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EVALUATION OF FAO AQUACROP MODEL FOR ABILITY TO SIMULATE ATTAINABLE YIELDS AND WATER USE FOR FIELD TOMATOES GROWN UNDER DEFICIT IRRIGATION IN HARARE, ZIMBABWE

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ABSTRACT

Crop simulation models have an important role in evaluating irrigation management strategies for improving agricultural water use. The aim of this study was to evaluate the AquaCrop model for ability to simulate water use and tomato (*Lycopersicon esculentum* Mill.) fruit yields under deficit irrigation conditions. A fieldexperiment was conducted at Thornpark, University of Zimbabwe Research site over four seasons (2014 and 2017). The data collected for yield and water use were used to run and evaluate the performance of AquaCrop in predicting water use efficiency and fruit yield. Four treatments defined in relation to 100% of the crop water requirement (ETc) were simulated: T_1 100% ETc; T_2 80% ETc; T_3 60% ETc and T_4 50% ETc. The model performance was satisfactory, with a good correlation between the simulated and observed soil water content (SWC) and fruit yield (FY). All the statistical indicators (The Normalised Root Mean Square Error (R^2), Root Mean Square Error (RMSE), Nush Sutcliffe Model Efficiency (EF), Pearson Correlation Coefficient (r), and Willmott's Index of Agreement (d)) used to compare the observed and predicted parameters, showed good performance; for example the EF showed values of 0.91 for SWC, the (r) showed values of 0.95 for SWC and a FY of 2.79 and 2.39 metric tonnes ha^{-1} for the simulated results. The results showed that the values of the simulated FY were consistent with the measured, with corresponding coefficients of determination (R^2) of 0.93. The results revealed AquaCropisable to simulate the yield of tomato and the seasonal water requirements to an appreciable degree. However, it must be pointed out that the calibration of AquaCrop suffered from lack of measured data on the progress of crop canopy cover, which is an important parameter used in developing the model. The results obtained showed that AquaCrop can be used effectively in simulating tomato production under deficit irrigation and, therefore, it can be used as a decision-making tool for irrigation management of tomatoes in Zimbabwe.

Key Words: Aquacrop, deficit irrigation, water use

RÉSUMÉ

Les modèles de simulation de cultures jouent un rôle important dans l'évaluation des stratégies de gestion de l'irrigation pour améliorer l'utilisation de l'eau agricole. Le but de cette étude était d'évaluer la capacité du modèle AquaCrop à simuler l'utilisation de l'eau et les rendements en fruits de la tomate (*Lycopersicon esculentum* Mill.) dans des conditions d'irrigation déficitaire. Une expérience sur le terrain a été menée à Thornpark, site de recherche de l'Université du Zimbabwe pendant quatre saisons (2014 et 2017). Les données collectées pour le rendement et l'utilisation de l'eau ont été utilisées pour exécuter et évaluer la performance du modèle d'AquaCrop dans la prédiction de l'efficacité de l'utilisation de l'eau et du rendement en fruits. Quatre traitements définis par rapport à 100 % des besoins en eau des cultures (ETc) ont été simulés. : T_1 100 % ETc ; T2 80 % ETc ; T_3 60 % ETc et T_4 50 % ETc. Les performances du modèle étaient satisfaisantes, avec une bonne corrélation entre la teneur en eau du sol (SWC) simulée et observée et le rendement en fruits (FY). les indicateurs statistiques (l'erreur quadratique moyenne normalisée (R^2), l'erreur quadratique moyenne (RMSE), l'efficacité du modèle de Nush Sutcliffe (EF), le coefficient de corrélation de Pearson (r) et l'indice de concordance de Willmott (d) utilisés pour comparer les paramètres observés et prédits, ont montré de bonnes performances ; par exemple, l'EF a montré des valeurs de 0,91 pour SWC, le (r) a montré des valeurs de 0,95 pour SWC et un AF de 2,79 et 2,39 tonnes métriques ha^{-1} pour les résultats simulés. Les résultats ont montré que les valeurs du FY simulé étaient cohérentes avec les mesures, avec des coefficients de détermination (R^2) correspondants de 0,93. Les résultats ont révélé que le modele d'AquaCrop est capable de simuler le rendement de la tomate et les besoins saisonniers en eau à un degré appréciable. Cependant, il faut souligner que le calibrage du modèle 'AquaCrop a souffert du manque de données mesurées sur l'évolution de la couverture végétale, qui est un paramètre important utilisé dans l'élaboration du modèle. Les résultats obtenus ont montré que modèle 'AquaCrop peut être utilisé efficacement pour simuler la production de tomates sous irrigation déficitaire et, par conséquent, il peut être utilisé comme outil d'aide à la décision pour la gestion de l'irrigation des tomates au Zimbabwe.

Mots Clés : Aquaculture, irrigation déficitaire, utilisation de l'eau

INTRODUCTION

An estimated 18600 Km^3 of water used annually for global food production (Rockstrom *et al.,* 2007), 35% is used for rainfall production, 10% for irrigated crops and 55% for grazing (Ridoutt *et al*., 2009). The conflicting demands of clean water for agriculture and land use, are known to reduce future expansion of freshwater irrigation and arable land (Mhizha *et al*., 2014). There is a growing need for industrial and domestic water use, which has led to a reduction in available water for irrigation; and therefore a growing need to improve the management of agricultural water resources, especially due to the increasing food needs, due to the increasing population (Jin *et al.,* 2014). In arid areas of Zimbabwe, rain as a source of water for agriculture is unevenly distributed (Botha *et al.*, 2011; Bello *et al.,* 2016). According to Rockstrom *et al.* (2009), maintaining the current levels of water use efficiency in agriculture constant, an estimated extra amount of approximately 5700 Km^3 of clean water will be needed annually to meet the estimated food needs by 2050 (Sam-Amoah *et al.*, 2013). The threat of climate change poses further challenges and concerns about food security and sustainability (Sam-Amoah *et al.*, 2013) in the context of limited agricultural water availability. Water availability is a common factor directly affecting agricultural production (Mohd *et al.*, 2018). Therefore, good agricultural water management strategies and water conservation agricultural practices are needed to ensure the long-term viability of the agricultural industry.

The use of deficit irrigation techniques provides a reduction in water use, without compromising fruit quality or yield if timed properly and well maintained (Dzikiti, 2007). Therefore, irrigated areas under deficit irrigation can be increased for the same water as used under conventional irrigation, which may increase overall yield. Deficit Irrigation is a method used worldwide due to its positive effects on yield, quality and nutritional status and is one of the most efficient crop irrigation systems that increases the water use efficiency for higher yields per unit of irrigation water (Kirda, 2002). Improving irrigation efficiency can go a long way in reducing the production costs of agriculture, making the industry more competitive and sustainable. Tomato (*Lycopersicon esculentum* Mill.) is one of the most popular vegetable crops in the world and has the greatest area under cultivation compared to other vegetables (Nangare *et al.*, 2016).

It is one of the most important fresh vegetables found in Zimbabwe, but its yield and quality are hampered by water shortages due to repeated droughts with serious economic consequences (Sen and Sevgican, 1999). Tomatoes play an important role in human nutrition by providing essential nutrients, vitamins and dietary fiber. Also, plant compounds known as antioxidants found in tomatoes have anti-inflammatory properties (Erica *et al.*, 2010). Tomatoes have been suggested as a good value plant that can increase income, thereby reducing risk, as well as providing essential nutrients for green or delicious recipes (Saunyama and Knapp, 2003). It is well known that there is a good relationship between adequate water supply, high yields and good quality in tomato crop production (Byari andAl-Sayed, 1999); which is why good water management is essential for sustainable tomato crop production. Therefore, the use of irrigation planning techniques should be the most important management method for all tomato growers. Tomato plants need a well-planned and efficient irrigation system to get good yields and better fruit quality.

Simulation models measuring the effects of water use on fruit yields at farm level can be an important tool in water management and irrigation (Sam-Amoah *et al.*, 2013). Testing the yield response to various water applications in the field and/or controlled experiments is tiresome and expensive (Bitri *et al.,* 2014); hence due to such limitations, modelling becomes a useful tool for studying and developing promising deficit irrigation strategies (Blum *et al.*, 2009; Geerts *et al.*, 2009). The model allows integrated testing of various yield factors such as biomass, canopy cover, water productivity and harvest index to determine the appropriate amount of irrigation for a variety of conditions (Liu *et al.*, 2007). The FAO AquaCrop model predicts plant water requirements, crop water productivity, and water use efficiency under water-restricting conditions (Bitri *et al.*, 2014). The model has been shown to simulate water scarcity correctly (Iqbal *et al.*, 2014; Xiangxiang *et al.*, 2013; Jin *et al.*, 2014), and has been used for corn (Mhizha *et al.*, 2014), wheat (Castañeda-Vera *et al.*, 2015), cotton (Lorite *et al.*, 2007), sunflower (Steduto *et al.*, 2009) and quinoa (Geert *et al.*, 2009) under different conditions (Bitri *et al.*, 2014). The ability of the AquaCrop model to simulate yield in response to water has been confirmed by various researchers (Heng *et al.*, 2009; Andarzian *et al.*, 2011). It has been reported that AquaCrop model can accurately simulate plant biomass, fruit yield and soil water dynamics under conventional and deficit irrigation conditions for many different plants (Bitri *et al.*, 2014). That is why the model has become a useful decision-making tool for modelling and developing crop-management strategies at farm level (Sam-Amoah *et al.*, 2013).

AquaCrop has been applied widely under different climate and soil conditions, without the need for local calibration and validation once it has been properly parameterised for a particular crop species (Salman *et al*., 2020). However, there are some parameters that are dependent on location, crop type or cultivar and management practices, which must be fitted by the user (Salman *et al*., 2020). The objective of this study was to evaluate the AquaCrop modelfor its ability to simulate tomato water use and yield under conventional and deficit irrigation in Harare, Zimbabwe.

AquaCrop concept. AquaCrop is a dynamic water-driven simulation model (Raes *et al*., 2018a) that requires a relatively low number of parameters and input data to simulate attainable yield and water use of herbaceous crops as a function of water consumption of the major field and vegetable crops cultivated worldwide (Zinyengere *et al*., 2011).The model has been used in multiple herbaceous crops for simulating biomass and yield under different field conditions across the world (Raes *et al*., 2018a). Its parameters are explicit, intuitive and maintains a sufficient balance between accuracy, simplicity and robustness (Steduto *et al*., 2009). The model's ability to use few parameters; while maintaining accuracy makes it attractive for marginal locations in Zimbabwe where some information may be unavailable (Zinyengere *et al*., 2011).

The model simulates the three major components, which require management i.e. the soil, plant and atmosphere continuum. AquaCrop models the soil, with its water balance; the plant, with its development, growth and yield processes; and the atmosphere, with its thermal regime, rainfall, evaporative demand and carbon dioxide concentration. Additionally, some management aspects are explicitly considered (e.g. irrigation and fertilisation) as they affect the soil water balance, crop development and the final yield (Raes *et al*., 2009). Required model inputs include the climate: (minimum and maximum temperature, precipitation and reference evapo-transpiration), crop characteristics: field management (fertility), and soil properties (Raes *et al*., 2009). AquaCrop computes plant growth and development processes on a daily basis ina specific location, from planting date to maturity, (FAO Irrigation and Drainage Paper no 66:Crop Yield Response to Water 3.1). AquaCrop's determination of crop yield (Y) is water based and the relative evapotranspiration (ET) is pivotal in determining the yield. ET isseparated into crop transpiration (Tr) and soil evaporation (E), so asto separate E to avoid the confusing effect of non-productive wateruse (Zinyengere *et al*., 2011).

The core function of AquaCrop is expressed by the equation

$B = WP \times Tr$ (Steduto *et al*., 2009);

Where:

B is the final biomass. The final yield (Y) is a function offinal biomass (B) and harvestable biomass expressed as HI (harvest index). WP is the water productivity (biomass per unit of cumulative transpiration), which tends to be constant for a given climatic condition (Steduto *et al.,* 2009).

The FAO AquaCrop model has been calibrated for tomato using historical datasets from irrigation experiments carried out between 2004 and 2012 in Northern Italy in the Po Valley; and also from irrigation experiments in varying locations and was declared applicable to a wide range of conditions and non-specific to a given crop cultivar (Heng *et al.,* 2009; Hsiao *et al.*, 2009; Battilani *et al.,* 2015). The calibrated parameters have then been validated on eight independent datasets collected in a period of time ranging from 2004 to 2010 and the model has been validated for soil water content, yield, harvest index, biomass and its partition in above ground vegetation and fruit (Battilani *et al*., 2015) and thecrop growth modelling of tomato with AquaCrop in the Mediterranean region has been assessed by several authors (Rinaldi *et al*., 2011; Katerji *et al*., 2013; Linker *et al*., 2016). The effect of climate change on tomato production in Tunisia was also evaluated, and the effects of some possible adaptation strategies were modelled with AquaCrop as well (Bird *et al.*, 2016). Despite this, the modelling performance of AquaCrop has not yet been optimised under the local conditions in Zimbabwe and the rest of sub Saharan Africa. In reality, the simulation of water use and yield of tomatoes has not yet been conducted in our local conditions. Thus the AquaCrop model has got files for the tomato crop and hence this study did not entail a full calibration and validation process. The model allows for the use of monthly or 10 daily weather data despite quantifying plant physiological response on a daily time-step (Raes *et al.*, 2009). These characteristics ensured that we could carry out simulations for Biomass and Crop Canopy at Thornpark station Harare, despite a lack of measured biomass and crop canopy data. The AquaCrop version 5.0 was used in this study.The most important set of model components for its core functions included:

Climate data. The climate data included reference evapotranspiration (ETo) to be calculated according to the FAO Penman-Monteith equation (Allen *et al.*, 1998). Maximum and minimum temperature (Tx and Tn, respectively), rainfall and the mean annual carbon dioxide (CO_2) concentration.These parameters were collected from an automatic weather station at the experimental site, except CO_2, concentration which was obtained within the model default dataset.

Crop characteristics. The crop characteristics were in two parts i.e.user-specific and the conservative parameters. The conservative parameters were categorised into crop parameters, phenology, development, and water stress groups. The crop parameters included soil water extraction pattern; canopy development, given as a percentage of canopy cover; normalised water productivity for biomass; crop coefficient for transpiration at full canopy; and water stress response coefficients for canopy expansion, stomatal closure, and early canopy decline (Greaves *et al.,* 2016).

Some of the user-specific parameters included plant density, emergence time, canopy senescence, maturity time, flowering period and duration of yield formation, rooting depth, and the reference harvest index. For irrigation purposes, we used the crop water requirements (CWR) as per field trials. In general, the input parameters were entered into the model as practiced in the field trials.

Soil characteristics and management practices. Soil texture was specified according to the soil analysis carried out on site (Mhizha, 2010) (Table 3). Management practices included irrigation method, application depth and time of irrigation events. fertilisation and mulching.

The rest of the fundamental model components and their detailed information, are found in the AquaCrop Reference Manual (Raes *et al.*, 2011), which is regularly updated as the model develops.

Rationale. FAO Irrigation and Drainage:-Crop Yield Response to Water (AquaCrop): 3.1 has calibrated crop parameters for several crops and provides them as default values in the crop files stored in AquaCrop database. The parameters fall into two categories, distinguished as the conservative or cultivar and condition dependent.

The conservative crop parameters do not change with time, management practices, climate, or geographical location. The decision to assign a particular parameter to the conservative category was based on conceptual and theoretical analysis, and on extensive empirical data demonstrating near constancy. Depending on extensiveness of the data sets used for the calibration, the calibrated value for a conservative parameter required some small adjustment which was done, based on high quality experimental data Table 5.The rest of the conservative parameters required no adjustment to the local conditions or for the common cultivars, and was used as such in simulations (Tables 1 and 5).

So far tests done show that the same value of a conservative parameter is applicable to many cultivars, although some deviation may be expected for cultivars of extreme characteristics (FAO Irrigation and Drainage Paper no 66:Crop Yield Response to Water 3.1 AquaCrop).

The cultivar and condition dependent parameters are generally known to vary with cultivars and situations. Outstanding examples are life-cycle length and phenology of cultivars. An overview is given of crop parameters that are likely to require an adjustment to account for local cultivar or environmental and management conditions (Table 2).

There was thoroughness on the calibration and the extensiveness of the data set on which the calibration was based and diverse data sets were necessary to cover a wide-range of climate and soil conditions, and more cultivars (FAO Irrigation and Drainage Paper no 66:Crop Yield Response to Water 3.1 AquaCrop: Tables 1 and 2).

Design and operation. The AquaCrop utilises canopy expansion, stomatal conductance, canopy senescence and harvest index as the key physiological processes which respond to water stress (Darko *et al.*, 2016).

The model accommodates fertility levels and water management systems, including rainfed, supplemental, deficit and full irrigation and simulations are routinely in thermal time, but can be carried out in calendar time (Darko *et al.*, 2016).

AquaCrop is aimed at users in agricultural extension services, governmental agencies, NGOs, farmers associations, irrigation personnel and researchers as well as policy makers for planning and assessing water needs (Darko *et al.*, 2016).

The model can be used to develop optimum planting period for different crops to increase and stabilise crop yields and 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 (Raes *et al.*, 2018a).

$$B = WP_{*}Tr \qquad (1)$$

Where:

B is the biomass produced cumulatively (kg per m^2); Tr is the crop transpiration (either mm or m^3 per unit surface), with the summation over the time period in which the biomass is produced; and WP is the water productivity parameter (either kg of biomass per m^2 and per mm, or kg of biomass per m^3 of water transpired)(Raes *et al.*, 2018a).

Fruit yield (Y). AquaCrop simulate fruit yield as a product of above-ground biomass and the harvest index as shown by Equation 2. HI is the ratio of fruit yield to total dry matter of the crop and is affected by water and temperature stress before the beginning of yield formation, at flowering and during yield formation. Thus, HI is constantly adjusted during yield formation (Raes *et al.*, 2018c) and is affected by water stress during various stages of crop development

For most crops, only part of the biomass produced is partitioned to the harvested organs to give yield (Y), and the ratio of yield to biomass is known as harvest index (HI), hence:

$$Y = HI \bullet B \qquad (2)$$

The underlying processes culminating in B and HI are largely distinct from each other. Therefore, separation of Y into B and HI makes it possible to consider effects of environmental conditions and stresses on B and HI separately (Raes *et al.*, 2018c).

TABLE 1. Conservative crop parameters

Crop growth and development	Base temperature and upper temperature for growing degree days
	Canopy size of the average seedling at 90 percent emergence (cco)
	Canopy growth coefficient (CGC); Canopy decline coefficient (CDC)
	Crop determinacy linked/unlinked with flowering; Excess of potential fruit (%)
Crop transpiration	Decline of crop coefficient as a result of ageing
Biomass production and field formation	Water productivity normalised for ETo and CO2 (WP*)
	Reduction coefficient describing the effect of the products synthesized during yield formation on the normalized water productivity
	Reference harvest index (HIo)
Stresses	
Water stresses	Upper and lower thresholds of soil-water depletion for canopy expansion and shape of the stress curve
	Upper threshold of soil-water depletion for stomatal closure and shape of the stress curve
	Upper threshold of soil-water depletion for early senescence and shape of the stress curve
	Upper threshold of soil-water depletion for failure of pollination and shape of the stress curve
	Possible increase of HI resulting from water stress before flowering
	Coefficient describing positive impact of restricted vegetative growth during yield formation on HI
	Coefficient describing negative impact of stomatal closure during yield formation on HI
	Allowable maximum increase of specified HI
	Anaerobiotic point (for effect of waterlogging on Tr)
Temperature stress	Minimum and maximum air temperature below which pollination starts to fail
	Minimum growing degrees required for full biomass production

Adapted from: FAO Irrigation and Drainage Paper no 66: Crop Yield Response to Water 3.1 AquaCrop

TABLE 2. List of crop parameters likely to require adjustments to account for the characteristics of the cultivar and local environment and management

Phenology (cultivar specific)	Time to flowering or the start of yield formation Length of the flowering stage Time to start of canopy senescence Time to maturity (i.e. the length of crop cycle)
Management dependent	Plant density Time to 90 percent emergence Maximum canopy cover (depends on plant density and cultivar, see Section 3.3)
Soil dependent	Maximum rooting depth Time to reach maximum rooting depth
Soil and management dependent	Response to soil fertility Soil salinity stress

Adapted from: FAO Irrigation and Drainage Paper no 66: Crop Yield Response to Water 3.1 AquaCrop

Transipiration (Tr). AquaCrop calculates transpiration as a product of crop coefficient (KCTr) and the evaporative power of the atmosphere (ETo). This calculation is done by considering the water stress factor (Ks) and KSTr as shown in Equation 3. In circumstances where water shortage provokes closure of stomatal openings, a stress coefficient (Kssto) is considered.

$$Tr = Ks\ K_{STr}\ (K_{CTr,x}CC^{+})ET_{0} \quad (3)$$

Applications AquaCrop brings out constraint crop production and water productivity and, therefore, an irrigation schedule can be developed to optimise production and maximise on water productivity (Mejias *et al.*, 2017). The model can be applied as a support for decision-making on water rationing and can also assess the performance of the system, through the water productivity or the yield that is produced per unit of water evapo-transpired (Mejias *et al.*, 2017). AquaCrop predicts crop production under different water-management conditions (deficit and conventional irrigation) and different management strategies (e.g. adjusting planting date, cultivar selection, fertilisation management), under the current and future climate changes (FAO, 2016).

MATERIALS AND METHODS

Research site. This study was confined to the University of Zimbabwe's Thornpark farm (17.42° S, 31.07° E and 1479 masl), located near Harare in Zimbabwe. The site falls into natural region IIa of the agro-ecological zones of Zimbabwe (Vincent and Thomas, 1961). Data from the Zimbabwe Meteorological Services Department for Harare for 36 years (1981 - 2017), showed that the mean monthly maximum temperature of 28°C were recorded in the month of November. Precipitation falls mainly in November to March; while the other months are generally dry. On average, the area receives a mean annual rainfall total of about 800 mm and has a mean monthly minimum temperature of 7 °C and a mean annual average temperature of 25°C in summer. The land is relatively flat with slopes of 2% or less and has deep to moderately deep well drained red clay-loam soils (Mhizha, 2010). The land has typical water holding capacity within 0.80 m of the soil of about 175 mm, with an available water content of 12 (%v/v) (Mhizha, 2010) (Table 3).

Experimental. The materials selected for the trials were commercial tomato (*Solanum lycopersicum L.*) Galina and Shanty varieties. The trials were randomised into four plots each measuring T1: 243.8 m^2, T2: 243.8 m^2, T3: 240.6 m^2 and T4: 240.6 m^2. Irrigation water was applied through stop valves on each drip line and a fertigation station through electro-valves. Water was drawn from a 100-metre-deep bore hole into a 1000 litre tank using a 100 metre three phase borehole submersible high-pressure water pump. From the 1000 litre tank, water would pass through domestic water meters placed before the drip lines of each treatment were a record of the amount of water used in cubic meters would be obtained. Pests and disease were managed according to the recommended guidelines from the industry and were followed from transplanting to harvesting and the fertiliser was applied once every week in solution. Similar management practices were applied to all trials and the fertiliser and chemicals were kept constant for all treatments, except for the irrigation amount which was the treatment variable.

Irrigation treatments. Four irrigation treatments based on the percentage of crop water requirements (CWR) were implemented in each of the four trials. The four irrigation treatments were: T1 = 100%, T2 = 80%, T3 = 60%, and T4 = 50% of crop water requirements (CWR). The CWR is the depth (or amount) of water needed to meet the water loss through evapotranspiration, that is the amount of water needed by a crop to grow optimally.

Each treatment carried equal number of plants with a plant spacing of 0.3 m and 0.5 m between adjacent rows. A localised drip irrigation system was used which had one drip emitter per plant. At the beginning of each day, CWR were determined for each treatment from data obtained from an automatic weather station at the site. The daily maximum and minimum temperature, relative humidity, wind speed, rainfall and solar radiation measured by the AWS were used in the computation of ETo. This was calculated using the FAO Penman-Monteith method as described by (Allen *et al.*, 1998). The ETo data was then used to determine CWR as follows:

CWR = ETo x Kc

Where:

Kc = crop factor (depends on type of crop, growth stage);and ETo = reference evapo-transpiration (mm/day).

Model validation. Field measurements taken during period 2014-2017 for trial 3 and 4were used for model validation. This involved

TABLE 3. Soil characteristics at the University of Zimbabwe Research site (Thornpark Farm)

Parameter	Description
Soil classification	Zimbabwe: 5 EI FAO: Haplic Lixisol
Depth	80 cm
Texture	Course sandy clay loam
Bulk density	1.3 -1.6 g cm^{-3}
Available water content	12 (%v/v)
Final infiltration rate	18 cm/hr

Adapted from (Mhizha, 2010)

comparing observed and simulated soil water and fruit yield at harvest under conventional and deficit irrigation. Measured crop growth variables, observed phenological stages, and conservative parameters were used in this phase (Heng *et al.*, 2009; Hsiao *et al.,* 2009). The procedure involved adjustment of sensitive parameters, mainly non-conservative parameters and assessing both the absolute and relative difference. For each change in input, simulations were done using the calibrated crop file and the corresponding irrigation file (Geerts *et al.*, 2009; Salemi *et al.,* 2011). Focusing on the calibrated crop parameters, plant density, and other crop growth data observed in the field, validations were executed. For each of the simulation runs, weather data, soil characteristics, irrigation applications, phenological stages, and sowing density were entered as observed.

Tenruns were used in the AquaCrop calibration to obtain the simulated results. The parameters were modified and calibrated until the absolute and relative errors of the observed *versus* simulated were very low (De Souza *et al.*, 2020) (Table 6). For each experiment we entered the conservative and non-conservative parameters specified for tomatoes and simulated in growing degree-days (GDD) mode as presented in the AquaCrop Reference Manual (Raes *et al.*, 2018). The growing degree-days mode was chosen since crop development is related to changes in temperature.

Analysis of model performance. The match between simulated and observed reference variables were assessed using goodness of fit tests comprising of: the Nash-Sutcliffe model efficiency (EF) (Nash and Sutcliffe, 1970; Krause *et al.*, 2005; Mhizha *et al.,* 2014) that was evaluated to assess the predictive power of the model; the root mean square error (RMSE), normalised root mean square error CV(RMSE),Pearson correlation coefficient (r) and Willmotts index of agreement (d) were evaluated to assess the error in the model estimates and the correlation between modelled and observed variables, respectively (Mhizha *et al.*, 2014).

In this study, the prediction model output for Yield and Water Use during harvest was used for model evaluation.

Model performance was assessed using E (Nash and Sutcliffe, 1970: Jin *et al.*, 2014) as follows:

$$E = 1 - \frac{\sum_{i=1}^{n} (S_i - O_i)^2}{\sum_{i=1}^{n} (O_i - \bar{O}_i)^2} \quad \text{.................. Equation 2}$$

Where:

S_i and O_i are predicted, and observed data, respectively.

$\bar{O}_i$ is the mean value of O_i, and n is the number of observations.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (S_i - O_i)^2}{n}} \quad \text{....... Equation 3}$$

E and R^2 was approaching one, and RMSE was near zero and these were indicators of improved model performance.

Root mean square error (RMSE). The root mean square error or RMSE is one of the widely used statistical parameters (Jacovides *et al.*, 1995) and measures the average size of the difference between predictions and observations (Saad *et al.,* 2014). It ranges from 0 to positive infinity, with the former indicating good and the latter poor model performance (Saad *et al.*, 2014).

Normalised root mean square error (NRMSE). RMSE can be normalised using the mean of the observed variable and is expressed as a percentage and gives an indication of the relative difference (Saad *et al*., 2014).

A simulation can be considered excellent if NRMSE is smaller than 10%, good if between 10 and 20%, fair if between 20 and 30% and poor if larger than 30% (Saad *et al*., 2014).

The Nush-Sutcliffe model efficiency coefficient (EF)

The Nush-Sutcliffe model efficiency coefficient (EF) determines the relative magnitude of the residual variance compared to the variance of the observations (Nash *et al*., 1970). EF can range from minus infinity to 1 (Saad *et al*., 2014). 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 and a negative EF occurs when the mean of the observations is a better prediction than the model (Saad *et al*., 2014).

Willmott's index of agreement (d). The index of agreement was proposed by Willmott *et al*. (1982), to measure the degree to which the observed data are approached by the predicted data (Saad *et al*., 2014). It represents the ratio between the mean square error and the "potential error", which is defined as the sum of the squared absolute values of the distances from the predicted values to the mean observed value and distances from the observed values to the mean observed value (Willmott *et al*., 1984; Saad *et al*., 2014). It overcomes the insensitivity of r^2 and EF to systematic over- or underestimations by the model (Willmott *et al*., 1984; Legates *et al*., 1999; Saad *et al.,* 2014). It ranges between 0 and 1, with 0 indicating no agreement and 1 indicating a perfect agreement between the predicted and observed data (Saad *et al*., 2014).

Sensitivity analysis. Uncertainty of input parameters in crop models and the cost of their experimental evaluation provides a reason for carrying out the sensitivity analysis, which allows identifying the most significant parameters for different crops and checksout whether the model output behaves as expected when the input varies. Sensitivity analysis identifies which parameters have a small or a large influence on the output and which parameters need to be estimated with maximum accuracy. Therefore, emphasis in this sensitivity study (Fig. 1) was placed on the variables that are commonly used as control variables in field trials as reported by (Mashonjowa, 2010). To evaluate the sensitivity of the model to individual parameters, each parameter was varied individually and the translation factor (Kx) calculated according to the equation reported by Mashonjowa (2010).

$$K_\xi = \frac{\left[\frac{d\Omega}{\Omega}\right]}{\left[\frac{d\xi}{\xi}\right]}$$

Where:

Ω is the output in question; and ζ is the parameter.

The translation factor gives the relative change of an output, Ω, as a result of a relative change of the input variable or parameter ζ (Mashonjowa, 2010).

Water stress can be inferred indirectly from the processes regulating leaf growth, described in the original SAFY model (Sivestro *et al*., 2017); and therefore, a sensitivity analysis was performed to determine which parameters highly affect the simulation results and these were calibrated more carefully. The rest of the parameters were adapted from literature and determined less accurately (Mashonjowa, 2010).

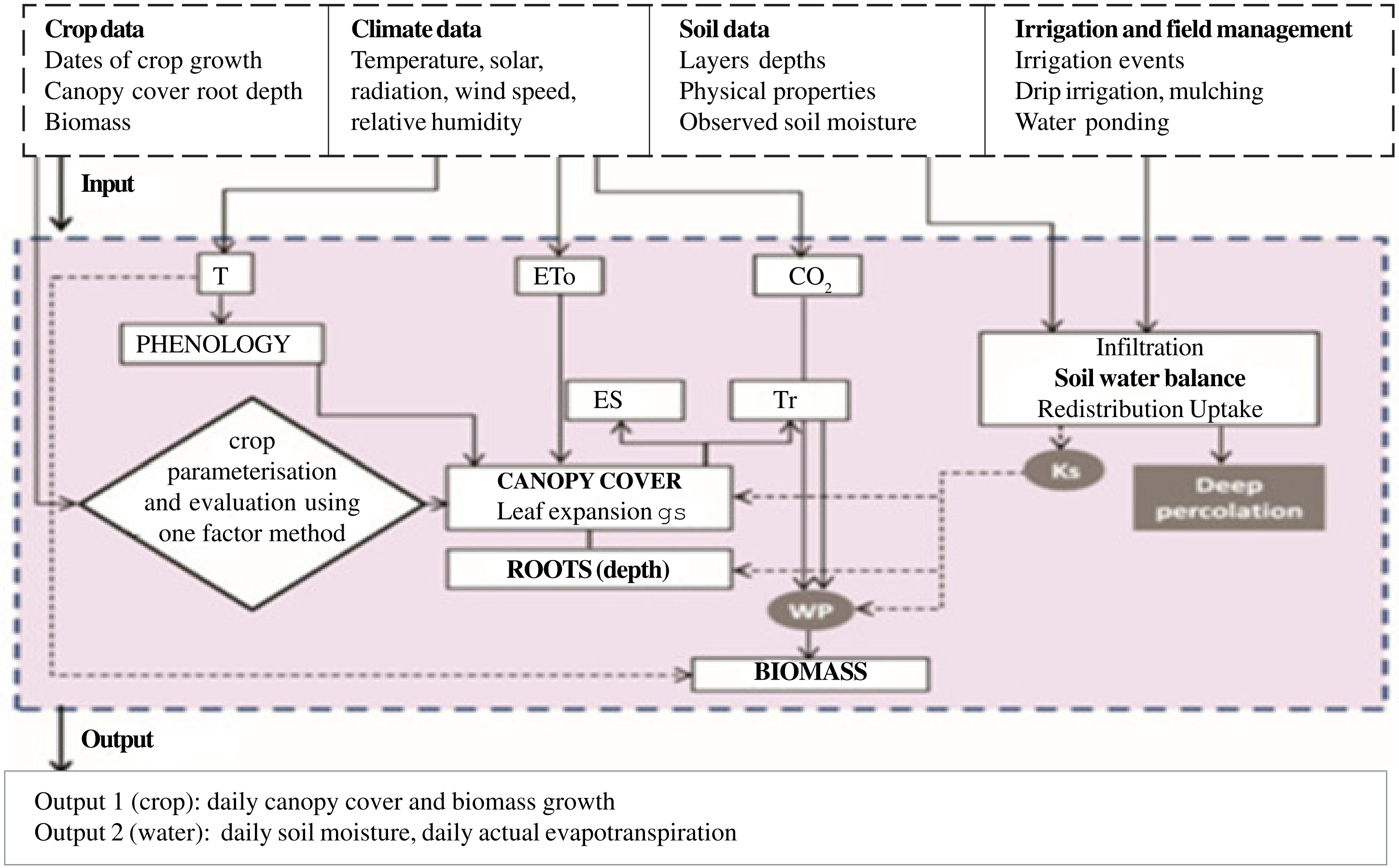

Figure 1. Flow chart for parameterisation of the AquaCrop adapted from Raes *et al*. (2009) and Steduto *et al*. (2009) . T = temperature, ETo = potential evapotranspiration, gs = stomatal conductance, WP = water productivity coefficient, Ks = stress coefficient, Es = soil temperature and Tr = crop transpiration.

RESULTS AND DISCUSSION

The results of the sensitivity tests (Table 4) were used to categorise the parameters and input variables as follows:

Category A: those for which the model was very sensitive (K> 0.05), and so were experimentally determined accurately (Table 4).

Category B: those for which the model was not as sensitive as Category A parameters (0.005 < Kd< 0.05), and so were determined experimentally, but with less accuracy than category A parameters (Table 4).

Category C: those for which the model was not sensitive (K< 0.005), and so their values were taken from literature (Mashonjowa *et al.,* 2007).

Dry (simulated) yield ranged from 2.39 t ha^{-1} at 100% CWR to 3.39 t ha^{-1} at 60% CWR with a biomass of 9.35 t ha^{-1} being achieved with the smallest amount of water (3328 mm) and a harvest index of 36.3% (Table 6). The harvest index at 60% and 80% showed no significant difference with values of 36.3 and 36.7%, respectively. Low values were obtained at 100 and 50% i.e. 35.3 and 35.6%, respectively (Table 7).

The values tallied with the observed measurements as the lowest value was also obtained at 100% CWR, with no significant difference at 60 and 80% (Table 6).

The values for simulated fruit yield were consistent with the measured values with corresponding coefficients of determination for (R^2) at 0.93 and water productivity of 1.19 kg yield m^{-3} at 60% CWR and the normalised water productivity values showed a significant increase with increase in the amount of irrigation water (Table 6). The RMSE of 0.34% was obtained for fruit yield as well as 15.1% for SWC. The size of error between the observed and simulated was not bad (Table 7) as the 'EF' 'd' and 'r' values showed a perfect match to the observed values indicating that the AquaCrop simulation model is good with results at 60% CWR with values of 0.97; 0.91; and 0.99, respectively (Table 7 and Fig. 3).

The validation dataset for Biomass showed Willmotts index of agreement at (1.00) indicating a perfect match, supported by Nush Sutcliffe at 0.98 and Pearson correlation coefficient of 0.99 (Table 7 and Fig. 4). There is close match between observed and simulated canopy cover supported by Willmotts Index of agreement (0.95), the Nush-Sutcliffe having value as 0.81 and Pearson correlation coefficient value of 0.91 indicating that the model efficiency for canopy cover is good (Table 7 and Fig. 5).

In general, the AquaCrop model worked well in simulating Soil Water Content, Canopy Cover, Biomass and Fruit Yield being confirmed by statistical indicators of 'r', 'd' and 'EF' given in Figure 2 and Table 7. However, in severely stressed treatments (50 and 60%) there were some mismatch between the model prediction and the observed values for Soil Water Content, Canopy Cover and to a lesser extent the fruit yield, but with an increase in crop water use the model simulation improved. The values between 80 and 100% for moderately stressed and non-stressed conditions worked well in predicting crop development, water use and fruit yield (Table 8).

During the simulation exercise it was observed that the performance of the AquaCrop depended on the water stress level experienced by the plant. The evolution of Canopy Cover and Soil Water Content was under estimated with values of 'r' at -0.27, -0.23 and 0.38, 0.52, respectively (Table 7), while the Biomass was generally over estimated for 'r' at 0.99 and 0.91 (Table 7) there was also under estimation at 50 and 60% with values of 'RMSE' at 0.67 and 3.53, respectively and hence the deviation between observed and simulated Canopy Cover and Biomass was more pronounced under water deficit conditions, becoming more intense as stress levels were increased. Therefore, simulations for Canopy Cover and Soil Water

TABLE 4. Model parameters and input variables (climate, management, soil and crop) as used in the sensitivity test and the categories they were put under

Parameter	Lower limit	Upper limit	Units	Category
Climate				
Air temperature	2.5	36	°C	A
Humidity	49	66	%	A
Radiation	5.4	6.7	KWh	A
Wind Speed	3.3	4.3	m/s	A
Rainfall	0.13	0.25	mm	A
CO_2 conc.	300	400	ppm	C
ETo	0.5	7	mm	A
Management				
Plants/ha	667	80000	plants/ha	A
Irrigation	18	132	mm	A
Irrigation water quality	0	4	dSm^{-1}	B
Soil				
Root deepening	20	100	cm	B
surface runoff	45	85	CN	C
Capillary rise	0	20	mm/day	C
Mulches	0	100	%	C
water table depth	0.5	5	m	C
Hydraulic properties of soil	70	150	mmm^{-1}	C
Crop				
Coefficient of positive impact on HI Vegetative growth	5	16	%	A
Allowable maximum increase of specified HI	5	58	%	A
Crop water productivity PWP	15	20	gm^{-2}	A

TABLE 4. Contd.

Parameter	Lower limit	Upper limit	Units	Category
Canopy cover after emergency CCo	2.77	9.97	%	A
Canopy Cover (maximum) CCx	70	95	%	A
Canopy growth coefficient CGC	10.2	15	%	A
Canopy decline coefficient CDC	10	35	days	A
Transplant to flowering	65	80	days	A
Transplant to recovery	1	5	days	A
Harvest Index HI	15	20.4	%	B
Length of crop cycle	7	125	days	A
Reference Harvest Index HI^{O}	16	18	%	A
Allowable max increase of specified HI	65	120	days	B
Soil water depletion threshold for canopy expansion	0.25	0.6	$Ks_{exp,w}$	A
Soil water depletion threshold for canopy senescence	0	1	$Ks_{exp,w}$	A
Soil water depletion threshold for stomatal control	0.5	100	Ks_{sen}	B
Soil water depletion threshold for failure of pollination	0	0.9	Ks_{sto}	B
Early canopy senescence	0	0.85	Ks_{pol}	B
Pollination: air temperature below which pollination starts to fail cold /heat stress	8	40	°C	B

TABLE 5. Conservative (user specific) parameters used for simulation

Parameter	Value	Unit
Plant density	6	plants m^{-2}
Number of plants	60000	p/ha
Time from transplanting to recover	6	d
CO_2 concentration default	1902-2099	ppm
From first day after transplanting	5 April-26 August	Days
Canopy cover initial	1.33	%
CC (90% emergence) /seed	10	cm^2/day
Restrictive soil layer	1	m
ET - Soil evaporation	50	K_e
ET - Crop transpiration	1.10	K_cT_r
PWP normalised for climate and CO_2	17	gm^{-2}
Reference harvest index	50	%
Canopy expansion under soil water stress	0.10	$Ks_{exp'w}$
Stomatal closure under soil water stress	0.45 (62%)	Ks_{sto}
Early canopy senescence under soil water stress	0.75	K_{ssen}
Aeration stress under soil water stress	10	K_{saer}
Reference harvest index (HIO)	50	%
Harvest index before flowering	52	%
Harvest index during flowering	0.80	%
Harvest index during yield formation	62.5	%
Crop development under air temperature stress		
Base temperature	5.5	°C
Upper temperature	30.0	°C
Biomass production under cold air temperature stress	0-11	°C
Pollination under air temperature stress [cold]	3-8	°C
Pollination under air temperature stress [heat]	40-45	°C
Maximum effective rooting depth	0.35	m
Growth Stages from day 1 after transplanting to:		
Max canopy cover	52 days	
Maturity	124	days
Recovering	5	days
Max rooting depth	62	days
Start of canopy senescence (decline)	110	days
Yield formation duration of flowering	51	days
Flowering from day 1 after transplant	87	days
Duration of flowering	10	days
Length building up HI	49	days

TABLE 5. Contd.

Parameter	Value	Unit
Irrigation method drip		
Irrigation events (100, 80, 60, and 50) Etc %		
Field management soil fertility (non limiting)		
Soil texture sandy-clay-loam soil		
Simulation period	25 April-26 August	days
Water productivity (WP*)	1	gm^{-2}
Field data		
Green canopy cover (CC)	38.8	%
Biomasss – Dry above ground (B)	3.98	$t\ ha^{-1}$
Yield (dry)	2.04	$t\ ha^{-1}$
Soil water content (SWC) 1	80	mm

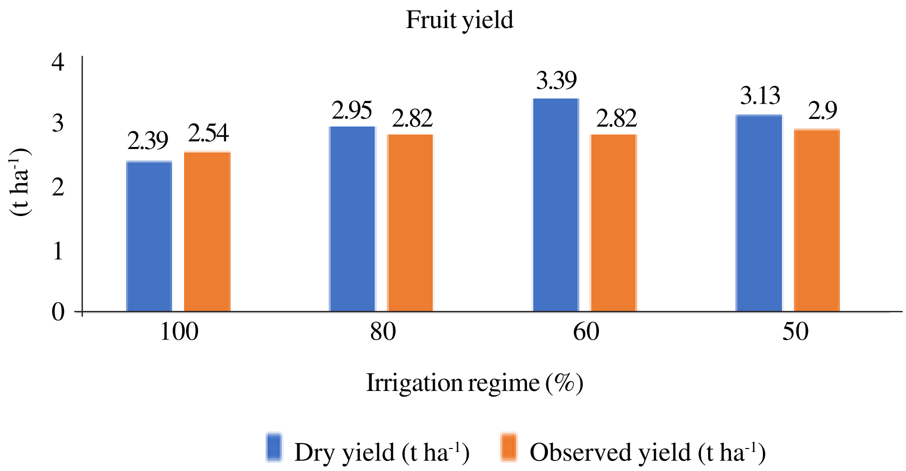

Figure 2. Fruit yield measurements in ton ha^{-1} for all treatments.

Content at 60 and 50% were not good for the model and in this case, modelling is not a substitute for field experiments but rather it is complimentary and hence it is recommended to test the model results by field experiments in the study area so that, one can validate the practical applicability of the study (Table 8). The negative values obtained for canopy cover and the low values for soil water content could have been attributed to, by lack of observed measurements during the experiment.

For fruit yield, large deviations between observed and simulated were seen at high stress levels 50 and 60% (Fig. 2). These results show that AquaCrop adequately predicts fruit yield under varying environmental conditions, although the accuracy of the model declines in severely stressed conditions, confirming

TABLE 6. Aquacrop simulation run of four trials from 2014-2017,assessing the model performance on Deficit Irrigation Practices (50-100)% CWR

Treatment (%)	**100**	95	90	85	**80**	75	70	65	**60**	55	**50**
PWP (kg (yield m^{-3})	**1.43**	1.41	1.39	1.38	**1.37**	1.34	1.27	1.22	**1.19**	1.21	**1.21**
Biomass (t ha^{-1})	**6.78**	7.25	7.53	7.99	**8.03**	8.14	8.16	8.29	**9.35**	8.68	**8.81**
Dry yield (t ha^{-1})	**2.39**	2.57	2.67	2.94	**2.95**	3.01	2.96	2.95	**3.39**	3.09	**3.13**
HI (%)	**35.3**	35.4	35.5	36.7	**36.7**	37.0	36.2	35.6	**36.3**	35.6	**35.6**
Observed yield (t ha^{-1})	**2.54**	**2.82**			**2.82**	**2.90**					

Bold letters stand for the yield obtained from four field treatments defined in relation to 100% ETc

conclusions drawn from (Heng *et al.,* 2009; De Casa *et al.,* 2013).

From the number of deviations observed in the study it shows that there is need for improvement of the model estimation of Water Use Efficiency and Fruit Yield suggesting that AquaCrop only reliably simulates WUE and Yield under well-watered conditions but tend to under-estimate both under levels of high stress.

CONCLUSION

The AquaCrop for tomatoes was able to simulate the dry yield in ton ha^{-1} and water productivity in kg m^{-3} accurately and the biomass in ton ha^{-1} for the local conditions in Zimbabwe, but it must be pointed out that the calibration of AquaCrop suffered from a lack of data from field measurements for Canopy Cover which is an important parameter used in simulation and validation of the model. It is therefore highly recommended that all field measurements be undertaken including Canopy Cover as this will reduce the size of errors in measurements for modelling and farmers are adviced to make use of less water stress situations in modelling if they are to produce an irrigation guideline(for a calendar)as the model prediction is good under non-stressed and moderate stress conditions. Prediction of Soil Water Content, Biomass and Fruit Yield under these conditions was acceptable, as indicated by the high coefficient of determination and deviations at <10%. In severely stressed conditions, low EF and 'd' (Table 7) for Yield indicated a reduction in the model reliabilityand these results related towater stress may provide information to model developers to carry out more simulations during fine tuning to further progress the role of water stress in the modelling of plant development.

Since the AquaCrop has been validated in this study for Soil Water Content, Fruit Yield, Biomass and Canopy Cover bringing out constraints to crop production and water productivity, an irrigation schedule in the form

TABLE 7. Average statistical evaluation of Model simulation @ 60% for soil water content, biomass, fruit yield and canopy cover for all trials

	Soil water content	Biomass	Fruit yield	Canopy cover
RMSE (%)	15.1	15.4	0.34	13.8
CV (RMSE) %	13.4	5.2	0.93	22.0
EF	0.91	0.98	-	0.81
d	0.97	1.00	-	0.9
r	0.95	0.88	0.87	0.99

TABLE 8. Statistical evaluation of model simulation for biomass, soil water content and canopy cover @100%, 80%, 60% and 50% ETc for all trials

	SWC				B				CC			
Percentage	100	80	60	50	100	80	60	50	100	80	60	50
(r	0.95	0.85	0.38	0.52	0.88	0.99	0.91	0.99	0.99	0.99	-0.27	-0.23
(RMSE)	15.1	35.4	99.0	123	15.4	1.26	3.53	0.67	13.8	9.08	8.20	48.7

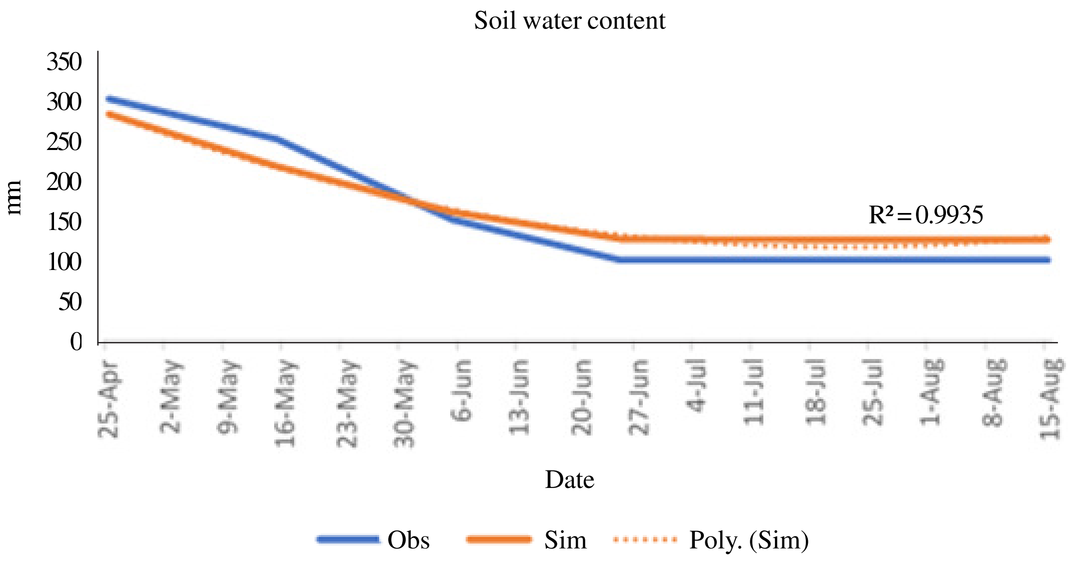

Figure 3. Relation between observed and simulated values of soil water content for the validation dataset.

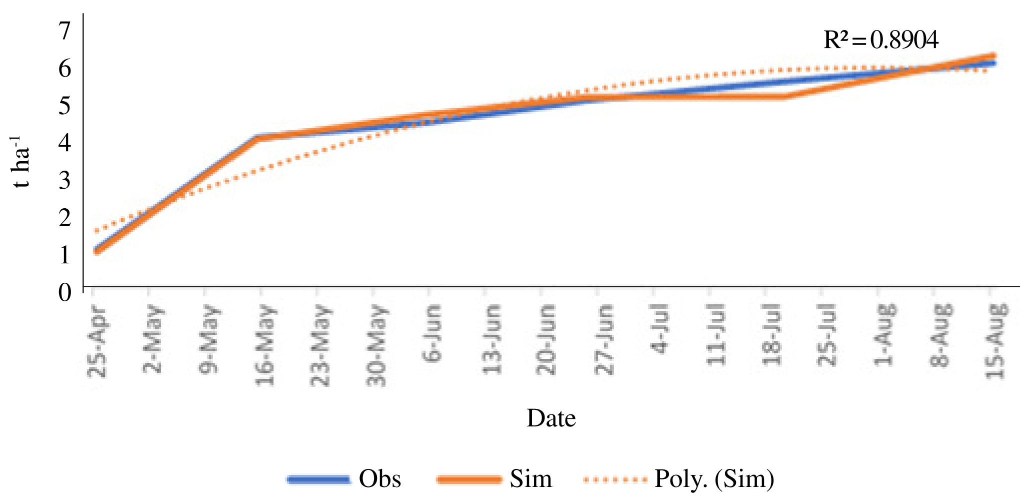

Figure 4. Relation between observed and simulated values of biomass for the validation dataset.

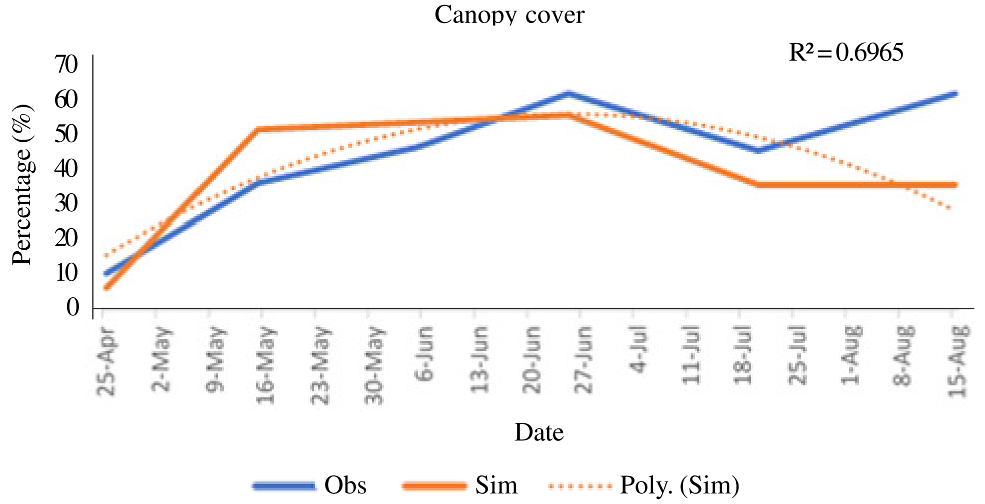

Figure 5. Relation between observed and simulated values of canopy cover for the validation dataset.

of an irrigation calendar can be developed to optimise yield that is produced per unit of water evapotranspired maximising on water productivity. This entails crop production under different water-management conditions (deficit irrigation) and management strategies such as adjustment of planting dates, cultivar selection and fertilisation management under the current scenarios and future climate changes.

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