canopy Analyzer (LICOR, USA). LAI values were converted to CC using the formula by Mabhaudhi et al. (2014) where; CC = 1 - DIFN Graphs of weekly CC were plotted and the time to which the canopy reached its constant peak was determined as the time to maximum canopy cover.	Growing Degree days	1 040
Time to canopy senescence	Time taken when at least 10% of leaves had senesced (chlorophyll degradation) without new leaves being formed to replace them.	Growing Degree days	1 592
Canopy decline	Time from maximum CC to when 50% of plants had reached senescence	days	23
Canopy growth coefficient (CGC)	Model derived	%/day	12.2
Canopy decline coefficient (CDC)	Model derived	%/GDD	0.683
Length building up HI	Time from flowering (50% of the plants had at least one open flower) to maturity (50% of plants reached physiological maturity).	Growing Degree days	943
Duration of flowering	This was defined as the period that 50% of the experimental plants had at least one flower that was open.	Growing Degree days	798
Time to flowering	This was the time taken for 50% of the experimental plants to have at least one fully opened flower.	Growing Degree days	595
Determinacy linked with flowering	Determinancy was defined as cessation of vegetative growth when the terminal flower of the main stem started to develop.	–	No
Minimum effective rooting depth	Obtained from GRDC (2017).	M	0.3
Upper temperature	Upper temperatures were obtained from Prasad et al. (2002)	˚C	28
Maximum air temperature affecting pollination	Obtained from Prasad et al. (2002)	˚C	34
Water productivity (WP)	This was obtained from the pot trials under 80% FC. Procedures are given in Section 2.3.2.	(g)/(m^2)	15
Reference HI (HI_o)	Determined from the OI trial as; HI = Yg/B where: Yg = economic yield based on grain yield (kg), and *B* = total biomass (kg)	%	24
Canopy expansion: (response to water stress)	Determined from values of weekly leaf area measured from the pot trial using the LI-3100C Leaf Area Meter (LICOR, USA).at different water regimes. Data on leaf area was analysed to determine the crop thresholds and sensitivity class.	–	Moderately tolerant
Stomatal closure (response to water stress)	Weekly stomatal conductance from three water regimes during the pot trial was measured using a Steady State Leaf Porometer Model SC-1 (Decagon Devices, USA) on the abaxial surface of a new fully expanded and fully exposed leaf. Data was analysed to determine sensitivity class.	–	Moderately sensitive
Early canopy senescence (response to water stress)	Determined from values of time to senescence measured during the pot trial at different water regimes. Time taken when at least 10% of leaves had senesced (chlorophyll degradation) without new leaves being formed to replace them. Data on time to senescence was analysed to determine the crop thresholds and sensitivity class.	–	Moderately tolerant
Aeration stress to waterlogging	Obtained from Liu et al. (2009)	–	Moderately tolerant
Overview of water stress effects on HI	The positive difference between the HI_o and HI under rainfed conditions was considered as the overall positive impact of water stress on HI.	%	6

(R^2 = 0.854 – 0.97; RMSE = 6.7 – 9.5%; $NRMSE_{cv}$ = 11.2 – 15.6%; EF = 0.62 – 0.88; D-index = 0.89 – 0.97) between observed and simulated values for CC under all the water treatments (Fig. 1). Despite being calibrated using data collected under optimum conditions, the model successfully simulated CC under water deficit conditions. However, the model underestimated CC between 60 and 120 days after planting (DAP) (period of maximum CC), and this was consistent across all the water treatments. The model's tendency to underestimate CC during maximum CC was also reported for cotton (Farahani et al., 2009), bambara groundnut (Karunaratne et al., 2011), potatoes (*Solanum tuberosum*) (Montoya et al., 2016) and soybean (Adeboye et al., 2017). This has been attributed to the model's inability to capture leaf appearance rate, especially for indeterminate cultivars. In groundnut, node production may continue up to maturity, given optimum

Table 3
Soil parameters used for the AquaCrop soil file.

Site	Horizon	Description	Thickness (m)	[a]Sat	[b]FC	[c]PWP	[d]Ksat (mm day^{-1})	[e]TAW (mm)
				——(% Vol) ——				
Ukulinga	1	Clay loam	0.40	48	40	21	25	78.4
Fountainhill	1	Sand	2.0	36	13	6	3000	140
Umbumbulu	1	Clay loam	0.40	46	35	17	125	72
	2	Clay	0.60	50	39	21	35	108

[a] Sat = Volumetric water content at saturation;.
[b] FC = Field capacity;.
[c] PWP = Permanent wilting point;.
[d] Ksat = Saturated hydraulic conductivity;.
[e] TAW = Total available water.

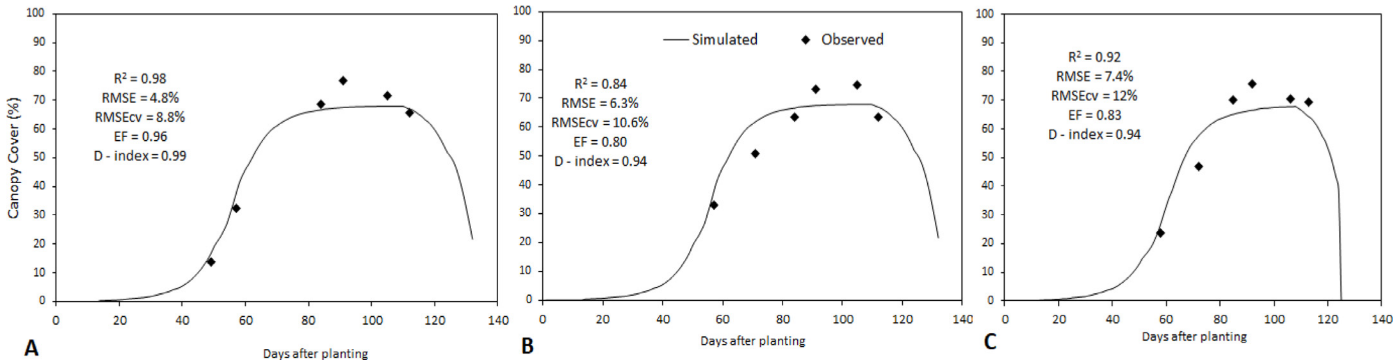

Fig. 1. Simulated and observed CC for groundnut under A) optimum irrigation B) deficit irrigation and C) rainfed conditions during the calibration season (2015/16) at Ukulinga.

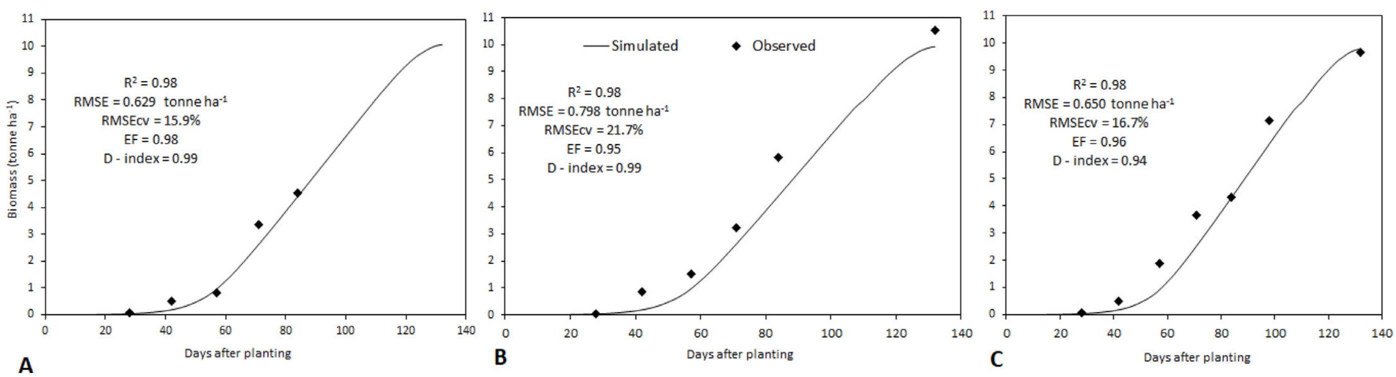

Fig. 2. Simulated and observed cumulative biomass for groundnut under A) optimum irrigation B) deficit irrigation and C) rainfed conditions during the calibration season (2015/16) at Ukulinga.

Table 4
Simulated and observed grain yield and evapotranspiration (ET) for groundnut during model calibration and testing at Ukulinga, Fountainhill and Umbumbulu.

		Final biomass			Final grain yield			Final ET		
		Simulated tonne ha^{-1}	Observed	Difference %	Simulated tonne ha^{-1}	Observed	Difference %	Simulated mm	Observed	Difference %
Calibration	OI	10.068	8.020	20.3	2.885	1.950	47.94	406	316	28.48
	DI	9.929	10.540	- 6	2.874	2.900	- 0.89	397	292	35.95
	RF	9.788	9.550	2	2.833	2.770	2.27	380	283	34.27
Testing	Fountainhill	8.439	6.855	18.77	2.088	2.387	−14.31	323	287	11.14
	Umbumbulu	6.491	6.669	−2.74	1.858	1.213	34.71	357	234	34.45

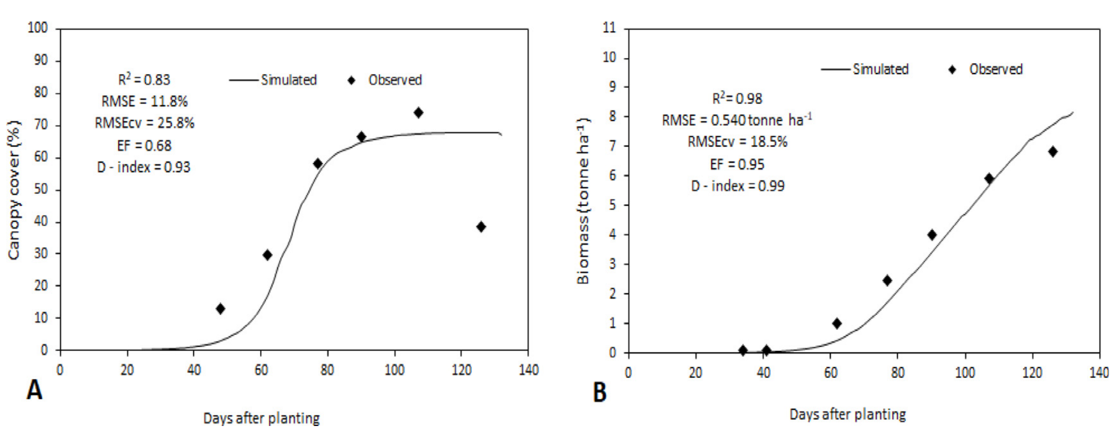

Fig. 3. Simulated and observed CC (A) and cumulative biomass (B) for groundnut at Fountainhill during model testing (2016/17 season).

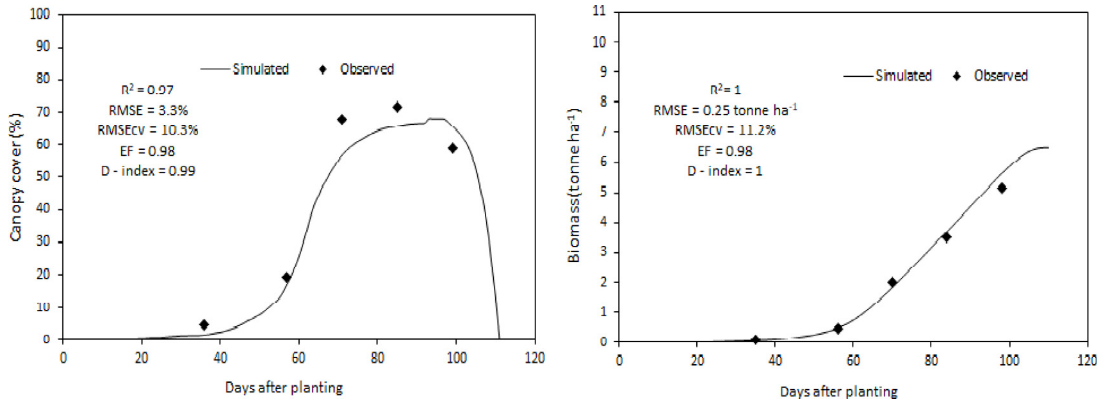

Fig. 4. Simulated and observed CC (A) and cumulative biomass (B) for groundnut at Umbumbulu during model testing (2016/17 season).

conditions (phyllochron and water availability) (Halilou et al., 2016). AquaCrop does not consider leaf appearance rate and phyllochron; this may explain the underestimation of simulated values. Groundnut could have increased leaf appearance rate in response to favourable environmental conditions during that period which was not captured by the model. Despite AquaCrop's approach of exponential growth and decay of canopy development followed by maximum CC, it was still able to simulate CC satisfactorily. This confirms AquaCrop's simplicity yet maintaining accuracy.

For biomass, model calibration showed a very good match under OI (R^2 = 0.98; RMSE = 0.629 tonne ha^{-1}; $NRMSE_{cv}$ = 15.9%; EF = 0.98; D-index = 0.99) and a good fit under DI (R^2 = 0.98; RMSE = 0.798 tonne ha^{-1}; $NRMSE_{cv}$ = 21.7%; EF = 0.95; D-index = 0.99) and RF treatments (R^2 = 0.98; RMSE = 0.650 tonne ha^{-1}; $NRMSE_{cv}$ = 16.7%; EF = 0.96; D-index = 0.94) (Fig. 2). The model simulated biomass under DI and RF relatively well, confirming its suitability for use under water deficit conditions. Although all the statistical indicators showed a good fit under DI and RF, the model tended to underestimate biomass. This could be a carry-over effect from underestimation of CC. Biomass is used to simulate yield by means of a HI. Under DI and RF, AquaCrop under- and overestimated grain yield by 0.8% and 2.2%, respectively, thus the model simulated yield accurately (Farahani et al., 2009) (Table 4). Since AquaCrop accurately simulated CC, biomass and yield under DI and RF, it can be inferred that it is a suitable model for simulating biomass and yield of groundnut under different water regimes.

The model overestimated final ET by 28% in the OI treatment, 35% in the DI treatment and 34% in the RF treatment (Table 4). One of the distinguishing features of AquaCrop is the separation of ET into evaporation (E_s) and transpiration (T_r) based on a simple CC model (Vanuytrecht et al., 2014). It would be assumed that since the model underestimated CC, which is proportional to T_r, (***cf.*** Section 2.1) then E_s would be the parameter overestimated. Based on RMSE values, there was more underestimation of CC under RF relative to DI and OI. To support the assumption, it was expected that results of simulated E_s relative to T_r under the different water regimes would show that there was more E_s relative to T_r under rainfed conditions. This was, however, not the case as proportion of E_s was the same under all the watering regimes. It is therefore not clear why the model overestimated ET.

3.2. Testing

The model was tested for its performance against independent data sets (Fountainhill and Umbumbulu) under water deficit conditions. For Fountainhill, overall model simulation of CC was good (R^2 = 0.83; RMSE = 11.8%; EF = 0.68; D-index = 0.93) although $NRMSE_{cv}$ showed moderately poor performance (25.8%) (Fig. 3); the model failed to capture canopy senesence and crop maturity. This could be as a result of the initial soil water conditions at Fountanhill. At planting, initial soil water content was 55% of TAW. Initial values of CC showed that the model underestimated CC (Fig. 3) during crop development as a result of delayed timing of crop establishment. As a result the model delayed time to senescence and time to maturity, leading to poor simulation of CC towards the end of the season. Steduto et al. (2009) reported on the sensitivity of the model to initial soil water conditions. This could be because the model only considers time to emergence under optimal conditions and does not consider the soil water upper and lower thresholds for emergence of different crops.

For biomass accumulation, model performance for Fountainhill was good to very good (R^2 = 0.98; RMSE = 0.540 tonne ha^{-1}; $NRMSE_{cv}$ = 18.5%; EF = 0.9; D-index = 0.99). The model underestimated biomass which was due carry over error from CC. Final biomass was overestimated by 18% despite underestimation of cumulative biomass (Table 4). The reason for this overestimation was not clear. Grain yield and ET were underestimated and overestimated by 14 and 11%, respectively, which was considered acceptable (Table 4). Despite the slightly poor $NRMSE_{cv}$ for CC (26.5%), the model perfomed well for Fountaihill.

For Umbumbulu, the model performed well in simulating both CC and cumulative biomass (R^2 = 0.97 and 1, respectively; RMSE = 3.3% and 0.25 tonne ha^{-1}, respectively; $NRMSE_{cv}$ = 10.3 and 11.2%, respectively, EF = 0.98 for both; D-index = 0.99 and 1) (Fig. 4). Consequently, only 2% underestimation of final biomass was observed which was accurate (Faharani et al., 2009). Despite the good simulation of CC and biomass, the model overestimated both final grain yield and ET (34%) (Table 4). The model simulated increase in HI of ≈ 5%. Umbumbulu was chracterised as extremely hot during that season. According to Prasad et al. (1999, 2000), the threshold day temperature for pollen production and viability for groundnut was 34 °C. The model was set to consider 34 °C as the threshold for pollination. Temperature data showed that during the reproductive stage there were 12 days above 34 °C. However, during the runs it could not be established if the model had captured pollination affected by heat stress and to what magnitude. Model output showed that HI had increased 5% and it was not clear which adjustments had been factored in. Without clear indication on the adjustments of HI, it could not be established why the model overestimated grain yield.

4. Conclusion

During calibration, the model simulated CC and cumulative biomass well under both OI and water deficit conditions. Consistent to all water treatments, the model tended to underestimate CC during maximum canopy cover. This was attributed to leaf appearance rate and phyllochron. The model overestimated ET which was attributed to overestimation of T_r and a need to improve crop transpiration coefficient (Kc_{Tr}) in AquaCrop. During model testing, at Umbumbulu and Fountainhill, the model simulated CC and biomass well. This indicates its suitability under deficit conditions. Overall, the model showed potential for simulating yield and ET under water deficit conditions. There is, however, need to improve model parameters before the model can be applied for different soils and climates.

Declaration of Competing Interest

The authors declare no conflict of interest.

Acknowledgements

The Water Research Commission of South Africais acknowledged for funding, directing and managing the research through WRC Project No. K5/2493//4 "Water use and nutritional water productivity of food crops for improved nutrition and health in poor rural households."

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.agrformet.2019.107850.

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