SOIL & CROP SCIENCES | RESEARCH ARTICLE

AquaCrop model calibration and validation for chickpea (Cicer arietinum) in Southern Africa.

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ABSTRACT: The study parameterised and validated performance of AquaCrop model, to simulate attainable yields for chickpea crop in response to the effects of planting date in the Northeastern Region of South Africa. Model calibration data were obtained from two field experiments of contrasting water regime, planted in 2014 winter season at University of Venda, South Africa, whilst data for model validation was obtained from 2015 planting season from the same station. The model performance was satisfactory, with a good combination between the simulated and observed canopy cover (CC), Soil water content (SWC), biomass (B) and grain yield (Y). All the statistical indicators (R², RMSE, and MAPE) used to compare field observed and model-predicted parameters, showed good performance. For example, the regression analysis of simulated and observed yield showed a good relationship with R² values of 0.949, 0.928 and 0.990 for early, normal and late planting dates, respectively, whilst RMSE was 0.135, 0.143 and 0.031 for early, normal and late planting dates. Similarly, SWC had strong regression relationship (R² = 0.982, 0.949, 0.954, respectively, and a RMSE of 0.226, 0.696 and 0.310, respectively, in early, normal and late planting date). The results indicate that the model could be used for evaluating the effects of different planting dates on chickpea yield.

Subjects: Agriculture & Environmental Sciences; Botany; Plant & Animal Ecology

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PUBLIC INTEREST STATEMENT

Chickpea Production is being introduced in South Africa. Thus, limited studies have been conducted to help farmers on appropriate agronomic practices needed to grow the crop profitably. Therefore, this study is part of a broad objective to develop sowing (planting date) criteria for chickpea in the region. The work is being conducted in two phases. The first phase involves modeling, and field trials to calibrate and validate the model’s performance. This first phase will also evaluate the optimal planting date guidelines that provide better biomass and grain yield in the region. The second phase of the study will determine the likely effect of planting date on chickpea biomass and yield under climate change scenario in North Eastern Region of South Africa. This research paper is from the first phase where a water-driven model (AquaCrop) was calibrated and validated to simulate chickpea aboveground biomass and grain yield under different planting dates in North Eastern Region of South Africa.
Keywords: AquaCrop model; Chickpea; Planting date

1. Introduction
Chickpea (*Cicer arietinum*) is a fairly drought tolerant legume crop that is widely cultivated in tropical and subtropical regions of the world (Devasirvatham & Tan, 2018; Statistics, 2019). Production of chickpea is growing in many countries because of its multiple uses as a source of food, livestock feed, fuel, and fertilizer (Gaur et al., 2019, 2010). The crop is currently being introduced in the dry and hot environments of northeastern region of South Africa to ameliorate problems of climate change and food insecurity. Despite chickpea’s ability to tolerate moisture stress, possible negative effects of climate change on future productivity of the crop has been documented (Kadiyala et al., 2016; Rani et al., 2020; Urgaya, 2016). Climate change in the form of increase in intensity and severity of drought, frost and heat waves may seriously alter the current planting dates in the region and consequently affect future yield of chickpea (Devasirvatham & Tan, 2018). Climate change is expected to cause a decrease in the length of the growing season in the Lowveld regions and the converse in the Highveld regions of Southern Africa (Tadross et al., 2009).

Amid challenges of climate change, the use of planting date has been reported as an important management strategy to improve yield under climate change conditions (Mhizha et al., 2014). Likewise, over the years, manipulation of planting date has been reported to improve biomass and grain yield of chickpea (Potioudis et al., 2019; Mubvuma et al., 2015). For example, in Southern Africa, Mubvuma et al. (2015) observed that planting date had a significant effect on chickpea growth parameters, yield and yield components. Similar reports have been given across the world and in different crops (Fiwa, 2015; Tsimba et al., 2013).

Whilst several authors seem to have a consensus on the importance of planting date, guidelines and procedures on when to plant chickpea in the region have not been developed. Hardly any study has reported planting dates for chickpea particularly in Southern Africa region. AquaCrop model is a crop simulation software that may be used to develop chickpea planting date guidelines for farmers and extension staff using climate data (Raes et al., 2018). AquaCrop model as a decision-support tool, may be used to assess the effect of different planting dates on evapo-transpiration (ET), crop canopy cover (CCC), biomass and grain yield of chickpea. Other than AquaCrop, several crop simulation models such as CERES (Jones & Kinyi, 1986), CropSyst (Stöckle et al., 2003), Cropwat (FAO, 1992), DSSAT cropping system (J.W. Jones et al., 2003), and APSIM (Keating et al., 2003) have been developed over the years. Although these models may be used for determining planting dates for farmers, the models are complex and thus rarely used by farmers, extension workers, and planners (Raes et al., 2018). Furthermore, the use of these models requires a large number of variables and input parameters which are not easily available for the diverse range of crops and sites around the world (Farahani et al., 2009; García-ViGarcía & Fereres, 2012). Therefore, there is a need for a crop simulation model that is sensitive enough to predict the response of biomass and grain yield to different planting dates, but yet is simple to run and requires limited number of input parameters.

The Food and Agriculture Organisation (FAO) developed AquaCrop model in an attempt to address the weaknesses of the earlier developed models. AquaCrop has the advantages of sufficiency, transparency, simplicity, accuracy and robustness (Raes et al., 2018a). The model simulation process is water-driven and requires a relatively low number of parameters and input data to simulate the yield response of crops to water ((Raes et al., 2018a; Jin et al., 2020). For AquaCrop model to be used for a specific crop, it needs to be calibrated and validated using field crop data and weather records. AquaCrop model has been calibrated and validated for maize (Hsiao et al., 2009; Jin et al., 2020), soybeans (Steduto et al., 2009), sorghum, sunflower (Stricevic et al., 2011), tomatoes (Katerji et al., 2013; Rinaldi et al., 2011), wheat (Upreti et al., 2020), sugar beet (Stricevic et al., 2011), potatoes (De La Casa et al., 2013), ground nuts (Chibarabada et al., 2020), rice (Raoufi & Soufizadeh, 2020), cotton (Farahani et al., 2009) and barley (López-Urrea...
et al., 2020). However, no published information is readily available on calibration and validation of AquaCrop for chickpea. Therefore, the objective of this study was to calibrate and validate the performance of AquaCrop model in simulating attainable yields of chickpea in response to different planting dates at a representative site of the dry environments of Northeastern South Africa.

1.1. Description of the AquaCrop model
AquaCrop is a water-driven crop yield simulation model (Raes et al., 2018a). The model has been used in multiple herbaceous crops for simulating biomass and yield under different field conditions across the world. The model can be used to develop optimum planting period for different crops to increase and stabilize crop yields. The model simulates aboveground biomass for each day during crop cycle as a function of water productivity and the sum of the ratio of crop transpiration over the reference evapotranspiration (equation 1).

\[ B = WP^* \sum_{i=1}^{T_r} \frac{T_r}{ET_o} \]  

(1)

Where \( WP^* \) is water productivity and is normalized for place and climate. \( T_r \) is crop transpiration and is normalised for climate by reference evapotranspiration for each day of transpiration.

\( Y = f_{HI} \times HI_o \times B \)  

(2)

Grain yield \( Y \): AquaCrop simulate grain yield as a product of above-ground biomass and the harvest index as shown by equation 2.

Transpiration \( (Tr) \): AquaCrop calculates transpiration as a product of crop coefficient \( K_{CT,\alpha} \) and the evaporative power of the atmosphere \( (ET_o) \). This calculation is done by considering the water stress factor \( K_s \) and \( K_{ST,\alpha} \) as shown in equation 3. In circumstances where water shortage provokes closure of stomatal openings, a stress coefficient \( (K_{ST,\alpha}) \) is considered.

\[ Tr = K_s \times K_{ST,\alpha} \times (K_{CT,\alpha} \times CC^*) \times ET_o \]  

(3)

Where \( CC^* \) is crop canopy cover adjusted for interrow micro-advection.

The operation of AquaCrop, its interface between soil and climate factors, and how it determines several parameters for crop growth is shown in Figure 1.

2. Materials and methods

2.1. Background
AquaCrop model has not been calibrated for chickpea. Thus, the model does not have files for chickpea. So this study entailed a full calibration process. However, we adopted soybean files from the model as a starting point and changed the files with newly developed chickpea files. Soybean files were chosen because it was the only crop closer to chickpea amongst calibrated crops in AquaCrop model. All parameters that specify the crop (conservative, cultivar-specific and variables) were calibrated for chickpea. Chickpea values for the parameters were either determined from field experiments, adopted from previous studies conducted in region or by fine-tuned by iteration method. Soybean files were only kept when we had no basis to improve their calibration.
2.2. Field experimental design

Two separate experiments were laid out in a split-plot design, with main plots consisting of planting date (1\textsuperscript{st} of May being the early planting, 14\textsuperscript{th} of May as the control/normal planting, and 28\textsuperscript{th} of May being the late planting date). These planting dates were selected based on previous studies (Mathews et al., 2011) in the region. Chickpea genotypes were used as sub-plot factor; four desi genotypes (Range 1, Range 3, Range 4 and Range 5) were sown in 2014, and 4 desi types and one Kabuli genotype (ICCV99010) were sown in 2015 season. Range 1 is early maturing and has a bushy canopy structure, Range 3 and ICCV 9901 are medium maturing cultivars and have an erect canopy, and Range 4 and Range 5 are late maturing and display a prostate and an erect canopy structure, respectively. Experiment one was well watered throughout the season, and experiment two was watered three times (at planting, flowering and pod formation). The total amount of water applied (including rainfall) in 2014 was 430 mm in experiment one and 175 mm in experiment two, whilst 435 mm and 235 mm was applied in 2015 in Experiment one and two, respectively. Variation in the total amount of water applied in 2014 and 2015 was caused by differences in initial soil moisture.

2.2.1. Data collection

2.3. Climate data

Climate data for the period of May to October for each winter season (2014 and 2015) was recorded from an automatic weather station that was already established at the experimental site (approximately 100 m from the experiments). The recorded data needed by AquaCrop model (5.0) included rainfall (mm), maximum and minimum air temperatures (°C), and reference evapotranspiration (mm) (calculated according to the FAO Penman-Monteith equation using ETo calculator version 3.2 software). This data set was for each day during the trial period. Carbon dioxide data for the experimental period was adopted from the model default file of Mauna Loa atmospheric CO\textsubscript{2} concentration (USA) from 1902 to 2109.

2.4. Soil data

Soil characteristic data were adopted from previous studies conducted in the study area (van Rensburg & Mzezewa 201; Fey, 2010; Soil Classification Working Group, 1991). The soil parameters needed by AquaCrop model included soil textural classes, water content (Volumetric) at permanent wilting point (PWP), saturation point (SAT) and at field capacity (FC), total available water (TAW) (mm), soil physical and hydraulic properties (K\textsubscript{sat}). Analysis of soil water content across the profile showed a maximum rooting depth of 2 m. A summary of soil data that was uploaded into the model is shown in Table 1.
| Soil property                                      | Soil Depth (mm) |
|--------------------------------------------------|-----------------|
|                                                  | 0–300           |
|                                                  | 300–600         |
|                                                  | 600–900         |
|                                                  | 900–1200        |
|                                                  | 1200–1500       |
| Type of soil                                     | Clay            |
|                                                  | Clay            |
|                                                  | Clay            |
|                                                  | Clay            |
|                                                  | Clay            |
| Field capacity                                    | 49.5 %          |
|                                                  | 48.2 %          |
|                                                  | 47.7 %          |
|                                                  | 47.6 %          |
|                                                  | 47.7 %          |
| Permanent wilting point                          | 28.6 %          |
|                                                  | 28.2 %          |
|                                                  | 28.2 %          |
|                                                  | 28.2 %          |
|                                                  | 28.2 %          |
| Total available water                            | 123 mm          |
|                                                  | 120 mm          |
|                                                  | 121 mm          |
|                                                  | 122 mm          |
|                                                  | 125 mm          |
| $K_{sat}$ (mm day$^{-1}$)                         | 24.2            |
|                                                  | 24.2            |
|                                                  | 24.2            |
|                                                  | 24.2            |
|                                                  | 24.2            |
| Bulk density (g cm$^{-3}$)                        | 1.11            |
|                                                  | 1.14            |
|                                                  | 1.12            |
|                                                  | 1.13            |
|                                                  | 1.20            |
2.5. Crop data

Field measurements were conducted on parameters that included above-ground biomass (measured at 14-day interval), number of plants per hectare, time from planting to 90% recovery (days), maximum canopy cover, \( CC_0 \) (%), time from emergence to start of senescence (days), time from planting to harvest maturity (days), time from planting to flowering (days), length of flowering stage (days), maximum effective rooting depth (m), time from sowing to maximum rooting depth (days), harvest index and grain yield.

Above-ground biomass was measured at 14-day interval starting from 28 days after crop emergence (DAE) until harvest maturity (HM) using destructive sampling method. All the plants from a quadrant of 0.36 m\(^2\) were cut at ground level, chopped, and oven dried at 80°C for 48 hours before recording sample dry weight (kg m\(^{-2}\)). For grain yield determination, 20 plant samples at harvest maturity stage, from a quadrant of 0.6 m\(^2\) were collected from the two innermost rows of each experimental unit and the pods were manually removed, threshed by hand, cleaned, air-dried, and weighed to determine grain yield (kg ha\(^{-1}\)). Harvest index was determined as the ratio of grain yield to total above-ground biomass.

Canopy cover was determined from the measured photosynthetically active radiation (PAR) using equation 4 (Farahani et al., 2009):

\[
CC = \left(1 - \frac{\text{PAR}_{\text{below canopy}}}{\text{PAR}_{\text{above canopy}}}\right) \times 100
\]  

(4)

The proportion of intercepted radiation by the crop canopy was measured at 7-day intervals between 28 and 105 DAE in both experiments using an AccuPAR, model LP-80 ceptometer (Decagon Devices Ltd., Pullman, USA, 2006). The measurements were taken between 1100 and 1300 hrs on clear, cloudless days. The ceptometer was placed horizontally above the canopy when measuring PAR above the canopy and positioned between the rows in such a manner that it was perpendicular to the rows when measuring PAR below the canopy.

Soil moisture content was measured at 7-day interval using a neutron probe. Measurements were taken between 14 and 105 DAE. On each occasion, the probe was lowered into access tubes that had been inserted in each experimental plot at sowing and 16 s counts readings \( N_{\text{soil}} \) were taken at 30, 60, 90 and 120 cm depth. Standard counts \( N_{\text{std}} \) were taken before taking any soil moisture readings; these readings were used to calculate count ratios: \( X (X = N_{\text{soil}}/N_{\text{std}}) \). Volumetric water content \( (\theta) \) at each depth was calculated using the calibration equations that have already been developed for the site (M. N.and Thangwana & Ogola, 2016) as shown below:

- 0.30 m depth: \( \theta = 0.0818x + 0.0268 \) (1)
- 0.60 m depth: \( \theta = 0.3227x - 0.2733 \) (2)
- 0.90 – 1.20 m depth: \( \theta = 0.3736x - 0.3297 \) (3)

Where \( x \) is the count ratio.

**Crop Transpiration**: transpiration \( (Tr) \) was determined from equation 5:

\[
Tr = ET - E
\]  

(5)

where \( E \) is evaporation from bare soil surface and \( ET \) is evapotranspiration from the crop.

\( ET \) was determined using the standard water balance equation 6:
\[ ET = \Delta S + P + I + U - D - R \] (6)

Where \( \Delta S \) is the change in storage (difference in volumetric water content of the entire profile between the first and last neutron probe readings), \( P \) is precipitation (mm), \( I \) is irrigation (mm), \( U \) is upward capillary, \( D \) is drainage and \( R \) is the surface runoff (Allen et al., 1998; Anwar et al., 1999). Considering the flatness of the field (less than 2% slope) and following earlier studies (M. N.and Thangwana & Ogola, 2016; Ogola et al., 2013; Ogola & Thangwana, 2013), rate of infiltration, drainage, capillary rise and surface runoff were minimal, insignificant and thus assumed to be negligible. Therefore, ET was estimated as a function of change in storage, irrigation and precipitation. The total irrigation amount of water applied in 2014 was 430 mm in experiment I and 230 mm in experiment II, whilst 435 mm and 235 mm were applied in 2015, in experiment I and II, respectively.

Evaporation was mostly from the wetted soil surface that was unshaded by the canopy and was measured at a depth of 5 and 15 cm on a daily basis using a hygrotech probe soil moisture sensor (Decagon Devices Ltd., Pullman, USA). Water productivity (WP) was determined as a ratio of biomass to cumulative normalized transpiration (equation 7). Transpiration was normalized using ETo calculated by Penman-Monteth equation (Allen et al., 1998) from the weather station.

\[ WP = \frac{B}{\sum \left( \frac{1}{t} \right)} \] (7)

2.6. Creating model input files

AquaCrop model requires soil, crop, climate and field management data for a specific area and time in order for it to simulate biomass and yield of crops. This data is uploaded into the model as files. Thus, soil, crop, climate and field management files were developed to calibrate/parameterise the model. Because AquaCrop model has not been parameterised for chickpea, the study used default parameter values of soybean crop on very few parameters that were difficult/impossible to measure using the available materials. This soyabean crop file is from AquaCrop model software, which contains crop parameters that were calibrated and validated by FAO (Raes et al., 2018b).

The soil data file was developed by specifying local soil type, texture, soil depth and number of soil horizons, slope, soil water content at field capacity and at permanent wilting point, total available water, saturated hydraulic conductivity, bulk density and the type of land use (Table 1). From this input specification, the model was able to generate a set of complete soil parameters, which are adjustable to the site specification. Developing a climate data file involved creating small sub-files of rainfall, temperature, reference evapotranspiration (ET\(_{0}\)), and carbon dioxide for the study area during the experimental period Raes et al., 2018b. Creating the sub-files involved uploading daily whether data into the model (including specifying the time and range of data). A collection of these sub-files was used to form a climate file for the study area. Carbon dioxide data was adopted from the model default file of Mauna Loa atmospheric CO\(_2\) concentration (USA) from 1902 to 2109. This adopted CO\(_2\) file is a global average representation by measurements at a station in Hawaii (Mauna Loa) and already uploaded as a default file within AquaCrop model. CO\(_2\) concentration is rarely measured at the weather station at study site and so the data could not otherwise be found for local conditions Raes et al., 2018b.

(Fey, 2010; Soil Classification Working Group, 1991; Van Rensburg & Mzezewa, 2011)

The reference evapotranspiration, ETo was collected from experimental weather station, and had already been calculated according to the Penman-Monteith equation using ETo calculator version 3.1 software (Allen et al., 1998). Similarly, rainfall, maximum and minimum temperatures were recorded from experimental weather station. The crop inputs to the model were made up of three types of parameters (conservative, management and cultivar-specific). The conservative parameters do not change with geographic location, time or management practices (Raes et al.,
| Date       | Amount of irrigation applied (mm) | 2014 season | 2015 season |
|------------|----------------------------------|-------------|-------------|
|            |                                  | Experiment I | Experiment II | Experiment I | Experiment II |
| 1 May      | 25                               | 65           | 30           | 30           |
| 14 May     | 30                               |              | 30           |
| 28 May     | 30                               |              | 30           |
| 03 June    | 40                               |              | 30           |
| 10 June    | 40                               | 55           | 40           | 80           |
| 17 June    | 40                               |              | 40           |
| 24 June    | 30                               |              | 30           |
| 01 July    | 40                               |              | 40           | 75           |
| 08 July    | 40                               | 55           | 40           |
| 22 July    | 40                               |              | 40           |
| 29 July    | 30                               |              | 30           |
| 12 August  | 30                               |              | 30           |
| 19 August  | 15                               |              | 15           |
| Total (mm) | 430                              | 175          | 435          | 235          |
However, because there were no predetermined parameters for chickpea crop in AquaCrop model, we adopted conservative parameters for soybeans were fine-tuned to match values for chickpea crop. The soybean conservative parameters that were fine-tuned/changed included: base temperature ($T_{\text{base}}$) (°C), upper temperature (°C), crop coefficient ($K_c$) when canopy is complete but prior to senescence, water productivity normalized for $E_T$ and $CO_2$ (WP* gram m$^{-2}$), possible increase (%) of harvest index (HI) due to water stress before flowering stage and during yield formation, coefficient describing negative impact of stomatal closure during yield formation on harvest index (dimensionless), allowable maximum increase (%) of specified HI, soil water depletion factor for canopy expansion—upper threshold (dimensionless), soil water depletion factor for canopy expansion—lower threshold (dimensionless), soil water depletion fraction for stomatal control—upper threshold (dimensionless), soil water depletion factor for canopy senescence—upper threshold (dimensionless) and minimum growing degrees required for full biomass production (“C.day$^{-1}$), heat stress temperature for pollination (dimensionless) and cold stress temperature for pollination (dimensionless).

The cultivar-specific parameters are less conservative and may vary with soil characteristics, field management or climatic conditions (Raes et al., 2018a). Therefore, these cultivar-specific parameters were uploaded into the model for it to assume the characteristics of the study area. During the development of the crop data file, the following subcomponent files were created: phenology (dimensionless), green canopy cover (%), rooting depth (m), crop transpiration (mm), soil evaporation (mm), above-ground biomass production (kg ha$^{-1}$) and reference harvest index (%).

The field management file was created and it specified the description of the soil conditions during planting stage of the crop (a wet soil with an average volumetric water content of 30%, a sub-soil of 25% as measured from the field was used, whilst a ground water of varying depth and salinity was used and was adopted from earlier studies in the region (Van Rensburg & Mzezewa, 2011). The field management file also specified the field condition at planting, which was free from mulching and was with soil bunds of less than or equal to 0.3 m in height as measured from the field. Soil fertility was non-limiting and weed management was perfect. An irrigation data file was created by specifying the irrigation method and irrigation events (irrigation time, water quality and net application amount) for each experiment (I and II) (Table 2). The study used sprinkler irrigation method.

### 2.6.1. Planting dates and cycle of the cultivars

During the first planting season, early planting date was on 05–01–2014, normal planting date was on 05–14–2014, whilst late planting date was on 05–28–2014. Similarly, the second planting season had early planting date on 05–01–2015, normal planting date on 05–14–2015, and late planting date on 05–28–2015. Chickpea genotypes were used as sub-plot factor; four desi genotypes (Range 1, Range 3, Range 4 and Range 5) were sown in 2014, and 4 desi types and one Kabuli genotype (ICCV99010) were sown in 2015 season. Range 1 is early maturing and had a growth cycle of 115 days, Range 3 and ICCV 9901 are medium maturing cultivars and had a growth cycle of 135 days an Range 4 and Range 5 are late maturing cultivars and had a growth cycle of 150 days.

### 2.7. Model parameterization

Parameterisation refers to high-level adjustment of specific model parameters (Farahhani et al., 2009) and is more than just calibration. There were no predetermined parameters for chickpea crop in AquaCrop model 5.0. However, we adopted soybean files from the model as a starting point and changed the files with new chickpea files during parameterization. Soybean crop was chosen because of its anatomy, physiological and biochemistry similarities with chickpea plant (De Camargo et al., 2019; Iniayal et al., 2019; Vollmann, 2016). For example, the two crops share C$_3$ carboxylation anatomy, and respond to water productivity in the same range of between 15 and 20 g m$^{-2}$ (Raes et al., 2018a). In addition, soybean and chickpea share similar plant canopy growth pattern that is characterised by poor initial canopy cover and also have the same physiological adaptations to water stress (Herridge et al., 2008; Miller et al., 2002; Toker & Mutlu, 2011). Thus,
Table 3. Summary of meteorological conditions recorded during the trial period (May—October 2014 and 2015)

| Year | Month   | $T_{\text{max}}$ | $T_{\text{min}}$ | $T_{\text{mean}}$ | CU | HU | Rainfall | VPD |
|------|---------|------------------|------------------|-------------------|----|----|----------|-----|
|      |         | (°C)             | (°C)             | (°C)              | (°C day$^{-1}$) | (°C day$^{-1}$) | (mm)    | (KPa) |
| 2014 | May     | 27.0             | 11.6             | 19.3              | 0  | 287.7 | 0.02     | 2.23  |
|      | June    | 26.2             | 9.0              | 17.6              | 14 | 223.3 | 0.00     | 2.24  |
|      | July    | 24.7             | 9.1              | 16.8              | 22 | 195.7 | 0.03     | 1.91  |
|      | August  | 28.0             | 10.0             | 17.7              | 2  | 293.5 | 0.02     | 2.31  |
|      | September | 31.4          | 13.6             | 21.5              | 0  | 365.4 | 0.37     | 2.54  |
|      | October | 33.0             | 15.3             | 22.5              | 0  | 383.8 | 0.83     | 2.25  |
|      | Mean    | 28.0             | 11.4             | 19.2              | 6.3| 291.6 | 0.211    | 2.24  |
| 2015 | May     | 29.4             | 12.8             | 21.1              | 0  | 324.7 | 0.00     | 2.14  |
|      | June    | 25.1             | 9.4              | 17.3              | 13 | 249.6 | 0.03     | 1.98  |
|      | July    | 26.1             | 10.6             | 18.4              | 15 | 228.0 | 0.02     | 1.99  |
|      | August  | 30.0             | 11.6             | 19.8              | 2  | 293.2 | 0.05     | 2.26  |
|      | September | 33.8         | 13.5             | 21.7              | 0  | 368.7 | 0.75     | 2.27  |
|      | October | 33.6             | 15.7             | 22.2              | 0  | 395.1 | 0.90     | 2.38  |
|      | Mean    | 29.7             | 12.3             | 20.1              | 5  | 309.9 | 0.29     | 2.17  |

* $T_{\text{max}}$ is the daily maximum temperature, $T_{\text{min}}$ is the daily minimum temperature, $T_{\text{mean}}$ is the mean temperature, CU is the cold units, HU is the growing degree days, Rainfall is the precipitation.

* Temperature was presented as the mean temperature for the month; rainfall was presented as total accumulated.
the following conservative parameters were parameterised to suit chickpea crop: \( T_{\text{base}} \) (°C), upper temperature (°C), crop coefficient \( K_c \) when canopy is complete but prior to senescence, water productivity normalized for ET\(_o\) and CO\(_2\) (WP\(^*\) gram m\(^{-2}\)), possible increase (%) of harvest index (HI) due to water stress before flowering stage and during yield formation, coefficient describing negative impact of stomatal closure during yield formation on harvest index (dimensionless), allowable maximum increase (%) of specified HI, soil water depletion factor for canopy expansion—upper threshold (dimensionless), soil water depletion factor for canopy expansion—lower threshold (dimensionless), soil water depletion fraction for stomatal control—upper threshold (dimensionless), soil water depletion factor for canopy senescence—upper threshold (dimensionless) and minimum growing degrees required for full biomass production (°C.day\(^{-1}\)). Field data from 2014 was used for model parameterisation.

The decision criteria in the parameterisation process were an objective method of measuring the parameter in the field and comparing it with model default values for soybean before replacing them. However, in very few parameters that were difficult or impossible to measure in the field, a trial and error method was used to parameterize them. These parameters include soil water depletion fraction for stomatal control—upper threshold \( P_{\text{st}} \) and coefficient describing negative impact of stomatal closure during yield formation on HI. The trial and error method was by iteration method of changing the model threshold values repeatedly until the model grain yield matched the measured grain yield in the field. A base temperature of 8°C instead of a default value of 10°C was used. This base temperature was adopted from previous studies for chickpea in the study area (N. M. Thangwana & Ogola, 2012). Upper temperature threshold for chickpea was changed from a default value of 35 to 32°C. This change was following the upper temperature threshold for chickpea reported by Devasirvatham et al. (2012).

2.8. Model validation
The parameterised AquaCrop model was tested using field data recorded during 2015 winter season. This involved uploading the necessary climate data for the 2015 growing season without entering any other files and comparing the model simulations with field observations.

2.9. Model quality assessment
The model evaluation criteria involved comparing experimental data that was measured from the field with the model simulated results. Performance of AquaCrop model was assessed using linear regression analysis \( R^2 \), the Normalised Root Mean Square Error (RMSE), the Nash-Sutcliffe model efficiency coefficient (EF), and the index of agreement (d). The choice of this assessment criterion
was adopted following earlier studies (Soddu et al., 2013; Geerts et al., 2009; Katerji et al., 2013; Mhizha et al., 2014; Xiangxiang et al., 2013). All the statistical tests were conducted using micro-
soft excel and XLSTAT version 2017. 04.32310 Addinsoft USA.

RMSE and d-index were calculated as shown in equations 8 and 9, respectively. The model was
considered to be excellent when the RMSE was less than 10, good when the RMSE was between 10
and 20, fairly acceptable when the RMSE was between 20 and 30, and poor when the value of
RMSE was higher than 30 (Jamieson et al., 1991; Katerji et al., 2013). A d-index value of 1 indicated
a perfect agreement between the simulated and observed data and 0 indicated no agreement,
a value of 0.5 was considered fairly acceptable.

\[
RMSE = \sqrt{\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{n}} - 100
\]

Where \(O_i\) and \(P_i\) are observed and simulated values, respectively, \(O\) is the average of all recorded
observations and \(n\) is the number of observations.

Figure 3. Comparison of model-simulated and field observed Soil Moisture Content. a, b and
c are the graph plots of early, normal and late planting dates, respectively.

Table 4. Statistical evaluation for model parameterisation

| Planting date | Parameter | n  | \(R^2\) | RMSE | d-index | EF   |
|---------------|-----------|----|--------|------|---------|------|
| Early Planting | CC        | 36 | 0.889  | 4.81 | 0.86    | 0.97 |
| (05–01-2014)  | Biomass   | 36 | 0.985  | 6.01 | 0.75    | 0.98 |
|               | \(E_{T_o}\) | 36 | 0.959  | 7.91 | 0.61    | 0.89 |
|               | SWC       | 36 | 0.946  | 6.79 | 0.65    | 0.94 |
|               | Yield     | 36 | 0.983  | 5.64 | 0.81    | 0.91 |
| Normal Planting | CC      | 36 | 0.949  | 4.96 | 0.84    | 0.96 |
| (05–14-2014)  | Biomass   | 36 | 0.998  | 6.24 | 0.74    | 0.97 |
|               | \(E_{T_o}\) | 36 | 0.937  | 7.92 | 0.61    | 0.90 |
|               | SWC       | 36 | 0.893  | 7.01 | 0.62    | 0.92 |
|               | Yield     | 36 | 0.970  | 5.81 | 0.80    | 0.90 |
| Late Planting  | CC        | 36 | 0.944  | 5.02 | 0.84    | 0.94 |
| (05–28-2014)  | Biomass   | 36 | 0.965  | 6.83 | 0.72    | 0.97 |
|               | \(E_{T_o}\) | 36 | 0.952  | 8.05 | 0.60    | 0.91 |
|               | SWC       | 36 | 0.950  | 7.26 | 0.63    | 0.92 |
|               | Yield     | 36 | 0.977  | 5.73 | 0.79    | 0.89 |
\[ d = 1 - \frac{\sum_{i=1}^{n} (P_i - O_i)^2}{\sum_{i=1}^{n} (|P_i - MO| + |O_i - MO|)^2} \]  

(9)

Where \( O_i \) and \( P_i \) are observed and simulated values, respectively, \( n \) is the number of observations, and \( MO \) is the mean of the observed variable.

3. Results and discussion

3.1. Weather conditions during the experimental period

In 2014, the variation of maximum monthly temperature was between 24.7°C (July) to 33.0°C (September) (Table 3). Minimum monthly temperatures ranged between 9.0°C in June and 15.3°C in October. The lowest mean monthly temperature, recorded in July, was 16.8°C. Total cold units (CU) were calculated from hourly data and were highest (22°C day\(^{-1}\)) in July. Average heat units (HU) per month was 291.6°C day\(^{-1}\). Highest HU was recorded in October (383.8°C day\(^{-1}\)), whilst the lowest units were observed in July (195.7°C day\(^{-1}\)). The variation of maximum temperature in 2015 was between 25.1°C (June) to 33.8°C (September). The lowest minimum monthly temperature was 9.4°C, recorded in June, whilst the highest minimum monthly temperature was 15.7°C, recorded in October. The maximum monthly average temperatures were 21.7°C and 22.2°C, recorded in September and October, respectively. Average heat units per month was 309.9°C days\(^{-1}\). Highest HU were recorded in October, whilst the lowest HU were recorded in July (228.0).
3.2. Parameterization of AquaCrop for chickpea

3.2.1. Canopy cover

During parameterization of canopy cover, the first stage was to determine the crop response to the environmental conditions and water balance in the root zone for AquaCrop model. This was performed through determining four water stress indices. Amongst the indices, three of them affected canopy cover and crop transpiration, whilst the other one had an impact on harvest index (HI). Data for field capacity (FC), available soil water content (SW) and total water content in the root zone (TAW) were extrapolated using graphs to represent daily data. Thus, parameterization of soil water depletion factor (P) was calculated on daily basis, following equation 10 below.

\[ P = \frac{FC - SW}{TAW} \]  

(10)

\( P \) (which included \( P_{\text{upper}} \) and \( P_{\text{lower}} \)) is defined as, the ratio of actual and total available soil water (Raes et al., 2018a). \( P_{\text{upper}} \) represents the upper threshold limit where no stress may affect the crop as long as water extraction does not exceed this threshold. Conversely, \( P_{\text{lower}} \) represents lower threshold, where depletion of soil water may increase water stress, though it will depend on crop characteristics such as sensitivity of the crop to water stress. Therefore, the calculated \( P \) thresholds were used as stress indices to parameterize the model. This enabled the model to simulate canopy cover. Canopy cover (CC) that expresses growth potential of chickpea crop was determined following equations 11 and 12, whilst canopy decline phase was determined following equation 13.

\[ CC = CC_o e^{CC_G} \]  

(11)

\[ CC = CC_x - 0.25 \left( \frac{CC_x}{CC_0} \right)^2 e^{-CC_G} \]  

(12)

\[ CC = CC_o \left[ 1 - 0.05 \right] \left[ e^{CC_G} - 1 \right] CC = CC_x \left[ 1 - 0.05 \left( \frac{3.33CC_G}{CC_x + 2.29} \right)^2 - 1 \right] \]  

(13)

Table 5. Comparison of model-simulated versus measured ET

| Experiment | Measured \( ET_o \) | Simulated \( ET_o \) | Measured \( WP^* \) | Simulated \( WP^* \) |
|------------|---------------------|--------------------|---------------------|
| I          | 682                 | 686                | 9.4                 | 7.0 |
| II         | 475                 | 484                | 8.6                 | 6.7 |

\( ET_o \) is Evapotranspiration, \( WP^* \) is normalized water productivity function.

3.2. Parameterization of AquaCrop for chickpea

Figure 6. Comparison of model-simulated and field observed yield. a, b and c are the regression model of simulated yield versus field observed yield for early, normal and late planting date, respectively.
Where CC is canopy cover at time t, CC₀ is the initial canopy cover at time t = 0, CGC is the canopy growth rate per day and CDC is canopy decline coefficient (Raes et al., 2018a).

By adopting a trial and error approach, chickpea canopy development was better simulated when a value of 8.5% increase per day for CGC and a value of 6.5% for daily decline was used. Furthermore, calculations for leaf expansion in } \( P_{\text{upper}} \), } \( P_{\text{lower}} \) and } \( f_{\text{shape}} \), respectively, using equation 8 were 0.3, 0.65, 4.0. The soil depletion threshold for canopy senescence (upper threshold) was 0.87, 0.85 and 0.82, respectively, for early, normal and late planting date. The } \( f_{\text{shape}} \) had a value of 0.30, 0.70 and 0.40, and was also calculated using equation 10.

After the parameterization of CC, evaluation of graph plots of the simulated CC were able to fit in well to plots of the field observed measurements of CC in all planting dates (Figure 2 a-f). However, the model overestimated CC between the days from 42 to 70 DAE and underestimated CC from 77 DAE until physiological maturity in early and normal planting dates. Similarly, the model overestimated CC between the days from 35 to 63 DAE and underestimated CC from 70 DAE until physiological maturity in late sowing. Although the overestimation and underestimation of CC was observed in all planting dates at different periods of growth, these variations were not significant as shown by error bars (Figure 2). Moreover, comparison of liner regression analysis (R²) (0.889, 0.949, 0.944), normalized RMSE (4.81%, 4.96%, 5.02%), d-index (0.86, 0.84, 0.84) and EF (0.97, 0.96, 0.94) (Table 4) in early, normal and late planting, respectively, showed excellent model performance in simulating CC.

Where } \( n \) is the sample size, } \( R^2 \) is the linear regression model, RMSE if the normalized root mean square error, MAPE is the mean absolute percentage error, Pr > F is a probability of F statistic, CC is the canopy cover, ET is the evapotranspiration, and SWC is the soil moisture content.

### 3.3. Soil water content

Water balance algorithm in AquaCrop is based on water storage capacity of the soil layers (Raes et al., 2018c). These soil layers were described by Smith (1990) in CROPWAT model. Parameterization of soil profile consisted of defining the total number of soil layers, as 5 layers for the study area. The layers had an approximate soil thickness of 0.3 m. The PWP was 21.0%, FC was 33.3%, SAT was 50.0%, TAW was 121 mm m⁻¹; the shear soil properties (Tau) was 0.26 and a soil restrictive layer of 3 m was used for the study (Table 1). Soil capillary was not measured in the study and therefore default values: } \( a = -0.5686 \) and } \( b = -1.831942 \) corresponding to vertisols was adopted from the model. In addition, all stress thresholds in AquaCrop that have been parameterized above have a direct function on soil water.

After parameterization, evaluation of graph plots of the simulated SWC were able to match with the graph plots of the field observed measurements of SWC in all planting dates (Figure 3 a-c), However, the model overestimated SWC between the days from 42 to 70 DAE but estimated SWC well from 77 DAE until physiological maturity in early and normal planting dates. Similarly, the model overestimated SWC during the days from 35 DAE to 63 DAE and under estimated SWC from 70 DAE until physiological maturity in late planting date. Although there was overestimation and under estimation of SWC as shown in Figure 3(a-c) at different periods of growth, these variations were not significant as shown by error bars. Moreover, comparison of regression analysis (R²) (0.946, 0.893, 0.950), normalized root mean square error (RMSE) (6.79, 7.01, 7.26), d-index (0.65, 0.62, 0.60) and EF (0.94, 0.92, 0.92) (Table 4) in early, normal and late planting, respectively, showed excellent model performance in simulating SWC.

### 3.4. Evapotranspiration, water productivity and biomass

AquaCrop model is water-driven (Raes et al., 2018a). Thus, accurate prediction of water that is lost by evapotranspiration is important for model biomass prediction. AquaCrop simulates biomass directly using the parameterized water productivity function (WP*) that is normalized for climate and place by ETo and carbon dioxide (Raes et al., 2018c). Equation 7 was used to determine WP*. Moreover, since
Table 6. Conservative and non-conservative parameters for chickpea in University of Venda

| University of Venda | Model Default values (soybeans) | EP | NP | LP |
|---------------------|---------------------------------|----|----|----|
| Planting Date       |                                  |    |    |    |
| A. Conservative crop parameters |                                 |    |    |    |
| Base temperature    | 8                               | 8  | 8  | 8  |
| Upper temperature   | 32                              | 32 | 32 | 32 |
| Crop coefficient when canopy is complete but prior to senescence | 2.8 | 2.8 | 2.8 | 1.10 |
| Water productivity normalized for ETo and CO2 (gram m⁻²) | 16 | 16 | 16 | 15 |
| Possible increase (%) of HI due to water stress before flowering | 0 | 0 | 0 | 0 |
| Growth during yield formation on HI | small | small | small | small |
| Yield formation on HI | small | small | small | small |
| Allowable maximum increase (%) of specified HI | 12 | 12 | 12 | 10 |
| Soil water depletion factor for canopy expansion—Upper threshold | 0.3 | 0.3 | 0.3 | 0.15 |
| Soil water depletion factor for canopy expansion—Lower threshold | 0.65 | 0.65 | 0.65 | 0.65 |
| Soil water depletion fraction for stomatal control—Upper threshold | 0.5 | 0.5 | 0.5 | 0.5 |
| Soil water depletion factor for canopy senescence—Upper threshold | 0.86 | 0.86 | 0.86 | 0.7 |
| Minimum growing degrees required for full biomass production (°C-day) | 1354 | 1354 | 1354 | 1295 |

(Continued)
| University of Venda | Model Default values (soybeans) |
|--------------------|-------------------------------|
| Planting Date      |                               |
| A. Conservative crop parameters |
| Heat stress temperature for pollination (°C) | 32  | 32  | 32  | 40  |
| Cold stress temperature for pollination (°C) | 8   | 8   | 8   | 8   |
| B. Non-conservative parameters |
| Plant density (no. of plants per hectare) | 333,333 | 333,333 | 333,333 | - |
| Emergence (days after sowing) | 12  | 13  | 13  | -   |
| Senescence (days after sowing) | 116 | 112 | 105 | -   |
| Maturity (days after sowing) | 133 | 125 | 114 | -   |
| Maximum canopy cover (%) | 93  | 70  | 64  | -   |
| Flowering (days after sowing) | 56  | 50  | 42  | -   |
| Maximum effective rooting depth (m) | 2   | 1.5 | 1.5 | -    |
| Reference harvest index (%) | 55  | 47  | 36  | -    |

*EP is early planting date, NP is normal planting date and LP is late planting date.
Figure 7. Comparison of model-simulated and field observed canopy cover. a, b and c are graph plots of early, normal and late planting dates, respectively, whilst d, e and f are regression model for canopy cover in early, normal and late planting date, respectively.

Figure 8. Comparison of model-simulated and field observed Soil Water Content. a, b and c are graph plots of early, normal and late planting dates, respectively.

Figure 9. Comparison of model-simulated and field observed above-ground biomass: a, b and c are graph plots of early, normal and late planting dates, respectively.
chickpea is rich in proteins, WP* was multiplied by an adjustment factor of 0.2 and WP* values of 16.92 kg ha⁻¹ mm⁻¹, 16.75 kg ha⁻¹ mm⁻¹, and 16.17 kg ha⁻¹ mm⁻¹ were obtained for the study (Figure 4). Furthermore, parameterization for Tᵣ and biomass depended on the determination of threshold P_upper and P_lower for stomatal closure. Because of unavailability of equipment to measure stomatal closure, a trial and error (Iteration method) was conducted until a suitable P_upper for stomatal closure of 0.55 and a f_shape of 0.4 was determined for Tᵣ prediction.

After parameterization, the model overestimated B between the days from 42 to 70 DAS and under estimated B from 77 DAS until physiological maturity in early and normal planting dates (Figure 5). Similarly, the model overestimated B between the days from 35 DAS to 63 DAS and under estimated B from 70 DAS until physiological maturity in late planting date. Although the overestimation and underestimation of B was observed at different growth periods, these variations were not significant as shown by error bars. Moreover, comparison of regression analysis (R²) (0.985, 0.998, 0.965), RMSE (6.01, 6.24, 6.89), d-index (0.75, 0.72, 0.68) and EF (0.98, 0.97, 0.97) (Table 4) in early, normal and late planting, respectively, showed excellent model performance in simulating B.

Furthermore, the simulated ET₀ compared well with the measured ET₀ in both experiments although the model ET₀ was slightly higher than the field measurements (Table 5). The higher model ET₀ could have been due to the estimation of P_upper for stomatal closure. ET₀ is strongly affected by P_upper for stomatal closure (Raes et al., 2018c). Thus, accurate calculation of P_upper for stomatal closure will improve ET₀ simulation.

3.5. Grain yield
Accurate prediction of yield in AquaCrop is based on good parameterization of the effect of water stress on HI at different growth stages such as before flowering, during flowering and at physiological maturity. The effects of water stress on HI before flowering was calculated by the model as a percentage of decrease/increase in HI as a function of total biomass measured at the peak vegetative stage. Similarly, the effect of water stress on HI during flowering was estimated as a percentage of decrease/increase in HI as a function of total flowers aborted between well-watered and water-stressed crop. However, because of difficulty in measuring Ks for stomatal closure, a default class of moderately tolerant to water stress corresponding to soil water depletion fraction (P) for failure of pollination of 0.88 and a range of 0.87–0.90 was used for the study. Likewise, a positive stress effect on HI was 2 and in the range of 1.5–2.9, whilst a negative stress effect on HI was 5 and in the range between 4.1 and 7.0. The excess of potential fruits suffered due to water stress was calculated as the differences in pod abortion percentages between well-watered and water-
| Experiment | Measured $ET_o$ | Simulated $ET_o$ | Measured WP* | Simulated WP* |
|------------|----------------|-----------------|--------------|---------------|
| I          | 705            | 9.5             | 7.2          | 8.3           |
| II         | 498            | 10.4            | 8.3          |               |

Table 7. Comparison of model-simulated versus measured ET

Source: Mubvuma et al., Cogent Food & Agriculture (2021), 7: 1898135

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| Planting date      | Parameter | n  | $R^2$ | RMSE | d-index | EF   |
|-------------------|-----------|----|-------|------|---------|------|
| Early Planting    | CC        | 36 | 0.979 | 5.84 | 0.81    | 0.98 |
| 01-05-2015        | Biomass   | 36 | 0.893 | 6.89 | 0.68    | 0.98 |
|                   | $ET_o$    | 36 | 0.951 | 8.65 | 0.59    | 0.85 |
|                   | SWC       | 36 | 0.982 | 8.26 | 0.62    | 0.90 |
|                   | Yield     | 36 | 0.950 | 5.91 | 0.60    | 0.89 |
| Normal Planting   | CC        | 36 | 0.986 | 5.89 | 0.79    | 0.99 |
| 14-05-2015        | Biomass   | 36 | 0.995 | 6.92 | 0.65    | 0.98 |
|                   | $ET_o$    | 36 | 0.968 | 8.73 | 0.58    | 0.91 |
|                   | SWC       | 36 | 0.949 | 8.84 | 0.60    | 0.89 |
|                   | Yield     | 36 | 0.931 | 6.03 | 0.60    | 0.89 |
| Late Planting     | CC        | 36 | 0.978 | 5.95 | 0.77    | 0.91 |
| 28-05-2015        | Biomass   | 36 | 0.982 | 6.98 | 0.62    | 0.98 |
|                   | $ET_o$    | 36 | 0.943 | 8.70 | 0.56    | 0.89 |
|                   | SWC       | 36 | 0.954 | 8.81 | 0.61    | 0.90 |
|                   | Yield     | 36 | 0.990 | 5.96 | 0.61    | 0.84 |
stressed crop. A class corresponding to this pod abortion variation between the two water regimes was selected from the model default values. Thus, excess of potential fruits was small (above 50).

After combining various effects of water stress on HI, the parameter was further adjusted by iterative method so that it matches field calculated HI at physiological maturity. This involved adjusting the maximum possible increase of HI. The extent of reduction in HI caused by extreme temperature or severe water stress during pollination time was calculated as the differences in flower abortion between well-watered and moisture stressed experiment. A class corresponding to this flower abortion variation between the two water regimes, selected from the model default values was small and in excess of 50. In general, the model was able to predict crop yield for all planting dates. The regression plot of simulated and observed yield showed a good relationship with $R^2$ values of 0.976, 0.969 and 0.992 for early, normal and late planting dates, whilst the normalized RMSE was 0.64, 5.81 and 5.86 for early, normal and late planting dates (Figure 6 and Table 4). This low RMSE clearly shows that the model error in predicting yield was low and gives confidence of a reliable simulation results. The $d$-index was 0.81, 0.80, and 0.79, whilst the EF was 0.91, 0.90, and 0.89 for early, normal and late planting dates.

3.6. A summary comparing default model conservative parameter values and the new parameterized values

A summary comparing default model conservative parameters values for soybeans and the new parameterized values for chickpea is shown in Table 6. Since there were no old parameters for chickpea, the study adopted default values for soybeans. The choice of soybeans is mainly because it comes from the same family group with chickpea (Sajja et al., 2017; Singh, 2017). These crops have similar physiology and yield development system though they vary in their tolerance to water stress. However, the highest challenge is that chickpea was calibrated for winter planting whilst soybean is a summer crop. Using default values of soybean which varies from chickpea on water stress may compromise the results, but soybean was chosen because it was the only crop that is parameterized in AquaCrop model which is closer to chickpea in terms of growth and development characteristics. Data that were used for parameterization was not used for testing the model.

3.7. Validation of the model

Validation of the model was done using field independent data observed during 2015 winter season. Graphical plotting of the simulated and observed parameters showed that AquaCrop model was able to predict CC, Biomass and SWC and yield and showed a strong correlation between observed and simulated parameters in all planting dates (Fig 7, 8, 9 and Table 8).

The model was able to predict crop yield for all planting dates (Figure 10). The regression plot of simulated and observed yield showed a good relationship with $R^2$ values of 0.949, 0.928 and 0.990 for early, normal and late planting dates, whilst the RMSE was 5.91, 6.03 and 5.96 for early, normal and late planting dates (Table 8). This low normalized RMSE clearly shows that the model error in predicting yield was low and gives confidence of reliable simulation results.

The simulated $E_{T_o}$ compared well with the measured $E_{T_o}$ in both experiments (Tables 7 and 8). Although the model $E_{T_o}$ was slightly higher than the field measurements, the results are consistent with earlier reports by Katerji et al. (2013) who reported that AquaCrop is less accurate in predicting $E_{T_o}$ under water-stressed crop.

Furthermore, SWC was simulated well in all planting dates. A good match between the observed and simulated SWC was observed during the first 42 DAE and from 70 DAE until physiological maturity stage in early and normal planting date. The late planting date had a good match between the simulated and observed SWC during the first 35 DAE and from 63 DAE until physiological maturity. The model struggled to simulate SWC during 42–70 DAE in early and normal planting and 35–63 DAE in late planting date. This period coincided with peak reproduction stages.
in all planting dates and may have resulted in peak water demand which was not well simulated by the model. During that same period SWC was observed to fall and almost approached PWP, suggesting that the model may have problems in simulating SWC under water limiting conditions. The overestimation of SWC observed in all planting dates during the peak reproduction stage may have been responsible for the overestimation of CC. AquaCrop model is water-driven (Raes et al., 2018a), thus an overestimation in SWC may result in overestimation in CC and all other crop physiological parameters that are water driven. In addition, the model also overestimated biomass during the same period, indicating that the problems experienced by the model in simulating SWC may also have affected simulating biomass during the same period. Indeed, biomass is calculated as a function of water productivity and transpiration in AquaCrop (Raes et al., 2018c). Therefore, overestimation in SWC may have resulted in overestimation of CC and biomass during the peak reproduction stage. However, a comparison of linear regression analysis ($R^2$) (0.982, 0.949, 0.954), Root mean square error (RMSE) (8.26, 8.84, 8.81), and the $d$-index was 0.62, 0.60, and 0.61, whilst the EF was 0.90, 0.89, and 0.90 for early, normal and late planting dates. (Table 8) in early, normal and late planting, respectively, showed a good model performance in simulating SWC in all planting dates. The match between observed and simulated SWC may indicate good model performance in simulating soil water fluxes in the root zone and also evaporation and transpiration of the crop.

In general, AquaCrop simulated above-ground biomass well. The simulated above-ground biomass development followed the normal growth curve and a graphical plotting of simulated and observed biomass fitted well (Figure 8). However, the model was less accurate in predicting above-ground biomass during the period from 37 DAE until 91 DAE in early planting and from 21 DAE to 71 DAE in late planting, whilst normal planting date had the best model prediction. Significant variations between the model simulated and field observed above-ground biomass was observed during the period from 56 to 63 DAE in early planting and from 49 to 60 DAE in late planting date, whilst no significant differences between simulated and observed was observed in normal planting. Field visual inspection of the late-planted crop during the first 30 DAE showed that the crop was less tolerant to low temperatures and experienced poor early growth during the coldest month of the winter season. Whilst temperature is well taken care of in AquaCrop (Steduto et al., 2009), this problem may have caused variations between the observed and simulated biomass during early growth stages in late planting date. Above-ground biomass in all planting dates was similar during the first 21 DAE, possibly because of the way AquaCrop calculate initial CC during early stages of growth. Initial CC is calculated as a function of plant density and mean canopy size per seedling (Steduto et al., 2009). However, the slight variation in CC though not significant observed amongst planting date during the early stages of growth may have been possibly due to differences in rate of mobilization of seed reserves and partially heterogeneity of germination (Steduto et al., 2009). Despite the significant variations between simulated and observed above-ground biomass in early and late planting, a comparison of linear regression analysis ($R^2$) (0.893, 0.995, 0.982), Root mean square error (RMSE) (6.89, 6.92, 698), and the $d$-index was 0.68, 0.65, and 0.62, whilst the EF was 0.98, 0.98, and 0.98 for early, normal and late planting dates. (Table 8) in early, normal and late planting, respectively, showed a good model performance in simulating above-ground biomass in all planting dates.

The results of this study, regardless of different crops used, are comparable to earlier studies with Quinoa (Geerts et al., 2009), winter wheat (Xiangxiang et al., 2013), with maize (Katerji et al. 2013). The good quality of the model simulation results in canopy cover and biomass implies that AquaCrop model was able to pick out significant differences for canopy cover and biomass that were caused by variation in planting date. Therefore, the model may also simulate biomass and canopy cover variations fairly well if the model is used to investigate scenario assessment of the effect of climate change on planting dates of chickpea in the same area of study.

$\text{ET}_0$ is Evapotranspiration, WP$^*$ is normalized water productivity function
Where \( n \) is the sample size, \( R^2 \) is the linear regression model, Normalised RMSE is the root mean square error, CC is the canopy cover, ET\(_o\) is the evapotranspiration, and SWC is the soil moisture content.

4. Conclusion

AquaCrop was well-calibrated and validated for simulating attainable yields in chickpea crop grown under different planting dates, in a representative site of the dry environments of Northeastern South Africa. All the statistical indicators used to compare field observed and model predicted parameters showed good model performance. The model predicted CC, SWC, and B and yield fairly well and picked out differences attributed to planting date in Northeastern South Africa. The validated model can be used for evaluating the effects of different planting dates on yield.

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