ASSESSING THE WATER PRODUCTIVITY OF SWEET POTATO (*IPOMOEA BATATAS* (L.) LAM.)

by

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PREFACE

The research contained in this dissertation was completed by the candidate while based in the Discipline of Hydrology, School of Agricultural, Earth and Environmental Sciences of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg Campus, South Africa. The research was financially supported by the Water Research Commission.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

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Signed: Mr RP Kunz

Date: 30 November 2022

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DECLARATION

I, Thando Lwandile Mthembu, declare that:

(i) the research reported in this dissertation, except where otherwise indicated or acknowledged, is my original work;

(ii) this dissertation has not been submitted in full or in part for any degree or examination to any other university;

(iii) this dissertation does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons;

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a) their words have been re-written but the general information attributed to them has been referenced;

b) where their exact words have been used, their writing has been placed inside quotation marks, and referenced;

(v) where I have used material for which publications followed, I have indicated in detail my role in the work;

(vi) this dissertation is primarily a collection of material, prepared by myself, published as journal articles or presented as a poster and oral presentations at conferences. In some cases, additional material has been included;

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Signed: Mr TL Mthembu

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ABSTRACT

In water-stressed countries like South Africa, the reliable quantification of actual crop evapotranspiration (ET_A) and yield across a wide range of environments is important for improved agricultural water management. In addition, researchers are shifting their primary focus from well-studied major crops to neglected and underutilised crops. Orange-fleshed sweet potato (*Ipomoea batatas* (L). Lam.) remains an underutilised root and tuber crop (RTC) in South Africa, despite its potential as being nutrient-dense, high yielding and water use efficient, as reported in local literature. When compared to conventional crops, knowledge is limited on the water use and yield of RTCs under rainfed and precision agricultural production in South Africa. It is therefore important to further investigate whether the water use of orange-fleshed sweet potato (OFSP) will hinder its production at the commercial scale. This study attempted to contribute towards the limited research on the crop water productivity (CWP) of OFSP. A rainfed field trial with optimum fertilisation was conducted at Fountainhill Estate (KwaZulu-Natal, South Africa) to estimate seasonal ET_A, yield and CWP. The soil water balance method was used to determine ET_A accumulated over the growing season from 14 December 2021 to 11 April 2022. Total ET_A for OFSP was estimated at 468.13 mm, which was used to calculate fresh and dry CWP values of 7.45 and 2.59 kg m^{-3}, based on final fresh and dry tuber yields of 34.89 and 12.12 t ha^{-1}, respectively. Harvested tuber and above-ground biomass samples were sent to a laboratory to analyse nutrient content (NC). The nutritional water productivity (NWP) was determined as the product of CWP and NC, highlighting the potential of OFSP to alleviate malnutrition, especially if grown in rural communities. Field observations were used to partially calibrate the Soil Water Balance (SWB) and AquaCrop models. These models were used to simulate ET_A, yield and biomass accumulation, from which CWP and NWP were calculated. Compared to observations, AquaCrop provided a better estimate of CWP (2.55 kg m^{-3}) relative to the SWB model (1.16 kg m^{-3}). However, AquaCrop simulated higher soil water content relative to measurements from volumetric soil water content sensors. This study showed that under suitable management practices, OFSP has the potential to be grown commercially, since the crop can produce high yields and nutrient contents under rainfed agricultural production. However, to improve production, future studies need to conduct research to improve tuber yield and biomass accumulation. Furthermore, the AquaCrop and SWB models should be calibrated and validated across different agroecological zones in South Africa.

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LIST OF ABBREVIATIONS

APSIM	Agricultural Production Systems Simulator
AVE	Average
AWS	Automatic Weather Station
β-c	Beta-carotene
DAFF	Department of Agriculture, Forestry and Fisheries
DAP	Days After Planting
DM	Dry Mass
DSSAT	Decision Support System for Agrotechnology
F1	Full NPK fertiliser application
F2	No NPK fertiliser application
FAO	Food and Agriculture Organisation
FAOSTAT	Food and Agriculture Organisation Corporate Statistical Database
FH	Fountainhill
FM	Fresh Mass
H1	No leaf/vine harvesting
H2	Leaf/vine harvesting
IBSNAT	International Benchmark Sites Network for Agrotechnology Transfer
ICFR	Institute for Commercial Forestry Research
IRGA	InfraRed Gas Analyser
KW	KwaNgwanase
LINTUL	Light Interception and Utilisation
LN	Leaf Number
LT	Leaf Temperature
n.d.	no data
NAMC	National Agricultural Marketing Council
SWB	Soil Water Balance
OFSP	Orange-fleshed sweet potato
PH	Plant Height
REPS	Replications
RTC	Root and tuber crop
SASRI	South African Sugarcane Research Institute
SC	Stomatal Conductance

SD	Standard Deviation
SDG	Sustainable Development Goal
SWB	Soil Water Balance
SWC	Soil Water Content
T_{DRY}	Mostly rainfed with supplemental irrigation treatment
T_{O1W}	Irrigated once in a week treatment
T_{O2W}	Irrigated once every two weeks treatment
T_{T1W}	Irrigated twice in one week treatment
UM	Umbumbulu
W1	Full amount of irrigation (no water stress)
W2	Supplemental irrigation (severe water stress)

LIST OF SYMBOLS WITH UNITS

A	Total cross-sectional area of the column (cm^2)
AGB	Above-ground biomass (kg ha^{-1} or t ha^{-1})
B	Total biomass (t ha^{-1})
CC	Canopy cover (%)
CC_O	Initial canopy cover at emergence (%)
CC_X	Maximum canopy cover percentage (%)
CC_X	Maximum canopy cover reached (%)
CDC	Canopy decline coefficient (% d^{-1})
CGC	Canopy growth coefficient (% d^{-1})
CN	Curve number
CO_2	Atmospheric carbon dioxide concentration (ppmv)
CO_2	Carbon dioxide (ppm)
CWP	Crop water productivity (kg m^{-3})
CWR	Crop water requirement (%)
d	Willmott's d Index
Δ	Slope of the saturation vapour pressure vs air temperature curve (kPa $^{o}C^{-1}$)
ΔSWC	Change in soil water content (mm)
DIFN	Diffuse non-intercepted radiation
Dr	Drainage (mm)
e_A	Actual vapour pressure (kPa)
e_S	Saturated vapor pressure (kPa)
ET	Evapotranspiration (mm)
ET_A	Actual crop evapotranspiration (mm)
ET_O	Reference crop evapotranspiration (mm)
ET_X	Maximum evapotranspiration (mm)
FC	Field capacity (volume %)
G	Soil heat flux density (MJ m^{-2} day^{-1})
γ	Psychrometric constant (kPa $^{o}C^{-1}$)
GDD	Growing degree-days accumulated for month (°C d)
HI	Harvest index (%)
H_I	Total hydraulic head at port I (cm)
H_J	Total hydraulic head at port J (cm)

I	Irrigation (mm)
k	Canopy extinction coefficient for solar radiation (fraction)
K_C	Crop coefficient (fraction)
K_{CB}	Crop transpiration coefficient (fraction)
K_{SAT}	Saturated hydraulic conductivity (mm d^{-1})
K_Y	Proportionality factor describing yield loss due to decreasing evapotranspiration
LAI	Leaf area index (m^2 m^{-2})
L_{IJ}	Length of the soil material between ports I and J (cm)
n	Number of observations
NC	Nutrient content (g kg^{-1})
NSE	Nash-Sutcliffe Efficiency index (fraction)
NWP	Nutritional water productivity (g m^{-3})
P	Precipitation (mm)
PWP	Permanent wilting point (volume %)
Q	Volumetric outflow rate (cm^3 s^{-1})
RAW	Readily available water (mm)
R	Surface runoff (mm)
R^2	Coefficient of determination (fraction or %)
RMSE	Root mean square error (t ha^{-1} or % or m^2 m^{-2})
R_N	Net radiation (MJ m^{-2} day^{-1})
SAT	Soil water content at saturation (volume %)
T	Air temperature (ºC)
TAW	Total available water (mm)
T_B	Base temperature (°C)
T_{MAX}	Maximum temperature (°C)
T_{MIN}	Minimum temperature (°C)
T_{UPPER}	Cut-off temperature (°C)
U	Capillary rise (mm)
u_2	Wind speed at 2 m height (m s^{-1})
Y	Tuber yield (t ha^{-1})
Y_A	Actual yield (t ha^{-1})
Y_T	Total yield (t ha^{-1})
Y_X	Maximum yield (t ha^{-1})

Z_{MAX} Maximum rooting depth (m)

Z_{MIN} Minimum rooting depth (m)

1. INTRODUCTION

1.1 Background

In South Africa, poor households are entirely dependent on government grants to purchase food (Modi and Mabhaudhi, 2020). The cost of a basic food basket in South Africa is approximately R928.11 per month (NAMC, 2021), which most poor households struggle to afford. One possible solution is encouraging these households to produce and consume their food. However, water scarcity in South Africa has negatively impacted the growing population and agricultural production, leading to food and nutrition insecurity (Modi and Mabhaudhi, 2017).

South Africa is projected to become drier due to climate change, and most of the current major crops may not be able to meet future food demands (Modi and Mabhaudhi, 2017). Projections of climate change and increased climatic variability have made it necessary for farmers to explore possible solutions and innovations to conserve as much water as possible, while producing more food (Mabhaudhi, 2012). Drought tolerant and water use efficient crops are considered important "future" crops because of their resilience to drier conditions and ability to produce higher yields under rainfed agriculture, whilst using less water (Chivenge et al., 2015). Such realisations have resulted in hydrology and crop science researchers shifting their focus and interest towards neglected and underutilised indigenous crops that show the potential to efficiently consume water whilst producing sufficient yields (Modi and Mabhaudhi, 2016).

Underutilised root and tuber crops (RTCs) indigenous to South Africa include, *inter alia*, sweet potato, taro and cassava (Modi and Mabhaudhi, 2016). These RTCs symbolise an important component of agrobiodiversity in South Africa (Mabhaudhi et al., 2016). Sweet potato (*Ipomoea batatas* (L.) Lam.) is considered an essential and underutilised RTC (Chivenge et al., 2015). Since sweet potato became indigenised in South Africa, it has been grown mostly in subtropical areas, including parts of KwaZulu-Natal (Laurie, 2010). Although taro (*Colocasia esculenta* (L.) Schott) originated in the Indo-Malay region (Mabhaudhi, 2012), it has become a staple crop in rural households along the coastal regions of KwaZulu-Natal and the Eastern Cape. However, taro is less commonly cultivated in the subtropical regions of the Mpumalanga and Limpopo provinces (Modi and Mabhaudhi, 2016). Cassava (*Manihot esculenta* Crantz) is believed to have originated in South America and was subsequently introduced to parts of southern Africa (Fregene and Puonti-Kaerlas, 2001). Cassava tubers are highly nutritious and parts of the KwaZulu-Natal, Eastern Cape, Limpopo and Mpumalanga provinces are deemed suitable for cassava production (Amelework et al., 2021).

1.2 Rationale and justification

Several RTCs could address food and nutrition insecurity issues in water-scarce environments, as these crops are known to be drought-tolerant and nutrient-dense (Chivenge et al., 2015). Mabhaudhi (2012) reported that some RTCs (e.g. sorghum) have high heat stress and drought tolerances and tend to be well-adapted to lower levels of water use. These characteristics suggest that RTCs may be ideal for production in countries susceptible to high rainfall variability, such as many parts of South Africa (Chivenge et al., 2015). Certain RTCs (e.g. sweet potato) have characteristics that make them suitable for production in marginal production areas and in agricultural systems with low input, which largely represents South Africa's rural landscape (Modi and Mabhaudhi, 2016).

Promoting the increased production of RTCs may address food and nutrition insecurity issues and offer opportunities to form autonomous pathways out of poverty for the rural poor (Mabhaudhi et al., 2016). Promoting-drought tolerant, water use efficient and nutrient-dense RTCs has the potential to address various Sustainable Development Goals (SDGs) (Lundqvist et al., 2021). These include alleviating poverty (SDG 1) and hunger (SDG 2) as well as promoting good health and well-being (SDG 3). RTCs can also help improve economic growth (SDG 8) via increased employment that may result from the expansion of agricultural production.

With sweet potato and taro being regarded as food security crops, promoting these RTCs at a commercial scale may help to improve food and nutrition security in the country and, in turn, alleviate rural poverty and malnutrition (Modi and Mabhaudhi, 2016). However, there is a lack of policy in South Africa to support the agricultural expansion of indigenous RTCs, despite evidence showing their potential in water-scarce environments (Mabhaudhi et al., 2016). This may be due to a lack of sufficient information describing the water use and yield of RTCs, which has hindered their promotion as suitable for commercial-scale production (Mabhaudhi, 2012). Due to the lack of sufficient research on the water requirements and potential yield of sweet potato and taro, these crops are largely grown on a subsistence scale (Sibiya, 2015; Motsa et al., 2015b).

There is a need to determine the water use, yield, water productivity and nutritional water productivity of underutilised and indigenous RTCs, as these crops may form a basis for innovative strategies that will be able to broaden the food basket (i.e. improve diet diversity), thus contributing to improved food security and potentially, the alleviation of malnutrition. The water use, yield and nutritional value of RTCs should be determined using a multi-disciplinary approach involving in-field measurements and simulations using a crop growth model (Modi and Mabhaudhi, 2020). This approach could provide valuable information regarding these crops' water productivity and nutritional water productivity. Such knowledge may help to promote their production at a commercial scale in South Africa.

Through the determination of water use, yield, water productivity and nutritional water productivity of RTCs, this research will contribute to filling existing knowledge gaps required to ascertain whether underutilised RTCs have the potential to be commercially produced under rainfed conditions, in water-scarce areas.

To identify underutilised crops with potential in South Africa, Modi and Mabhaudhi (2016) reviewed literature and focussed on drought and heat stress tolerance as well as nutritional composition. The authors then identified 13 underutilised crops classified as priority drought-tolerant and nutrient-dense crops. Sweet potato and taro were identified as underutilised indigenous RTCs having the greatest potential to exhibit qualities of drought tolerance and being nutrient-dense (Modi and Mabhaudhi, 2016). Based on this, the literature review presented in this study focused on these two RTCs, which were then synthesised to highlight existing knowledge and potential gaps.

Taro landraces have lower water use efficiencies than other RTCs, such as potato (Mabhaudhi, 2012). Masango (2015) and Mulovhedzi (2017) highlighted the potential of orange-fleshed sweet potato (OFSP) to be water use efficient under rainfed agricultural production. However, a knowledge gap regarding the water productivity of OFSP remains due to the limited knowledge about this crop. Therefore, this study focussed on enhancing the existing knowledge base on the water productivity of OFSP.

1.3 Aims and objectives of the study

The main aim of this study was to quantify the yield, water use and nutrient content of sweet potato grown under rainfed conditions, from which the crop and nutritional water productivity were determined. The research questions addressed by this study were as follows:

- What is the water use and yield of rainfed orange-fleshed sweet potato?
- What is the crop and nutritional water productivity of this crop?
- Can the water use, yield and water productivity of this crop be adequately simulated using a crop model?

The specific objectives of this study were to:

- establish a field experiment to quantify the crop's water use and yield,
- measure the nutrient content of harvested material in a laboratory,
- estimate both crop and nutritional water productivity,
- use field observations to partially calibrate two crop models, and
- simulate the crop's water use and yield under rainfed conditions with optimal fertilisation.

This study highlights the limited research available on the water use and yield of sweet potato compared to taro. It also provides additional information needed to enhance the knowledge base of sweet potato production, which may help to promote production at the commercial scale.

1.4 Dissertation outline

This dissertation consists of five chapters which are outlined as follows:

- Chapter 1 provides a general introduction to the study, which outlines the potential of root and tuber crops to alleviate malnutrition and food insecurity in water-scarce areas.
- A review of available literature on the water use, yield and nutritional value of sweet potato and taro is given in Chapter 2, from which knowledge gaps were identified.
- Chapter 3 provides a detailed description of the methodologies used to achieve the aims and objectives of this study.
- In Chapter 4, results related to weather, soil water content, crop health and development, biomass accumulation and tuber yield are presented and discussed. Actual crop evapotranspiration, crop and nutritional water productivity results, as well as the modelling component of this study, are also presented and discussed.

- The final chapter (Chapter 5) provides a synthesis of the approach followed and main findings, thus highlighting the contributions of this research. Recommendations for future research are included in this chapter.

2. REVIEW OF LITERATURE

Growing crops that are considered nutrient-dense and water use efficient can positively contribute towards alleviating malnutrition and reduce the impact of agricultural production on the county's limited water resources (Mabhaudhi et al., 2016). A review of available literature was conducted to determine sweet potato's water use, yield and nutritional value, which was then compared to similar information for taro.

2.1 Environmental conditions suitable for crop growth

2.1.1 Sweet potato

Sweet potato is well suited to subtropical and tropical growing conditions (Dladla et al., 2019), where average night-time temperatures range from 15 to 25°C (Masango, 2015). Although regions, where annual rainfall ranges from 750 to 1000 mm, are most suited to sweet potato, 500 mm is acceptable, provided that all other conditions are optimal (Masango, 2015). An air temperature range from 21 to 29°C is considered optimum for sweet potato growth. Sweet potato can tolerate average temperatures as low and high as 18 and 35°C, respectively (DAFF, 2011). The ability of OFSP to adapt easily to a wide range of ecologies suggests that the crop has the potential to produce high yields (Motsa et al., 2015a). However, this crop can also be produced with low inputs under sub-optimal weather conditions and on marginal soils (Motsa et al., 2015a). According to Dladla et al. (2019), such growing conditions are associated with uneven rainfall distribution, high temperatures and high evapotranspiration rates. Sweet potato is well suited to loamy, sandy and clayey soil textures (Masango, 2015).

2.1.2 Taro

Taro grows optimally in warm conditions where frost occurrence is minimal (Sibiya, 2015). It grows well in areas with 1) elevations ranging from sea level to 1800 m, 2) average temperatures ranging from 21 to 27°C, and 3) annual rainfalls of 800 mm or more (Modi and Mabhaudhi, 2016). Shange (2004) reported that taro could grow in soils ranging from well-drained, aerated soils to soils that experience waterlogging for prolonged periods. However, to ensure maximum growth, the crop prefers sandy loam soils with good drainage and high organic matter content (Shange, 2004).

Due to lowland taro landraces' high soil water requirement (e.g. KwaNgwanase), some farmers grow the crop in waterlogged areas such as marshes and wetlands (Everson and Mengistu, 2011), particularly along the coastal regions of KwaZulu-Natal. Thus, lowland taro landraces are highly tolerant of waterlogging. The crop is also grown in the Limpopo and Mpumalanga provinces, including the Pondoland region of the Eastern Cape. Since lowland landraces are more sensitive to conditions of limited water availability, they should not be considered for low-input farming under rainfed conditions in South Africa.

In contrast, upland (Umbumbulu) taro landraces have a greater degree of stomatal control and, thus, can minimise water loss via transpiration. This means they exhibit higher water productivity compared to the lowland landrace. Hence, this landrace is better suited to water-scarce conditions (Uyeda et al., 2011; Mabhaudhi, 2012), where it can produce sufficient yields and, thus, can positively contribute to food security.

2.2 Crop water use, yield and water productivity

Crop water use is the actual crop evapotranspiration (ET_A) accumulated over the growing season. It is a combination of the evaporation of water from soil and plant surfaces, as well as transpired water (Allen et al., 1998). The latter results in plant growth and leaf cooling (Molden, 1997). Fresh yield is the mass of marketable produce immediately after harvest, while dry yield refers to the remaining mass after drying. Crop water productivity (CWP) is the total production of fresh or dry matter per unit volume of either transpiration or evapotranspiration accumulated over the growing season (Molden, 1997). The harvest index (HI) refers to the ratio of the tuber yield to the total biomass. The latter combines the above-ground biomass (e.g. leaves) and tuber yield (i.e. below-ground biomass).

2.2.1 Sweet potato

Using the soil water balance method, Masango (2015) estimated the water use of rainfed and irrigated sweet potato. Water treatments were as follows: a) mostly rainfed with supplemental irrigation (T_{DRY}); b) irrigation applied once every two weeks (T_{O2W}); c) irrigation applied once a week (T_{O1W}); and d) irrigation applied twice in a week (T_{T1W}). From **Table 2.1**, crop evapotranspiration of the T_{T1W} treatment was 38% greater than that of the T_{DRY} treatment. There was a 7.1% difference in the yield of treatment T_{DRY} and T_{T1W}. Masango (2015) reported that owing to the large differences in the ET_A of sweet potato under the T_{DRY} and T_{T1W} treatments, the same was expected for yield. However, the yield of the two treatments was not significantly different. This is because crop growth and the degree of yield reduction resulting from water deficits depend on various factors, such as the timing and duration of the water deficit (FAO, 2002).

Table 2.1: Yield and water balance components per treatment for sweet potato, from which crop water use (ET_A) and water productivity (CWP) were estimated (Masango, 2015)

Treatments	**P (mm)**	**I (mm)**	**ΔS (mm)**	**ET_A (mm)**	**Yield (dry t ha^{-1})**	**CWP (kg m^{-3})**
T_{DRY}	301	50	-7	298	7.6	2.55
T_{O2W}	-	232	89	321	6.6	2.06
T_{O1W}	-	282	83	365	6.5	1.78
T_{T1W}	-	447	31	478	7.1	1.49

T_{DRY} = rainfed with supplemental irrigation; T_{O2W} = irrigated once every two weeks; T_{O1W} = irrigated once in a week; T_{T1W} = irrigated twice in one week; P = precipitation; I = irrigation; ΔS = change in soil water content

Pandey et al. (2000) reported that CWP increases by improving yield or decreasing ET_A. From **Table 2.1**, CWP was highest under rainfed conditions and decreased with increasing irrigation. Since sweet potato can produce higher yields under water limiting relative to optimum conditions (Motsa et al., 2015b), the yield decreased with increasing irrigation (except for the T_{T1W} water treatment). Therefore, the impact of increased irrigation on yield resulted in a decrease in CWP.

Dladla et al. (2019) studied the water use, yield and CWP of three cultivars of sweet potato under two different agronomic practices (flattened and peaked ridges) at two locations (Umbumbulu and Fountainhill in KwaZulu-Natal, South Africa). Total biomass production comprises the above-ground biomass and tuber yield and at Fountainhill, was 60 to 70% lower than at Umbumbulu (**Table 2.2**). Similarly, fresh tuber yield was higher at Umbumbulu (13.2 to 35.5 t ha^{-1}) than at Fountainhill (7.6 to 17.8 t ha^{-1}). Although yields were lower at Fountainhill, the HI was approximately 30 to 50% higher when compared to Umbumbulu. This suggests that at Umbumbulu, the crop comprised greater above-ground biomass than tuber yield. This can be due to the environment at Umbumbulu favouring vine and leaf growth at the expense of tuber growth. However, it could also be due to tubers at Umbumbulu being harvested before the completion of tuber yield formation.

Table 2.2: Water use and yield components of three sweet potato cultivars (A40, A45 and 199062.1) under two ridge types (peaked and flattened) at Fountainhill (FH) and Umbumbulu (UM) (Dladla et al., 2019)

Site	Ridge type	Cultivar	Total biomass (t ha^{-1})	Fresh yield (t ha^{-1})	ET_A (mm)	CWP (kg m^{-3})	HI (%)
FH	Peak	A40 A45 199062.1	24.7 21.5 20.7	17.8 16.0 13.7	911 1042 660	1.95 1.54 2.08	72.1 74.4 66.2
FH	Flat	A40 A45 199062.1	11.6 12.3 13.1	9.0 7.6 8.0	992 944 1077	0.91 0.81 0.74	77.6 61.8 61.1
UM	Peak	A40 A45 199062.1	77.3 60.1 69.9	35.5 22.5 31.1	532 548 558	6.67 4.11 5.57	45.9 37.4 44.5
UM	Flat	A40 A45 199062.1	61.3 44.0 56.6	22.9 13.2 22.4	655 609 615	3.50 2.17 3.64	37.4 30.0 39.6

Dladla et al. (2019) calculated the water use of sweet potato as a residual of the soil water balance equation (**Table 2.2**). Plants at Fountainhill used approximately 50% more water than at Umbumbulu. The authors indicated that sweet potato at Fountainhill took longer to reach maturity, which may have contributed to its higher water use. Dladla et al. (2019) planted sweet potato in January 2017 and harvested it after 20 weeks (Dladla, 2017). However, using rainfall data from the South African Sugarcane Research Institute (SASRI), the total monthly rainfall from January to May 2017 was 504 mm. This is lower than ET_A values that ranged from 660 to 1077 mm at Fountainhill. Furthermore, daily averaged reference evapotranspiration (ET_O) decreased from 4.1 mm (January) to 1.8 mm (May), from which total ET_O was estimated at 482 mm for the five months. Thus, dryland crop coefficients (ET_A/ET_O) ranged from 1.36 to 2.23, which is incorrect.

For the total biomass at Umbumbulu, ridge types and cultivars and the interaction between the two did not differ significantly. At Fountainhill, there was a significant difference in the total biomass between ridge types, while the interaction between cultivars and ridge types did not differ significantly. Fresh root yield at Fountainhill did not significantly differ between the interaction of ridge types and cultivars. However, it only differed significantly between the ridge types. At Umbumbulu, fresh root yield differed significantly between cultivars but not between the interaction of the cultivars and ridge types.

The higher water use and lower sweet potato yield at Fountainhill resulted in lower CWP estimates (0.74 to 2.08 kg m^{-3}) relative to Umbumbulu (2.17 to 6.67 kg m^{-3}), as shown in **Table 2.2**. Dladla et al. (2019) stated that the results obtained at Umbumbulu were in the same range as those from previously conducted studies (e.g. Önder et al., 2015). From **Table 2.2**, planting sweet potato on ridges maximises biomass production and yield, as ridging allows for root expansion and improved water conservation. Thus, CWP values were lower for flattened ridges due to lower yields when compared to values for peaked ridges. In contrast, Bombik et al. (2013) reported that sweet potato biomass and yield favoured flattened ridges. McNulty and Grace (2009) noted that flattened ridges under sandy soils might prevent soil erosion and promote water conservation.

Table 2.3 shows the dry tuber yield, total biomass (above-ground biomass and tuber yield), ET_A and CWP of OFSP, which were obtained from open-field experiments conducted at Rooiland (Pretoria, South Africa) over the 2013/14 and 2014/15 seasons (Nyathi, 2019). Treatments included the following: full irrigation amount (W1) vs supplemental irrigation (W2); full NPK fertiliser application (F1) vs no NPK fertiliser application (F2); and no leaf/vine harvesting (H1) vs leaf/vine harvesting (H2). As expected, the dry tuber yield was highest for the 2013/14 (10.0 t ha^{-1}) and 2014/15 (17.0 t ha^{-1}) seasons when there were no water and soil fertility stresses, as well as no leaf harvesting (W1F1H1). The opposite treatment, which combined water and soil fertility stresses as well as leaf harvesting (W2F2H2), produced the lowest tuber yields in both seasons. Leaf harvesting can therefore cause substantial reductions in tuber yield production (Nyathi, 2019), possibly due to reduced crop photosynthesis. Although yields were lower due to leaf harvesting, it highlights the ability of OFSP to be a dual-purpose crop.

There were no significant differences between irrigation treatments and soil fertilisation for the harvested above-ground biomass and CWP over both growing seasons. For both seasons, the

ET_A of OFSP was lower under conditions of severe water and soil fertility stress and higher under the non-stressed water and fertility treatments. The stressed treatment combinations with no leaf harvesting produced reasonable amounts of dry total biomass and tuber yield, thus illustrating the capability of OFSP to survive under water-stressed conditions. ET_A values were higher during the second (2014/15) relative to the first (2013/14) season (**Table 2.3**), which could be attributed to the length of the growing period (150 vs 130 days, respectively).

Table 2.3: Dry tuber yield, total biomass, ET_A and CWP of orange-fleshed sweet potato (Nyathi, 2019)

Season	Treatments	Total biomass (t ha^{-1})	Tuber yield (t ha^{-1})	ET_A (mm)	CWP (dry kg m^{-3})
2013/14	W1F1H1	13.0	10.0	491	2.04
	W1F1H2	10.0	5.7	427	1.33
	W1F2H1	10.0	8.1	460	1.76
	W1F2H2	8.8	4.7	446	1.05
	W2F1H1	8.2	5.8	244	2.38
	W2F1H2	8.7	5.8	257	2.26
	W2F2H1	7.1	5.9	218	2.71
	W2F2H2	7.4	4.4	231	1.90
2014/15	W1F1H1	20.0	17.0	658	2.58
	W1F1H2	14.0	11.0	629	1.75
	W1F2H1	13.0	11.0	595	1.85
	W1F2H2	10.0	7.1	592	1.20
	W2F1H1	15.0	13.0	467	2.78
	W2F1H2	14.0	11.0	462	2.38
	W2F2H1	8.2	6.5	447	1.45
	W2F2H2	7.7	5.2	439	1.18

W1 = full irrigation amount (no water stress); W2 = supplemental irrigation (water stress); F1 = full fertiliser application; F2 = no fertiliser application; H1 = no leaf/vine harvesting; H2 = leaf/vine harvesting

The CWP of OFSP tubers from the open-field experiments ranged from 1.05 to 2.71 dry kg m^{-3} and 1.18 to 2.78 dry kg m^{-3} for the 2013/14 and 2014/15 seasons, respectively (**Table 2.3**). The water-stressed with no leaf harvesting treatment (W2F2H1 and W2F1H1) resulted in the highest exhibited CWP of 2.71 and 2.78 dry kg m^{-3}, respectively. This is supported by Motsa et al. (2015b), who noted that sweet potato could produce high yields and, thus, exhibit higher CWP values under water-stressed conditions. This shows that OFSP has the potential to be grown by rural-poor households under low agricultural input where crops are mostly rainfed.

2.2.2 Taro

Mabhaudhi (2012) investigated the evapotranspiration (ET_A) and yield of two taro landraces grown over two seasons and found that with decreasing water application rates (100, 60 and 30% of crop water requirement or CWR), the final biomass of taro decreased. The upland Umbumbulu (UM) landrace, which is more adapted to water-limited conditions, produced a final biomass that was higher than the KwaNgwanase (KW) landrace under all the irrigation treatments (**Table 2.4**). Hence, the KW landrace was negatively affected by water-limited conditions. The UM landrace has good stomatal control, enabling it to minimise water loss through transpiration and thus, produces more biomass and a higher yield than the KW landrace (Mabhaudhi, 2012). The final biomass for both taro landraces was significantly different between the growing seasons. Furthermore, results of final biomass were also significantly different between irrigation regimes and landraces.

Table 2.4: Yield, yield components (biomass, corm number and corm mass) and CWP of two taro landraces (KW=KwaNgwanase; UM=Umbumbulu) grown under a rainshelter at three irrigation levels (30, 60 and 100% of CWR) during the 2010/11 and 2011/12 seasons (Mabhaudhi, 2012)

Season	% of CWR	Land-race	Per plant			Fresh yield ($t\ ha^{-1}$)	Harvest index (%)	CWP ($kg\ m^{-3}$)
			Biomass (kg)	Corm number	Corm mass (kg)			
2010/11	30	UM	0.248	9.06	0.220	6.10	87	0.15
		KW	0.183	3.88	0.156	4.32	86	0.11
	60	UM	0.370	8.11	0.336	9.31	90	0.17
		KW	0.164	6.20	0.138	3.83	86	0.07
	100	UM	0.377	9.06	0.324	9.00	85	0.12
		KW	0.227	3.46	0.152	4.23	57	0.06
2011/12	30	UM	0.886	16.56	0.457	12.96	62	0.53
		KW	0.288	2.44	0.205	5.70	71	0.17
	60	UM	1.086	22.56	0.804	22.32	74	0.49
		KW	0.478	3.28	0.386	10.70	82	0.22
	100	UM	1.368	21.78	0.861	23.90	63	0.44
		KW	0.822	4.28	0.625	17.33	79	0.27

Mabhaudhi (2012) also found that the irrigation treatments impacted the final yield, which was lower at reduced water application rates. Compared to the fully irrigated treatment (i.e. 100% of CWR), tuber yield was 15% and 47% lower at 60% and 30% of CWR, respectively. Furthermore, high corm numbers per plant did not translate to high yields, suggesting that under conditions of limited water availability, corm mass (not corm number) is more important (Mabhaudhi, 2012). The reduction of yield due to limited water availability is caused by reductions in canopy growth and production of biomass (Badr et al., 2012). More importantly, Mabhaudhi (2012) found that during the 2011/12 growing season, for the UM landrace with the lowest treatment (**Table 2.4**), the yield was higher than the global average yield estimate of 6.5 t ha^{-1} (FAOSTAT, 2012).

With regards to the CWP, significant differences were observed between both seasons. However, no significant differences in the CWP were observed between the irrigation treatments. The UM and KW taro landraces had an average CWP of 0.32 and 0.15 kg m^{-3}, respectively. The reason why the UM landrace was approximately twice more water use efficient than the KW landrace is supported by Uyeda et al. (2011), who reported that upland taro landraces are more water use efficient than lowland varieties, which are more suited to waterlogged conditions. However, Everson and Mengistu (2011) found that taro grown in a *Cyperus latifolius* marsh, where water availability is non-limiting to growth, did not necessarily mean high evapotranspiration rates. They calculated the crop coefficient (K_C) as the ratio of measured ET (using an eddy covariance system) and reference crop evapotranspiration (ET_O). Daily K_C values (4 in November 2009 and 6 in January 2010) varied between 0.46 and 0.81, suggesting that taro was relatively conservative in terms of water use (Everson and Mengistu, 2011).

2.3 Nutrient content

2.3.1 Sweet potato

Sweet potato is regarded as one of the most drought-tolerant crops that can also supply substantial vitamin and mineral amounts (Leighton, 2008). Sweet potato provides adequate amounts of starch and protein and is nutrient-dense as the tubers and leaves also contain nearly all nutrients (both macro and micro), substantial amounts of vitamin C, fair amounts of vitamin B complex and folic acid (Mabhaudhi et al., 2019).

According to Labadarios et al. (2005), vitamin A deficiency in South Africa remains a health issue for growing children and teenage women. OFSP cultivars are good sources of natural β-carotene (Van Jaarsveld et al., 2006), a precursor of vitamin A. The consumption of boiled OFSP varieties can improve the status of vitamin A in children (Low et al., 2017). These varieties should therefore be promoted in developing countries (Wenhold et al., 2007). Thus, the South African Medical Research Council and the Agricultural Research Council now promote the production of foods rich in natural β-carotene (Masango, 2015).

Table 2.5 presents the nutrient content (NC) for Fe, Zn and β-carotene of OFSP tubers expressed on a dry mass basis, as measured by Nyathi (2019) for the 2013/14 and 2014/15 seasons. The OFSP tubers are rich in β-carotene with mean values of 2250 and 1980 mg kg^{-1} for the non-harvested (H1) and harvested (H2) leaves, respectively. For the H1 treatment, the mean β-carotene content for the fully irrigated (W1) treatment was 2155 mg kg^{-1}, which increased to 2342 mg kg^{-1} under the supplemental irrigation (W2) treatment. Similarly, for the H2 treatments, the mean β-carotene content was 1855 mg kg^{-1} (W1 treatment), which increased to 2108 mg kg^{-1} (W2 treatment). Hence, β-carotene was higher under water stressed conditions, irrespective of leaf harvesting. This highlights the ability of OFSP tubers produced under rainfed conditions (with supplemental irrigation) to positively contribute to alleviating deficiencies in β-carotene. For the water and soil fertility stress (W2F2) treatment, tuber contents of Fe and Zn were higher when leaves were not harvested compared to when there was leaf harvesting. This suggests that under low agricultural input, Fe and Zn content in OFSP tubers can be maximised, provided there is no leaf/vine harvesting. Nyathi (2019) stated that leaf/vine harvesting should not be considered for market-oriented farming due to the high potential of reduced yields and nutritional concentrations of Fe, Zn and β-carotene.

Table 2.5: Nutritional content (Fe, Zn and β-carotene in mg kg^{-1}) of OFSP tubers obtained for the 2013/14 and 2014/15 growing seasons (Nyathi, 2019)

Treatments		Fe	Zn	β-carotene
H1	**W1F1S1**	39	17	2350
	W1F1S2	45	13	2210
	W1F2S1	51	14	1850
	W1F2S2	70	11	2210
	W2F1S1	29	14	1820
	W2F1S2	87	12	2480
	W2F2S1	38	17	2140
	W2F2S2	112	13	2930
	Mean	**60**	**14**	**2250**
H2	**W1F1S1**	46	16	2140
	W1F1S2	35	9	1730
	W1F2S1	48	16	1820
	W1F2S2	70	10	1730
	W2F1S1	43	13	2030
	W2F1S2	62	10	2180
	W2F2S1	27	14	1930
	W2F2S2	38	11	2290
	Mean	**46**	**12**	**1980**

W1 = full irrigation amount (no water stress); W2 = supplemental irrigation (severe water stress); F1 = full fertiliser application; F2 = no fertiliser application; H1 = no leaf/vine harvesting; H2 = leaf/vine harvesting; S1 = 2013/14; S2 = 2014/15

Table 2.6 provides the NC of sweet potato cultivars grown under optimum and water-limited conditions (Mabhaudhi et al., 2019). The A45 and 199062.1 cultivars exhibited the highest and lowest energy contents for the water-limiting treatment, respectively. Mabhaudhi et al. (2019) reported that in some instances, the protein content of sweet potato cultivars increases with increasing water use. This is because the highest protein content in the A40 (75.1 g kg^{-1}) and A45 (61.8 g kg^{-1}) cultivars, was observed under the fully irrigated treatment. From the 30% to the 100% water treatment, the NC of Ca, Mg and Na in all the cultivars (except the 199062.1 cultivar for Mg and Na) increased. β-carotene was higher under the 30% of CWR treatment for all cultivars. This shows that sweet potato cultivars can produce high amounts of β-carotene under water-limiting conditions. This further supports the study conducted by Masango (2015). The β-carotene content of the orange-fleshed varieties (A45 and 199062.1) for both water treatments was considerably higher than that for the white-fleshed (A40) cultivar. Thus, the cultivation of OFSP varieties should be promoted rather than white-fleshed varieties. The β-carotene content of OFSP tubers shown in **Table 2.6** was substantially lower than that obtained by Nyathi (2019) (cf. **Table 2.5**), which cannot be explained (i.e. unlikely due to cultivar differences alone).

Table 2.6: Nutritional value of three sweet potato cultivars under two water treatments (Mabhaudhi et al., 2019)

Water treatment	Cultivar	Nutritional content								
		(MJ kg^{-1})	(g kg^{-1})		(mg kg^{-1})					
		Ene	**Fat**	**Pro**	**Ca**	**Mg**	**Na**	**Zn**	**Fe**	**B-c**
100% of CWR	A40	574	7.3	75.1	5.3	1.3	2.1	9.0	399	2
	A45	448	9.1	61.8	2.4	0.7	2.4	15.4	622	198
	199062.1	489	14.3	43.0	4.8	0.9	0.8	13.4	529	53
30% of CWR	A40	555	7.5	53.6	5.1	1.2	1.0	16.8	868	29
	A45	584	9.4	38.9	1.3	0.6	1.0	11.0	269	232
	199062.1	471	1.4	53.8	4.6	1.0	1.1	14.4	428	101

Ene = Energy; Pro = Protein; B-c = β-carotene

2.3.2 Taro

The high nutritional value of taro is one of the main reasons for promoting its commercial-scale production. Mabhaudhi et al. (2016) stated that taro leaves are 1) high in minerals (e.g. Na, Zn and Fe) and vitamins (e.g. A, B and C), and 2) suitable for human consumption. Vitamin B and C complexes (niacin, thiamine and riboflavin) found in taro leaves and corms are essential for a healthy diet. The starch contained in the corms is generally high and highly digestible. Therefore, taro may be consumed as a source of carbohydrates and protein (Mabhaudhi et al., 2016). Taro’s high potassium-to-food ratio is recommended for people with high blood pressure (Modi and Mabhaudhi, 2016) and can potentially reduce high cholesterol levels.

Table 2.7 provides the mineral composition of taro tubers, which varies under water-limited (30% of CWR) and fully irrigated (100% of CWR) conditions. For example, Na, Fe, Al and Mn decreased by 38.2, 45.0, 37.3 and 21.0% when fully irrigated, whereas Cu increased by 29.0%, respectively. Since Na, Fe, Al and Mn contents were higher under water-limited conditions (**Table 2.7**), this supports the finding by Chivenge et al. (2015) that certain nutrient-dense RTCs can address nutrition insecurity issues in environments that are water scarce. However, since Cu levels were higher under irrigated conditions, this highlights the positive effects of relieving water stress on nutrient content.

Table 2.7: Average nutritional content of taro tubers (UM landrace) under two water treatments (Shelembe, 2020)

Crop water requirement (% of CWR)	Nutritional content (mg kg^{-1})				
	Na	Fe	Al	Mn	Cu
30	371.77	83.27	62.93	7.84	3.56
100	229.91	45.77	39.48	6.19	4.59

2.4 Nutritional water productivity

Nutritional water productivity (NWP) measures the nutrient content per unit of water consumed by a crop (Renault and Wallender, 2000). Promoting the production of crops high in nutrients per unit of water consumed may help to alleviate malnutrition in poor rural areas (Renault and Wallender, 2000), particularly in rural and water-scarce areas (Masango, 2015).

2.4.1 Sweet potato

Masango (2015) investigated the response of OFSP tubers under various irrigation treatments. From **Table 2.8**, sweet potato grown mainly under rainfed conditions (with only supplemental irrigation; T_{DRY}) exhibited the highest NWP for β-carotene (1177 mg m^{-3}). This further highlights the water use efficient and nutritious benefits of OFSP.

Table 2.8: Nutritional water productivity values of the β-carotene (NWP_{BC}) of orange fleshed sweet potato (Masango, 2015)

Treatment	NWP_{BC} (mg m^{-3})
T_{T1W}	656
T_{O1W}	718
T_{O2W}	796
T_{DRY}	1177

T_{DRY} = mostly rainfed with supplemental irrigation; T_{O2W} = irrigated once every two weeks; T_{O1W} = irrigated once in a week; T_{T1W} = irrigated twice in one week

Mulovhedzi (2017) estimated the NWP for OFSP and white-fleshed sweet potato (WFSP) under full irrigation (FI), supplemental irrigation (SI) and rainfed (RF) treatments (**Table 2.9**). For both the OFSP and WFSP, the NWP for β-carotene was higher under the RF relative to the FI and SI treatments. This further highlights the ability of sweet potato to exhibit high β-carotene contents in a water use efficient manner. OFSP exhibited substantially higher NWP values for all treatments for β-carotene relative to the WFSP. The WFSP exhibited higher NWP values for Fe (13.9 to 19.0 mg m^{-3}) and Zn (7.6 to 12.0 mg m^{-3}) relative to those of OFSP, which ranged from 11.7 to 14.5 mg m^{-3} and 6.4 to 7.0 mg m^{-3}, respectively. Ultimately, white- and orange-fleshed sweet potato varieties can contribute to malnutrition alleviation. However, OFSP has a greater potential to exhibit considerably higher β-carotene contents, especially under rainfed conditions.

Table 2.9: Nutritional water productivity of orange- and white-fleshed sweet potato under three water treatments (Mulovhedzi, 2017)

Variety	Treatments	Nutritional water productivity mg m^{-3}		
		Fe	Zn	β-carotene
OFSP	FI	14.5	7.0	95.9
	SI	12.6	6.7	93.9
	RF	11.7	6.4	108.5
WFSP	FI	16.5	7.6	11.4
	SI	13.9	7.6	18.6
	RF	19.0	12.0	22.2

FI = full irrigation; SI = supplemental irrigation; RF = rainfed

Mabhaudhi et al. (2019) estimated the NWP of orange- (A45 and 199062.1) and white-fleshed (A40) sweet potato cultivars under water-limited conditions and found that it was higher relative to optimum conditions (**Table 2.10**). They showed that NWP for energy and fat content was highest for the 199062.1 cultivar under both water treatments. The NWP increased from the non-stressed (100% of CWR) to the water-stressed (30% of CWR) treatment for all cultivars. When comparing the orange-fleshed 199062.1 to the white-fleshed A40 cultivar under the 30% CWR treatment, except for Fe, all NWP values for the A40 cultivar were lower than those of the 199062.1 cultivar. Under water-limiting conditions, the β-carotene content of the 199062.1 cultivar was 527% higher than the A40 cultivar. Therefore, OFSP can be considered a staple crop for dwellers in rural and water-scarce areas as the crop shows great potential for exhibiting high nutrient contents while efficiently consuming water. For at least one of the cultivars, the change in the NWP from 30 to 100% of CWR was statistically different (Mabhaudhi et al., 2019).

Table 2.10: Nutritional water productivity of three sweet potato cultivars under two water treatments (Mabhaudhi et al., 2019)

Water treat-ment	Culti-var	Nutritional water productivity								
		(MJ m^{-3})	(g m^{-3})		(mg m^{-3})					
		Ene	**Pro**	**Fat**	**Fe**	**β-c**	**Zn**	**Ca**	**Na**	**Mg**
100% of CWR	A40	2700	354	34	1877	9	42	25.4	9.88	5.58
	A45	2122	295	43	2968	945	72	11.9	11.45	3.82
	199062.1	4004	352	117	4325	433	106	62.8	7.36	7.36
30% of CWR	A40	5740	555	77	8968	300	176	52.7	10.33	12.40
	A45	7500	499	121	3464	2976	141	16.7	14.11	7.70
	199062.1	8783	1405	268	7978	1881	261	85.7	22.47	18.64

Ene = Energy; Pro = Protein; β-c = β-carotene

Lundqvist et al. (2021) estimated NWP of the calorific, mineral and vitamin content of sweet potato grown across three seasons (2015 to 2018) in Ethiopia under two treatments (lowest and highest ET_A). **Table 2.11** and **Table 2.12** showed that the NWP of minerals and vitamins was substantially higher under the lowest water treatment. The same trend was shown by Masango (2015) and Mabhaudhi et al. (2019). These results again show that sweet potato has the potential to produce a higher amount of nutrients per unit of water consumed under water-stressed conditions. Thus, this crop has the potential to sustain poor rural households located in marginal areas, as OFSP produces not only relatively high yields (Motsa et al., 2015b; Masango, 2015) but also a high amount of nutrients, whilst efficiently using water.

Table 2.11: Nutritional water productivity (NWP) of calorific and mineral content values for sweet potato grown in Ethiopia under minimum and maximum crop evapotranspiration (ET_A) conditions (Lundqvist et al., 2021)

Nutritional water productivity of minerals													
	kcal m^{-3}	g m^{-3}	mg m^{-3}			mg m^{-3}							
Water use	Ene	Car	Fat	Pro	Fib	K	Ca	P	Mg	Na	Fe	Zn	Cu
Lowest ET_A	11779.0	2442.4	173.2	112.6	95.3	21739.1	4503.7	2944.7	2165.3	606.3	294.5	26.0	17.3
Highest ET_A	7538.5	1563.1	110.9	72.1	61.0	13913.0	2882.4	1884.6	1385.8	388.0	188.5	16.6	11.1

Ene = Energy; Car = Carbohydrates (incl. fiber); Pro = Protein; Fib = Fiber

Table 2.12: Nutritional water productivity (NWP) of vitamins provided by sweet potato grown in Ethiopia under minimum and maximum crop evapotranspiration (ET_A) conditions (Lundqvist et al., 2021)

Nutritional water productivity of vitamins									
	µg m^{-3}	mg m^{-3}					µg m^{-3}	mg m^{-3}	µg m^{-3}
Water use	β-c	Thi	Rib	Nia	Vit C	Vit B6	Fol	Vit E	Vit K
Lowest ET_A	0.0	6.9	4.3	77.9	207.9	18.1	952.7	25.1	155.9
Highest ET_A	0.0	4.4	2.8	49.9	133.0	11.6	609.7	16.1	99.8

β-c = Beta-carotene; Thi = Thiamine; Rib = Riboflavin; Nia = Niacin; Vit = Vitamin; Fol = Folate

2.4.2 Taro

The NWP reported by Shelembe (2020) for taro is presented in **Table 2.13**. All nutrients had higher NWP values under water-stressed (30% of CWR) compared to well-watered (100% of CWR) conditions. This supports Mabhaudhi's (2012) statement that certain RTCs are drought-tolerant and well-adapted to low levels of water use. This shows that taro (UM landrace) cultivation under rainfed agriculture has the potential to contribute positively to malnutrition alleviation.

Table 2.13: Nutritional water productivity values for upland (Umbumbulu) taro landrace (Shelembe, 2020)

	Nutritional water productivity (mg m^{-3})				
% of CWR	**Na**	**Fe**	**Al**	**Mn**	**Cu**
30	2889.41	643.33	486.45	58.90	27.73
100	1487.33	269.29	255.87	39.33	29.79

2.5 Crop simulation models

Crop modelling is the simulation of crop development by numerically integrating constituent processes using various computer programs (Sinclair and Seligman, 1996). Crop models are important as they can be used as tools for decision making, yield forecasting and assessing climate change impacts (Mabhaudhi, 2012). The modelling of water use and growth of root and tuber crops has not been given the same attention in model development, improvement and testing as that for other conventional crops (Mabhaudhi et al., 2020). An overview of crop simulation models used for simulating growth and yield of certain root and tuber crops is provided next.

2.5.1 Soil Water Balance

The Soil Water Balance (SWB) model is a user-friendly, real-time, generic crop growth and irrigation scheduling model (Annandale et al., 1999; Annandale et al., 2000; Jovanovic and Annandale, 2000). The model simulates the soil water balance using soil, crop and weather management data (Jovanovic and Annandale, 2000). The SWB model describes crop development using thermal time and therefore, eliminates the need to use various crop factors for various regions and planting dates (Jovanovic and Annandale, 2000).

The model divides the soil profile into eleven layers, each with its physical attributes and soil depth. The model simulates leaf area, which is then used to calculate the fraction of radiation intercepted by the canopy. Potential evapotranspiration is split into transpiration and soil water evaporation, with the latter only occurring from the topsoil layer. The model uses the curve number method to calculate runoff. Once interception of rainfall by the canopy and runoff losses have been accounted for, the soil water balance is then calculated (Jovanovic and Annandale, 2000). Drainage occurs when the soil layer's water content exceeds field capacity, which is dependent on a drainage factor, i.e., a soil-specific parameter provided by the user.

The relationship between dry matter production and crop transition (from one growth stage to another) requires a correction to account for environmental conditions such as the vapour pressure deficit (Tanner and Sinclair, 1983). Dry matter production is accumulated daily, which is limited either by transpiration or by radiation (Fessehazion et al., 2014). Calculated dry matter accumulation is then partitioned into roots, stems, leaves and grain (Annandale et al., 1999). Partitioning is dependent on crop phenology and yield, which are calculated as functions of water stress and thermal time (Fessehazion et al., 2014). The model does not account for the presence of insects or weeds (Jovanovic and Annandale, 2000).

2.5.2 AquaCrop

Steduto et al. (2012) described AquaCrop as a water-driven, canopy-level model developed by the Food and Agriculture Organisation (FAO), that simulates crop biomass and yield in response to water availability under dryland and irrigated agriculture. AquaCrop evolved from the CropWat model, which is described in FAO's Irrigation and Drainage Paper No. 33 (Doorenbos and Kassam, 1979). However, improvements in accuracy were made whilst retaining the model's overall robustness and simplicity (Mabhaudhi, 2012). Both AquaCrop and CropWat are based on the following equation:

$$\left(\frac{Y_X - Y_A}{Y_X}\right) = K_Y \left(\frac{ET_X - ET_A}{ET_X}\right) \qquad \textbf{Equation 1}$$

where Y_X is maximum yield, Y_A is actual yield, ET_X is maximum evapotranspiration, ET_A is actual evapotranspiration and K_Y is a proportionality factor describing yield loss due to decreasing evapotranspiration.

AquaCrop is applicable across a wide spectrum of crop production systems (Steduto et al., 2012). Under moderate water stress conditions, the model performs fairly well relative to severe water stress conditions (Heng et al., 2009; Battisti et al., 2017). The model also uses the soil water balance method to simulate crop water use (FAO, 2017a). Under the model's management component, it accounts for irrigation, soil fertility and the presence of weeds (Mabhaudhi, 2012). However, biotic factors including pests and diseases are not considered by AquaCrop (Steduto et al., 2009). Unlike the SWB model, AquaCrop does not account for interception loss (Steduto et al., 2012). This suggests that the model would struggle to adequately simulate water use and yield of crops with high leaf area indices.

2.5.3 APSIM

The Agricultural Production Systems Simulator (APSIM) model operates on a daily time-step and simulates cropping systems by combining biophysical and management modules within a central engine (Keating et al., 2003; Mabhaudhi et al., 2020). The model uses radiation use efficiency to calculate potential biomass production, which is constrained by climate and available leaf area. Keating et al. (2003) stated that soil water, nitrogen and phosphorus availability can limit potential production simulated by the model. The model can simulate the interaction of soil water, carbon, nitrogen and phosphorus within cropping systems, driven by daily climate data such as solar radiation, rainfall and air temperature (both minimum and maximum).

APSIM can be used as a tool to provide accurate simulations of crop production related to climate, genotype, soil and farmer management factors (Keating et al., 2003). The advantage of this model is that it can incorporate models formed in various fragmented research projects (Mabhaudhi et al., 2020). This makes the model capable of enabling research from a particular discipline to contribute positively to another.

APSIM is dynamic and customisable to accommodate various simulations for different users (McCown et al., 1996). For example, a simulation of residue dynamics in wheat systems can incorporate modules describing soil nitrogen, soil water, surface organic matter and management. Furthermore, a study of water productivity in irrigated rice systems can include modules describing soil water and nitrogen. Instead of incorporating a surface organic matter module, the model can include modules deemed more appropriate for simulating irrigation and the effects of management (Mabhaudhi et al., 2020).

2.5.4 DSSAT

The Decision Support System for Agrotechnology (DSSAT) was formed by international scientists as part of the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) project (Singels et al., 2010). The initial development of the DSSAT model was aimed at making improved decisions by integrating information about soil, climate, crops and management (Singels et al., 2010). DSSAT has evolved into a collection of independent programs operating together. Hence, the DSSAT suite houses various crop simulation models (Jones et al., 2003), such as CERES Maize (Jones and Kiniry, 1986), CROPGRO (Boote et al., 2002) and CANEGRO (Singels et al., 2008).

2.5.5 LINTUL

The Light Interception and Utilisation (LINTUL) crop growth model can provide reliable crop growth simulations under potential and water-limited conditions (Mabhaudhi et al., 2020). The main processes simulated by LINTUL include photosynthesis, phenology, assimilate distribution over crop organs, evapotranspiration and a soil water balance (Splitters and Schapendonk, 1990). The model uses the incoming solar radiation intercepted by the crop canopy and light use efficiency to calculate photosynthesis. Originally, the model assumed that nutrient supply and crop management were optimal. More recently, LINTUL has been further updated to provide simulations of water and nitrogen-limited conditions (Mabhaudhi et al., 2020).

LINTUL-POTATO was developed for use in ideotyping and agro-zoning to describe dry matter production and its distribution for potatoes grown under field conditions, which varies according to photoperiod and air temperature (Haverkort and Kooman, 1997). The model prioritises temperature-dependent crop development to provide simulations of dry matter allocations to plant organs (Mabhaudhi et al., 2020). Modifications to the original LINTUL model were also done to include various development and growth phases of cassava under water-limited (i.e. rainfed) conditions.

2.6 Discussion and conclusions

The CWP metric measures how efficiently a plant utilises water and converts it into yield (Masango, 2015). Modi and Mabhaudhi (2020) stated that the main aim of crop production is to produce “more crop” while using water efficiently. To help provide sufficient food for the growing population, areas should be expanded under irrigation, which could lead to further depletion of available water resources (Modi and Mabhaudhi, 2016). Thus, it is crucial to improve water productivity within existing rainfed agricultural systems (Renault and Wallender, 2000).

Compared to staple food crops such as maize and soybean, RTCs exhibit resilience under water stressed conditions and can produce higher yields using less water. Both sweet potato and taro are regarded as dual-purpose crops, as both their leaves and tubers can be consumed. Although sweet potato leaves can be harvested during the growing season, this reduces tuber yield (Islam, 2006; Nyathi, 2019). However, Nyathi (2019) found that the β-carotene content increased under water-stressed conditions, irrespective of leaf harvesting.

Sweet potato is known for its low water use under rainfed conditions (Masango, 2015) and, thus, is considered water use efficient with a moderate to high NWP (Masango, 2015; Mabhaudhi et al., 2019). This highlights the crop's ability to respond well to soil water deficits. Masango (2015), Mulovhedzi (2017) and Mabhaudhi et al. (2019) reported that sweet potato exhibits high NC and CWP values, which translates to high NWP values under water limiting relative to optimum conditions. This highlights sweet potato's drought tolerance and high yielding potential under low input, rainfed agriculture. OFSP tubers and leaves exhibit substantially higher β-carotene than other indigenous root and tuber crops (e.g. taro). Therefore, this study sought to enhance the existing knowledge base pertaining to the cultivation of OFSP as this RTC has the potential to contribute to the alleviation of vitamin A deficiencies in a water use efficient manner.

Taro landraces have a low CWP compared to that of other RTCs, such as potato (Uyeda et al., 2011; Badr et al., 2012; Mabhaudhi, 2012;). Mabhaudhi (2012) showed that decreasing the applied irrigation amount did not substantially increase taro's CWP. Furthermore, Mabhaudhi (2012) reported that taro yields are negatively affected by decreasing water application rates, due to lower biomass production. Hence, reducing the amount of applied irrigation was ineffective in substantially increasing taro's CWP. According to Badr et al. (2012), certain RTC landraces struggle under water-limited conditions due to a lack of defensive mechanisms that enable the crop to consume water while maintaining canopy expansion and biomass production efficiently. The final biomass of taro landraces is likely to decrease under rainfed agricultural production, where prolonged periods of water stress are likely to occur. However, upland landraces exhibit better stomatal control and, thus, are more water use efficient when compared to lowland landraces.

From the literature review, more information exists for sweet potato when compared to taro. Due to sweet potato’s high drought tolerance (Motsa et al., 2015b), the crop can adapt to a wide range of agroecologies and thus, has the potential to produce high yields under water-stressed conditions (Motsa et al., 2015a). Sweet potato, therefore, exhibits a higher crop and nutritional water productivity when compared to taro. However, information regarding the water use, yield, CWP and NWP of OFSP remains insufficient to form reliable conclusions. Results from different studies are also inconsistent and contradictory. Nyathi (2019) highlighted the importance of future research assessing NWP across agroecologies. To address these knowledge gaps, the water use and yield of OFSP were measured under rainfed conditions, along with the nutrient contents of leaves and tubers, from which information on CWP and NWP was gleaned.

There is limited research related to modelling crops such as sweet potato, taro, tannia and yam (Mabhaudhi et al., 2020). This lack of knowledge may be a bottleneck to the mainstreaming of these crops into existing production systems within South Africa. Therefore, a modelling component involving two crop simulation models was included in this study to enhance the existing knowledge base on OFSP.

3. MATERIALS AND METHODS

This chapter highlights the various approaches taken to achieve the aims and objectives of the study. The information provided in this chapter includes the following: a description of the experimental site and planting material; agronomic practices conducted at the experimental site; a collection of data related to weather, crop water use, growth and final yield over the growing season; and the determination of CWP and NWP, with the latter requiring laboratory analysis of nutrient content. The final section describes the crop modelling component of this study, which utilised the field measurements.

3.1 Site description

A field experiment was conducted from December 2021 to April 2022 at Fountainhill Estate (29°27'08''S; 30°32'38''E; elevation 853 m a.s.l.), which is located near Wartburg, KwaZulu-Natal, South Africa (**Figure 3.1**). Climate data was obtained from the South African Sugarcane Research Institute (SASRI) weather portal for an Automatic Weather Station located at Fountainhill. From January 2016 to December 2021, the annual rainfall at the site ranged from 603.4 to 792.8 mm. The mean annual air temperature is approximately 16.5°C, while the minimum and maximum mean monthly air temperatures are approximately 10.2 and 24.7°C, respectively.

The estate is located within the mistbelt and moist midland bio-resource group (Modi and Mabhaudhi, 2020) and is considered sub-humid. Therefore, Fountainhill is not ideally suited for the optimum growth of sweet potato (Dladla et al., 2019). Hence, above-ground biomass and tuber yield should be lower compared to sub-tropical sites such as Umbumbulu. Since the study wanted to include members of the nearby Swayimane community to assist with establishing, weeding and harvesting the field trial, Fountainhill was chosen as the experimental site.

Figure 3.1: Satellite-derived image showing the location of the experimental site at Fountainhill Estate (source: Google Earth®)

3.2 Planting material

The orange-fleshed sweet potato variety (not the white/cream-fleshed variety) was selected for this study because of its high β-carotene content (Mabhaudhi et al., 2019), as discussed in **Section 2.3.1**. In September 2021, approximately 100 sweet potato vine cuttings of the orange-fleshed sweet potato (199062.1 variety) were obtained from the Cedara College of Agriculture, Howick, KwaZulu-Natal, South Africa. The vine cuttings were then propagated at the University of KwaZulu-Natal's 1) Ukulinga research farm and 2) Agronomy greenhouse tunnels (cf. **Figure 7.1** in **APPENDIX A**). This was done to ensure sufficient material was available for planting a 50 m by 50 m area (2500 m^2) at the experimental site.

3.3 Agronomic practices

Information pertaining to site preparation and planting of the crop is detailed in the following subsections. In addition, fertilisation application and weed control measures are also discussed.

3.3.1 Site preparation

Mechanical ploughing and disking of the experimental site were completed by the Fountainhill Estate staff on the 7th of December 2021, a week prior to the commencement of planting. During this process, all weeds were removed. The perimeter fence was then strengthened and secured better to prevent animals (e.g. nyalas, porcupines and bushpigs) on the eco-estate from entering the experimental site. This task was completed with the assistance of staff from the University of KwaZulu-Natal's Ukulinga research farm.

3.3.2 Planting

In areas that experience mild frost, a mid-November to mid-December planting period is deemed most suitable for sweet potato (DAFF, 2011). Hence, the crop was planted on the 14th of December 2021. Sweet potato vines were hand planted on ridges with an inter- and intra-row spacing of 1 and 0.5 m, respectively (i.e. 20000 plants per hectare). This task was completed with assistance from contracted workers from the nearby Swayimane community. The size of the planted area was 2500 m^2.

3.3.3 Fertiliser application

Prior to planting, soil samples taken at a depth of 0.15 m for fertility analysis were sent to the Soil Analytical Services Laboratory based at Cedara, KwaZulu-Natal. Based on the results (**Table 3.1**), Gromor Accelerator® (30 g kg^{-1} N; 15 g kg^{-1} P; 15 g kg^{-1} K) was recommended to be applied at planting at a rate of 3333 kg ha^{-1}. The fertiliser application rate was calculated by accounting for the amount of pure Nitrogen (in kg ha^{-1}) recommended by Cedara, the pure Nitrogen content of the Gromor Accelerator® fertiliser and the trial site area. In each row, fertiliser granules were applied 10 cm away from each transplanted vine.

Table 3.1: Soil chemical properties for the sweet potato experimental site

Soil fertility characteristics										
mg L^{-1}								%		
P	**K**	**Ca**	**Mg**	**Zn**	**Mn**	**Cu**	**pH (KCl)**	**Org. C**	**N**	**Clay**
239.5	378.5	913.5	159.0	4.8	28.2	17.0	4.0	1.9	0.1	12.5

3.3.4 Pest control

During sweet potato propagation, the crops were sprayed with Kemprin insecticide (a/l cypermethrin), diluted at a rate of 185 ml per 16 L of water. The same insecticide was sprayed halfway through the growing season at the experimental site at the same dilution rate.

3.3.5 Weed control

Prior to planting and midway through the growing season, weed growth was controlled by spraying the experimental site with Gramoxone (pre-emergent herbicide) at a dilution rate of 200 ml per 16 L of water. However, high temperatures and frequent rainfall events that occurred after planting, resulted in rapid weed development. Due to the University being closed in the last week of December 2021, it was not possible to organise casual workers to assist with weeding. Hence, this task was delayed to the end of January 2022. The delay in weeding influenced initial crop growth and it also delayed crop measurements.

3.4 Data collection

Data collection involved measuring and monitoring weather variables, soil water content, crop growth and physiological development. However, crop growth measurements were taken from the 9th of February to the 11th of April 2022 (i.e. 57 to 118 days after planting) because the high temperatures and frequent rainfall events that occurred after planting, resulted in rapid weed development (cf. **Section 3.3.5**). Representative plants were identified for weekly growth measurements across the remainder of the season (cf. **Figure 3.2** in **Section 3.4.1.2**).

3.4.1 Weather data

3.4.1.1 Rainfall

An Automatic Weather Station (AWS) was installed by SASRI at Fountainhill Estate in 2015 (AWS-512; 29°27'02"S; 30°32'42" E; elevation 853 m a.s.l.), which provided a climatic record of approximately eight years in length (i.e. 2015 to 2022). In addition, another SASRI AWS is located at Bruyns Hill (AWS-455; 29°25'00"S; 30°41'00" E; elevation 990 m a.s.l.), which is located approximately 14 km from Fountainhill Estate. This AWS provided a 26-year (i.e. 1997 to 2022) climatic record. Rainfall data was obtained from the SASRI weather portal for the AWS located at Fountainhill Estate.

3.4.1.2 Other weather variables

A micrometeorological station was installed at the experimental site (**Figure 3.2**) for measuring air temperature and relative humidity using an HMP45C-L probe (Campbell Scientific Inc., Logan, Utah, USA) installed 2 m above the crop canopy. Similarly, net radiation was measured using an NR-lite net radiometer (Kipp and Zonen, Delft, The Netherlands) installed 2.5 m above the crop canopy. These variables were used to calculate ET_O. The other instrumentation shown in **Figure 3.2** (e.g. fine-wire thermocouples) were utilised by another PhD student.

All sensors (including soil water content probes; cf. **Section 3.4.2.1**) were connected to a CR1000 data logger (Campbell Scientific Inc., Logan, Utah, USA) installed in a weatherproof enclosure. The data logger and sensors were powered by two 12 VDC (100 Ah) batteries housed in a strong metal box, which were recharged by a solar panel installed above the strong box at the site (**Figure 3.2**). Measurements were recorded at 15-minute intervals, which were averaged to hourly and then daily data values by the data logger. Experimental site visits were conducted weekly to download stored data from the data logger and to collect growth data from the crop.

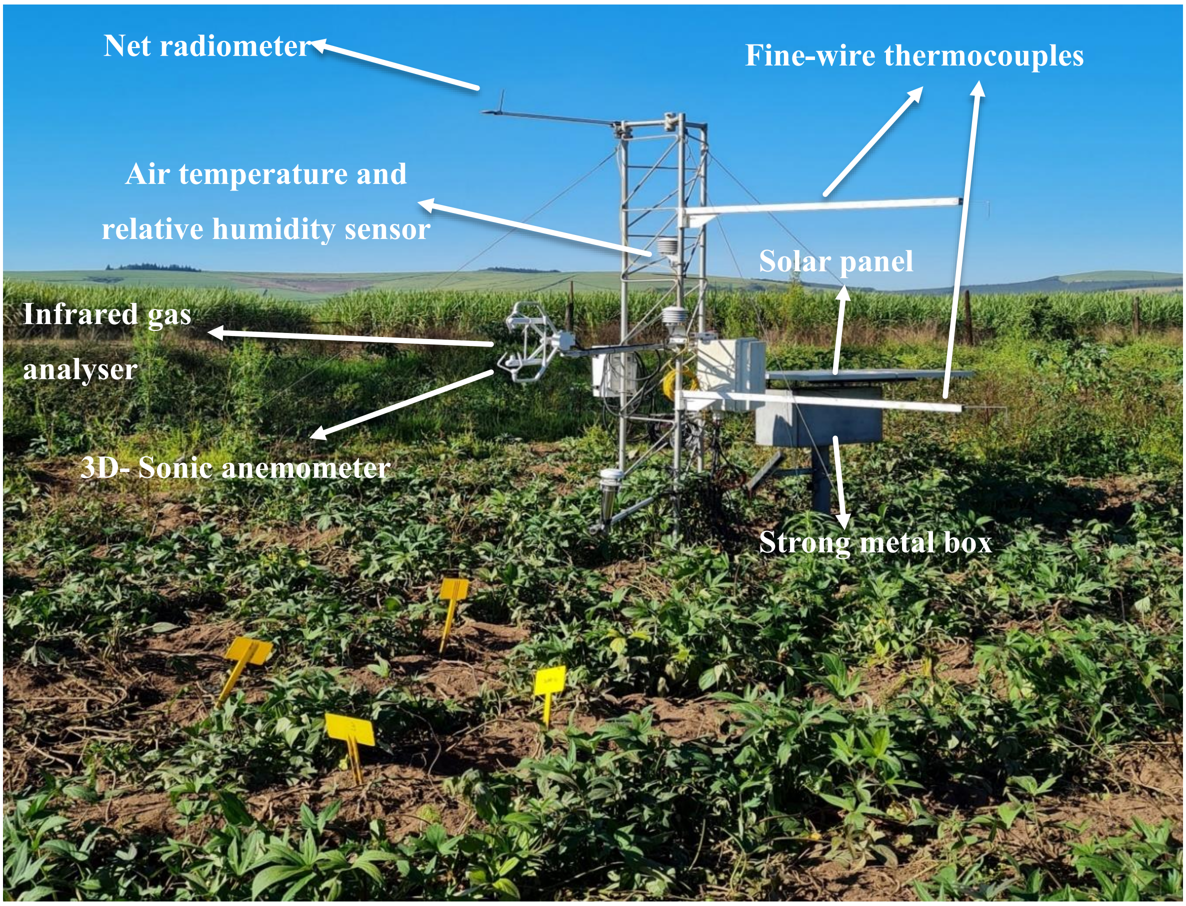

Figure 3.2: Micrometeorological station installed at the experimental site at Fountainhill Estate, with crop growth at day 57 after planting

3.4.1.3 Reference crop evapotranspiration

The potential rate of evapotranspiration occurring from a hypothetical reference surface that is not short of water is referred to as reference crop evapotranspiration (ET_O) (Allen et al., 1998). The reference surface resembles a short, green grass surface with the following characteristics: uniform height of 0.12 m, albedo of 0.23 and surface resistance of 70 s m^{-1} (Allen et al., 1998). This FAO-56 approach uses the following modified Penman-Monteith equation to calculate ET_O:

$$ETo = \frac{0.408\Delta(R_N - G) + \gamma \frac{900}{T + 273} u_2(e_S - e_A)}{\Delta + \gamma(1 + 0.34\, u_2)} \qquad \textbf{Equation 2}$$

where R_N = net radiation (MJ m^{-2} day^{-1}), T = air temperature (ºC), u_2 = daily average wind speed at 2.0 m height (m s^{-1}), G = soil heat flux density (MJ m^{-2} day^{-1}), e_S = saturated vapor pressure (kPa), e_A = actual vapour pressure (kPa), Δ = slope of the saturation vapour pressure vs air temperature curve (kPa ºC^{-1}) and γ = psychrometric constant (kPa ºC^{-1}). The data logger calculates hourly estimates of ET_O using the above equation, which are then summed to daily values. Kunz et al. (2020) showed that daily ET_O summed from hourly values provides slightly more accurate results than using **Equation 2** with daily data.

3.4.2 Soils data

3.4.2.1 Volumetric water content

Volumetric water content can be used to estimate soil water changes in the field (Marshall and Holmes, 1988). Measuring soil moisture is important as it provides information on the extraction and availability of water within the crop's root zone (Stevens, 2007). Furthermore, measurements made throughout the season at various soil depths can provide estimates of changes in soil water storage and drainage (Zeleke and Wade, 2012). The quantity of water in the rhizosphere can be determined 1) directly by measuring soil water content, and 2) indirectly by quantifying matric and soil water potential (Stevens, 2007; Lembede, 2017). In this study, the first option was used, where three CS650 probes (Campbell Scientific, Utah, USA) were used to directly quantify volumetric water content at three depths (0.15, 0.30 and 0.60 m). However, one week after planting, the CS650 probes stopped working correctly. Attempts were made to purchase three new CS650 probes, but the supplier was out of stock. Therefore, the faulty probes were only replaced with CS616 probes (Campbell Scientific, Utah, USA) in early

February 2022, due to the field technician being on extended sick leave. This also explains why plant growth measurements only began 57 days after planting.

Additional CS616 probes were unavailable to estimate drainage beyond the effective rooting zone. Furthermore, a hard layer of sandstone was found below 60 cm, which prevented the installation of additional sensors to measure drainage beyond the effective rooting zone. Hence, drainage and capillary rise were assumed to be negligible. The initial and final soil water content was therefore measured by the CS650 and CS616 soil moisture probes, respectively.

3.4.2.2 Soil textural analysis

To determine the soil water availability at the experimental site, soil texture was measured in the laboratory. Soil texture refers to the relative portion of sand, silt and clay particles in soil samples (Xia et al., 2020). Soil samples were obtained from 0.15, 0.30 and 0.60 m depths using an auger, which were then sent to the Soil Analytical Services Laboratory (Cedara, KwaZulu-Natal) for analysis. **Table 3.2** shows the particle size distribution remained constant with depth and thus, the uniform soil texture is a loamy sand.

Table 3.2: Soil particle size distribution and textural classes obtained from samples taken at three depths at the Fountainhill experimental site

Soil profile depth	Clay	Fine Silt	Sand	Soil textural class
	(< 0.002 mm)	(0.02 - 0.002 mm)	(0.02 - 2 mm)	
m	%	%	%	
0.15	8	5	87	Loamy sand
0.30	8	4	88	
0.60	7	4	89	

3.4.2.3 Soil water retention

Prior to planting, dry bulk density was determined by digging a 1 m by 1 m pit to obtain undisturbed soil cores at the three depths. These undisturbed soil cores were oven-dried at constant temperature (105°C) for 24 hours and then weighed to determine the mass of dry soil. The soil volume in each core was determined and used to calculate dry bulk density. Values were then used to estimate total porosity (saturation), as given in **Table 3.3**.

Table 3.3: Estimated dry bulk density, soil water retention parameters and saturated soil hydraulic conductivity obtained for the Fountainhill experimental site

Soil water characteristics	Units	Depth (m)		
		0.15	**0.30**	**0.60**
Dry bulk density	g cm^{-3}	1.5	1.8	1.8
Saturation (SAT)	% vol	40	31	32
Field capacity (FC)	% vol	31	21	20
Permanent wilting point (PWP)	% vol	7	5	8
Saturated hydraulic conductivity (K_{SAT})	mm day^{-1}	541.1	136.6	763.8

Thereafter, soil water retention data was obtained using the controlled outflow pressure apparatus in the Soil and Water Laboratory at the University of KwaZulu-Natal (UKZN). The detailed methodology, as described by Mokonoto (2018), was followed in this study. Soil water retention curves were then developed using the Van Genuchten equation (Van Genuchten, 1980), with data outputted by the outflow pressure apparatus. From the soil water retention curves, volumetric water content (in %) at field capacity (FC) and permanent wilting point (PWP) were estimated using a pressure head of -10 and -1500 kPa, respectively (**Table 3.3**).

Using the constant-head permeameter method, saturated hydraulic conductivity (K_{SAT}) was determined on packed soil columns. This method involves applying Darcy's law to saturated soil tubes of the same cross-sectional area (Klute, 1965). This law (**Equation 3**) describes the basic flow of water through soils (Klute, 1965) as follows:

$$K_{SAT} = \frac{\Delta L_{IJ}}{H_I - H_J} \cdot \frac{Q}{A} \qquad \textbf{Equation 3}$$

where K_{SAT} = saturated hydraulic conductivity of the soil (mm d^{-1}), L_{IJ} = length of the soil material between ports I and J (cm), H_I and H_J = total hydraulic head at port I and J (cm), Q = volumetric outflow rate (cm^3 s^{-1}), and A = total cross-sectional area of the column (cm^2).

3.4.3 Plant health

Over the measurement period, plant health was determined by measuring chlorophyll content index and stomatal conductance. These measurements are described next in greater detail.

3.4.3.1 Chlorophyll content index

Chlorophyll content index (CCI) is an important indicator of plant health (Kunz et al., 2020). Furthermore, this index is useful in monitoring how crops respond to low levels of water availability under rainfed agricultural production (Mabhaudhi, 2012). For example, water deficits negatively impact a crop's CCI by reducing it. For this study, CCI was measured using a chlorophyll meter (SPAD-502 Plus; Konica Minolta, Osaka, Japan). According to Süb et al. (2015), two different wavelengths transmitted by the chlorophyll meter are influenced by the crop's chlorophyll content. The adaxial surface of the second youngest fully unfolded leaf was used for CCI measurements over the measurement period as suggested by Mabhaudhi (2012).

3.4.3.2 Stomatal conductance

Stomatal conductance (SC) is the rate at which carbon dioxide (CO_2) and water vapour diffuses in and out of leaf stomata, respectively (Mabhaudhi, 2012). The opening and closing of stomata determine the rate of diffusion, and thus, SC can be considered an important indicator of plant water stress (Cornic and Massacci, 1996). One of a crop's defence mechanisms to water stress is stomatal closure, which reduces the transpiration and photosynthetic rates and increases leaf temperature. These changes result in reduced plant growth (Mabhaudhi, 2012).

For this study, a steady-state leaf porometer (model SC-1; Decagon Devices, Pullman, Washington) was used to measure SC and leaf temperature. Measurements were taken weekly between 12h00 and 13h30 on days with sufficient sunlight with minimal to no cloud cover. SC measurements were undertaken on the abaxial surface of young, healthy leaves, as suggested by Mabhaudhi (2012).

3.4.4 Crop development

A quadrant approach was used for continuous data collection over the growing season. Four 1 m by 1 m quadrants were randomly set up at the experimental site, each containing four plants. Plants near the borders of the field were avoided to minimise edge effects. From day 57 after planting, weekly measurements of crop development from 16 plants were undertaken. These included plant height, leaf number, leaf area index and canopy cover development, as described next in more detail.

3.4.4.1 Plant height

Plant height (PH) refers to the distance from the soil surface to the tip of the youngest developing leaf (before floral initiation) or the growing panicle tip (post floral initiation) (Hadebe et al., 2017). Thus, plant height was measured every week using a tape measure.

3.4.4.2 Leaf number

Leaf number (LN) was counted using a method suggested by Mabhaudhi et al. (2013), which considers leaves that were fully unfolded, expanded and photosynthetically active (i.e. at least a 50% green leaf area). Hadebe (2016) defined a fully formed leaf as when the initial unifoliolate leaf can be seen without dissecting the plant.

3.4.4.3 Leaf area index

Leaf area index (LAI) represents the ratio of one-sided leaf area per unit ground surface area occupied by the plant (LI-COR, 2009). For this study, an LAI-2200 portable leaf area meter (LI-COR, 2009) was used to measure LAI. To ensure adequate light interception by the canopy, measurements were taken from above and below the crop canopy, preferably on sunny days.

3.4.4.4 Canopy cover development

Canopy cover (*CC* in %) development was estimated from *LAI* measurements using the Beer-Lambert equation as suggested by Vose et al. (1995) as follows:

$$CC = 100(1 - e^{-k \cdot LAI}) \qquad \textbf{Equation 4}$$

where *k* represents the light extinction coefficient. Masango (2015) measured *k* for sweet potato (0.85), which was used in this study.

The preferred method of calculating *CC* uses *LAI* measurements to compute the diffuse non-intercepted radiation (DIFN). This method was not used because the data card in the LAI meter was faulty. DIFN values enable *CC* development to be calculated using the following equation as suggested by Mabhaudhi et al. (2014):

$$CC = 100(100 - DIFN) \qquad \textbf{Equation 5}$$

3.4.4.5 Phenological development

Crop development was observed at various phenological stages over the growing season. These include the time from transplanting to: recovered plant, maximum rooting depth, start of leaf senescence, start of yield formation and harvest maturity. For example, when at least 10% of the crop foliage has senesced without the formation of any new foliage, then leaf senescence has occurred (Mabhaudhi et al., 2014). For this study, crop phenological stages were initially recorded in calendar days, which were then converted to growing-degree days (GDD). The same method used by the AquaCrop model was adopted in this study, which is called "Method 3". The latter was adapted from "Method 2", that was initially developed by McMaster and Wilhem (1997).

3.4.5 Biomass accumulation and tuber formation

To determine both fresh and dry above-ground biomass (AGB) accumulation and tuber formation over the growing season, a destructive sampling technique was used where three sweet potato plants were randomly selected across the field every week. The selected plants were removed from the field, stripped of plant roots, and then taken back to UKZN's Soil and Water Laboratory. The plants were weighed to determine fresh AGB and tuber yield. Thereafter, they were oven-dried at constant temperature (75°C) for 48 hours, then re-weighed to obtain the dry AGB and tuber yield.

3.4.6 Actual crop evapotranspiration

Actual crop evapotranspiration (ET_A) can be estimated using remote sensing and conventional micrometeorological methods such as eddy covariance, surface renewal and surface layer scintillometry (Kunz et al., 2015; Mbangiwa et al., 2019). Although these methods provide accurate estimates of crop water use, they are costly to implement and data analysis is complex. Furthermore, these methods are not suited to small research plots as they require adequate fetch (Mbangiwa et al. 2019). For this study, crop water use over the growing season was estimated using the soil water balance empirical method. Hence, ET_A was estimated as a residual of the soil water balance equation as suggested by Ranna and Katerji (2000) as follows:

$$ET_A = I + P + U - R - Dr \pm \Delta SWC \qquad \textbf{Equation 6}$$

where ET_A = actual crop evapotranspiration (mm), I = irrigation in mm (zero for rainfed conditions), P = precipitation (mm), U = capillary rise in mm (assumed to be zero or negligible for a deep ground water table), R = surface runoff in mm (which is usually assumed to be negligible for flat terrain), Dr = drainage in mm (also assumed to be zero or negligible) and ΔSWC = change in soil water content (in mm). Based on these assumptions, crop water use under rainfed conditions can be estimated from daily measurements of rainfall and soil water content. As noted in **Section 3.4.1**, daily rainfall data was obtained from the SASRI weather portal for the AWS located at Fountainhill Estate. Surface runoff was not measured using runoff plots as the gradient of the trial site is negligible. Soil water content was measured at three depths (0.15, 0.30 and 0.60 m) using CS650 (initially) and CS616 probes as explained in **Section 3.4.2.1**.

3.4.7 Final biomass and tuber yield

A total of 30 plants from two rows were harvested at the end of the season. Harvested plants were then separated into leaves, vines and tubers (excluding roots). The same procedure described above was used to determine the fresh (cf. **Figure 7.2** in **APPENDIX A**) and dry mass of harvested material. The harvest index (*HI*) was calculated as the ratio of the tuber yield (*Y*) to total biomass (*B*) and expressed as a percentage using the following equation as given by Mabhaudhi (2012):

$$HI = 100 \cdot \frac{Y}{B}$$ **Equation 7**

3.5 Crop and nutritional water productivity

The crop water use determined using the soil water balance equation (cf. **Section 3.4.6**) was used to calculate crop water productivity (*CWP* in kg m^{-3}) using the following equation as given by Renault and Wallender (2000):

$$CWP = \frac{Y}{ET_A}$$ **Equation 8**

where Y is crop yield (dry kg ha^{-1}) and ET_A is actual crop evapotranspiration (m^3 ha^{-1}).

Nutritional water productivity (*NWP* in g m^{-3}) was calculated using the following equation as suggested by Renault and Wallender (2000):

$$NWP = CWP \cdot NC \quad \textbf{Equation 9}$$

where *CWP* is crop water productivity (dry kg m^{-3}) and *NC* represents the nutrient content (in mg) per unit mass (kg) of leaves or tubers (i.e. mg kg^{-1}). Five fresh tuber and leaf samples were initially stored at -20°C to preserve nutrient content. Thereafter, samples were oven-dried, then ground and milled before being sent for nutrient content analysis by the Analytical and Research Laboratory at the Institute for Commercial Forestry Research (ICFR) in Pietermaritzburg, KwaZulu-Natal. The following elements were measured: B, Ca, Cu, Fe, K, Mg, Mn, Mo, Na, P, and Zn. For the analysis of Mo, a standard was imported from the USA. In addition, total C, N and S was also determined.

Two fresh tuber samples were peeled, chopped into cubes and freeze-dried at -80°C for 96 hours. The samples were then blended to form a powder to enable the analysis of β-carotene content in the Horticulture and Crop Science Laboratory at UKZN. A method described in detail by Biswas et al. (2011) was used to analyse β-carotene content, which requires acetone as an extractant (i.e. solvent), followed by UV-VIS spectrometric detection. A β-carotene analysis of OFSP leaves was not undertaken due to a lack of time, as the freeze dryer was only repaired in late November 2022.

3.6 Linking field measurements to crop modelling

As noted in **Section 1.2**, Modi and Mabhaudhi (2020) stated that a multi-disciplinary approach involving in-field measurements and crop model simulations should be used to determine the water use and yield of RTCs. Hence, this study's modelling component involved using two crop simulation models, which are described next.

3.6.1 Model selection

Beletse et al. (2013) ran AquaCrop for OFSP and concluded that the model was a useful tool for providing reliable water use and yield simulations. However, the authors suggested that the model should be refined with more data from various locations and varying OFSP varieties. Masango (2015) ran the Soil Water Balance model for OFSP and found it useful for assessing water requirements and yields. These models are also familiar to the Centre for Water Resources Research at UKZN and they are frequently used by postgraduate hydrology and crop science students. Furthermore, due to the availability of crop parameters for OFSP to run both models, the Soil Water Balance and AquaCrop model were therefore selected to meet the objectives of this study. The main aim was to partially calibrate existing crop parameters by fine-tuning them for local climate and cultivar conditions, then to validate each model's performance against observed growth and yield data. This was done to determine if the models are well suited for application across different agroecological zones and for different OFSP cultivars.

3.6.2 Model inputs

Both models require location (latitude, longitude and altitude), climate and soil data as inputs, as well as the planting date and plant density. Each of these model inputs is described next.

3.6.2.1 Climate data

For both models, rainfall data was obtained from the SASRI weather portal for the AWS located at Fountainhill Estate. The micrometeorological station installed at the experimental site provided net radiation, air temperature, relative humidity and wind speed (cf. **Section 3.4.1**).

The latest SWB model version could not be obtained from the Department of Plant and Soil Sciences' website (https://www.up.ac.za/plant-and-soil-sciences) at the University of Pretoria. In addition, the SWB model was also not available for download on the software developer's website (https://www.nbsystems.co.za/downloads.html). Hence, an older version (no. 19.05.2010) of the model was used in this study. Problems were also experienced in running SWB on a Windows 10 computer, which could explain why the model is no longer available for download. Climate data was imported into the SWB model's weather database called WDB. This process was done by creating a climate file in .CSV format that consisted of net radiation, minimum and maximum air temperature, minimum and maximum relative humidity, wind speed and rainfall.

AquaCrop requires separate input climate files of daily rainfall (.PLU file extension), temperature (.TNX) and reference crop evapotranspiration (.ETO), together with the names of these time series files stored in the .CLI file. For this study, the default ambient carbon dioxide (CO_2) concentrations packaged with the model for Mauna Loa (Hawaii) were used. Version 6 of the model was obtained from FAO's website (https://www.fao.org/aquacrop/software/en/) and used in this study.

ET_O values calculated by the data logger were deemed unrealistic (i.e. too low) and thus, were not used in this study. This was possibly due to inaccurate inputs of latitude, longitude and instrument heights in the data logger program. Hence, reference crop evapotranspiration was calculated using the 1) SWB model, and 2) ET_O Calculator. The latter is a software utility developed by the FAO's Land and Water Division. The ET_O Calculator values were then compared to those obtained from the 1) SWB model, and 2) AWS located at Fountainhill Estate.

A comparison between ET_O measured by the Fountainhill Estate AWS and ET_O estimated by the ET_O Calculator from data measured at the trial site is shown in **Figure 8.1** (cf. **APPENDIX B**). The latter values are higher, probably due to the Fountainhill AWS not being properly maintained as a result of the COVID-19 pandemic and associated lockdown periods. Similarly, another scatter plot of ET_O simulated by the SWB model versus ET_O estimated by the ET_O Calculator is shown in **Figure 8.2** (cf. **APPENDIX B**). It is unknown why the SWB values are also lower than those calculated using the ET_O Calculator.

Rainfall is very important for crop production. The scatter plot (cf. **Figure 8.3** in **APPENDIX B**) of rainfall data from the Fountainhill Estate AWS versus rainfall data from the Bruyns Hill AWS shows a relatively poor correlation. For this reason, it would have been better to install a tipping bucket rain gauge at the trial site. This work also highlights the importance of thoroughly checking input climate data before being used for model simulations.

3.6.2.2 Soils data

Inputs of soil depth, initial soil water content, field capacity and permanent wilting point are required by both simulation models. Measured values, as described in **Section 3.4.2.3**, were depth-weighted and used to provide the required inputs for a single soil profile of 0.60 m in depth. This approach was justified due to the uniformity of the soil with depth, as shown in **Table 3.2** (cf. **Section 3.4.2.2**). Both models also require a curve number for estimating runoff production. A value of 61 was used, based on the saturated hydraulic conductivity (K_{SAT}) of the topsoil horizon (FAO, 2017b) (**Table 3.4**). The initial soil water content was obtained from the volumetric water measurements provided by the CS650 soil moisture sensors (cf. **Section 3.4.2.1**).

Table 3.4: Summary of depth-weighted soil parameters used as input for the SWB and AquaCrop model

Soil parameters	Units	Values
Soil texture		Loamy sand
Soil profile depth	m	0.6
Curve number		61
Saturation	% vol	33.8
Field capacity	% vol	23.0
Permanent wilting point	% vol	7.0
Initial soil water content	mm	44.2

In addition, the SWB model requires dry bulk density as inputs for the top and bottom soil layers and thus, values of 1.5 and 1.8 g cm^{-3} were used, respectively. In addition, the drainage rate and factor were slightly modified from Masango (2015) to reduce simulated runoff and were set to 70 mm d^{-1} and 0.7, respectively.

Additional soils-related inputs required by AquaCrop include K_{SAT} for the soil profile, total available water (TAW) and readily available water (RAW). The K_{SAT} values determined using the constant-head permeameter method (cf. **Section 3.4.2.3**) for the three soil depths were also depth-weighted accordingly. Total available water (TAW) was determined as the difference between the water content at field capacity and permanent wilting point (FAO, 2017b). Readily available water (RAW) was also estimated from field capacity and permanent wilting point as per the equation (2.23s – 4; p 2-266) provided by Raes et al. (2018). K_{SAT}, TAW and RAW values used as model inputs were 551.5 mm d^{-1}, 160 mm m^{-1} and 8 mm, respectively.

3.6.2.3 Planting date and density

For both models, the planting date and plant density were set to the 14th of December 2021 and 20000 plants ha^{-1}, respectively. This was done to mimic field conditions as described in **Section 3.3.2**.

3.6.3 Default crop parameters

3.6.3.1 SWB

The SWB model was calibrated and validated for the Resisto cultivar of OFSP by Masango (2015). Masango (2015) obtained growth and yield data from field trials undertaken at Hatfield (University of Pretoria experimental farm) during the 2011/12 season. As noted in **Section**

3.4.4.4, the extinction coefficient (0.85) used to estimate CC from LAI was derived by Masango (2015). Statistical measures of measured and simulated data exhibited an acceptable accuracy. For example, the coefficient of determination (R^2) and Willmott's index of agreement (d) for the LAI was 0.80 and 0.90, respectively, while that for the dry yield was 0.97 and 0.86, respectively. A list of all crop parameters used to run the SWB model is provided in **Table 9.1** in **APPENDIX C**.

3.6.3.2 AquaCrop

The AquaCrop model was calibrated and validated for OFSP (Isondlo cultivar) and sweet potato (Ganja, Uplifta and Yellow Belly cultivars) by Beletse et al. (2013) and Rankine et al. (2015), respectively. Beletse et al. (2013) used field observations obtained during the 2008/09 and 2009/10 growing seasons from an irrigated experiment under a rain shelter located at the Agricultural Research Council's Roodeplaat Vegetable and Ornamental Plant Institute (Northeast of Pretoria, Gauteng). Three irrigation regimes were used, namely fully irrigated and two drier treatments where irrigation was applied to refill the soil profile to 60% and 30% of field capacity (FC). The model was calibrated using data collected from the irrigated trials conducted in the first season. The model was validated against an independent dataset collected in the second season. The model predicted biomass, canopy cover and the harvestable yield for both stressed (30 and 60% of FC) and non-stressed (fully irrigated) treatments reasonably well. Correlation coefficients (R^2) ranged from 0.92 to 0.96 for canopy cover and biomass production. The agreement between observed and simulated values of biomass was excellent for the stressed treatment (30% of FC). However, the model over-estimated yield for the medium irrigation treatment (60% of FC).

Furthermore, Rankine et al. (2015) obtained growth and yield data from field trials undertaken at two agroecological zones (Devon, Manchester in 2012/13 and Ebony Park, Clarendon, in 2013) in south-central Jamaica under rainfed and irrigated agriculture. The canopy cover was reasonably well simulated by the model. The overall simulation of biomass was good, with deviations of less than 28%. The model validation showed that irrigated yields were under-estimated by 34% and rainfed yields were over-estimated by 182%. For the irrigated treatment, the results were influenced by the earlier maturity date in the model relative to the actual harvest date. Very few tubers formed under rainfed conditions at the second site, which resulted in the model overestimating the actual yield. Rankine et al. (2015) concluded that parameterising root and tuber crops in AquaCrop is more challenging than other crops.

Many attempts were made to obtain the full crop parameter file from Beletse et al. (2013), which were unsuccessful and thus, published parameter values were used in this study. However, a full crop parameter file was obtained from Rankine et al. (2015). Hence, all the crop parameters published by Beletse et al. (2013) were used in this study. For missing parameters, values were obtained from the crop parameter file provided by Rankine et al. (2015), which is not ideal. A list of important crop parameters used in this study is provided in (cf. **APPENDIX C**).

3.6.4 Model calibration

Conducting field trials in varying agroecological zones is deemed necessary to obtain crop data for partially calibrating crop models, i.e. for "fine-tuning" existing crop parameters. In this study, both models were partially calibrated by slightly adjusting certain model parameters as suggested by Steduto et al. (2012), which is discussed next in more detail.

Steduto et al. (2012) stated that to perform a partial model calibration, crop parameters that need adjusting include the: 1) maximum rooting depth (Z_{MAX}), 2) time required for Z_{MAX} to be reached, 3) time required to reach various phenological growth stages (e.g. emergence, flowering, canopy senescence and maturity), 4) maximum canopy cover (CC_X), 5) response to soil fertility, and 6) length of the crop cycle. Furthermore, FAO (2017b) stated that certain non-conservative parameters could also be "fine-tuned" for specific cultivars.

Therefore, to better represent local growing conditions and the OFSP landrace grown in this study, various model parameters were adjusted based on field observations at the experimental site. For example, the Z_{MAX} parameter was observed at physiological maturity by digging a trench between the rows within the 1 m by 1 m quadrants, then measuring Z_{MAX} as the maximum depth reached by the rooting system. Most of the crop phenological parameters were initially observed in calendar days, which were then converted to growing-degree days within AquaCrop, as suggested by FAO (2017b). Owing to the crop being harvested prematurely (to prevent further animal damage), time to reach flowering was not observed. Hence, secondary data was sourced from literature.

As recommended by Raes et al. (2009), the initial canopy cover (CC_O) was computed in AquaCrop using initial leaf area and planting density as model inputs. The development of canopy cover (CC) per growing-degree day was calculated by AquaCrop as the canopy growth coefficient, which needs the observed maximum canopy cover percentage (CC_X) and the time to reach CC_X. As mentioned in **Section 3.4.4.4**, CC was not measured in the field, but was estimated from LAI measurements (see **Section 3.4.4.3**).

Maximum evapotranspiration was obtained by a PhD student working at the same site. The highest ET_A (7.11 mm) was measured 112 days after planting (Reddy, 2022; pers. comm.) and this value was used as the daily maximum transpiration of the crop.

3.6.5 Field management options

Under the field management options in AquaCrop, the non-limiting fertility option was selected, due to applying fertiliser at the required rate (cf. **Section 3.3.3**). Soil cover by mulch was not considered. Factors that affect surface runoff were also not invoked, due to the flat terrain at the experimental site. Although weed management was not ideal at the beginning of the trial (cf. **Section 3.4**), the field trial was kept relatively weed-free for the duration of the data collection period, i.e. from day 57 after planting onwards. Hence, the option to suppress canopy cover development of the crop due to the presence of weeds was not considered. An irrigation file was not created as the crop was grown under rainfed conditions.

3.6.6 Model simulations

Simulated tuber yield and crop water use (accumulated ET_A) from the SWB and AquaCrop models were used to calculate the CWP and NWP of OFSP. In addition, simulations of LAI (SWB model), CC (AquaCrop), AGB, tuber yield and soil water content were compared to field measurements and the results are presented in **Section 4.9**.

3.6.7 Model evaluation

Evaluating model performance is important in assessing model robustness (Krause et al., 2005). In this study, various statistical indicators were used to assess the goodness-of-fit when comparing model simulations to field observations. The specific statistical indicators used included the following: Pearson coefficient of determination (R^2), root mean square error (RMSE), Willmott’s index of agreement (d) and the Nash-Sutcliffe model efficiency coefficient (NSE) as well as the number of observations (n).

The R^2 measures the dispersion amongst observed and simulated data and ranges from 0 to 1, with values close to 0 and 1 indicating a poor and very good fit, respectively. However, this statistical indicator can be misleading, especially if the number of data points is low. This is because models may over- or under-estimate observations, but still exhibit high values of R^2 (Krause et al., 2005). This highlights the importance of including other statistical indicators to test model robustness.

The RMSE, which ranges from 0 to positive infinity, also measures the degree to which the observed and simulated data differs. Legates and McCabe (1999) stated that errors are squared, thus resulting in more and less weighting being given to higher and lower values, respectively. Similarly, this statistical indicator cannot distinguish between over- and under-estimations.

The NSE statistic can also be used to assess and quantitatively describe the accuracy between observed and simulated model outputs. It ranges from negative infinity to 1, with values closer to 1 indicating good model performance (Gebremedhin et al., 2015).

The Willmott's index of agreement (d) measures the degree to which the model can accurately simulate observed data. This index also ranges from 0 (poor agreement) to 1 (good agreement) (Willmott, 1982).

4. RESULTS AND DISCUSSION

This section presents and discusses the results obtained in this study. The weather and soil water content measured over the growing season are given first, followed by the results related to crop health, development, biomass accumulation and tuber yield. Thereafter, actual crop water use, crop water productivity and nutritional water productivity results are given. The final section contains the results of the modelling component of this study.

4.1 Weather conditions

The total amount of rainfall over the 118-day growing season was 472.9 mm, which is deemed adequate based on rainfall totals given in **Section 2.1.1**. Although there were 77 days that received less than 2 mm of rainfall, there were no dry spells long enough to negatively impact crop development. **Figure 4.1** highlights the hot and wet conditions experienced during the month after planting, which initially had a major impact on the excessive weed growth experienced after planting (cf. **Section 3.4**).

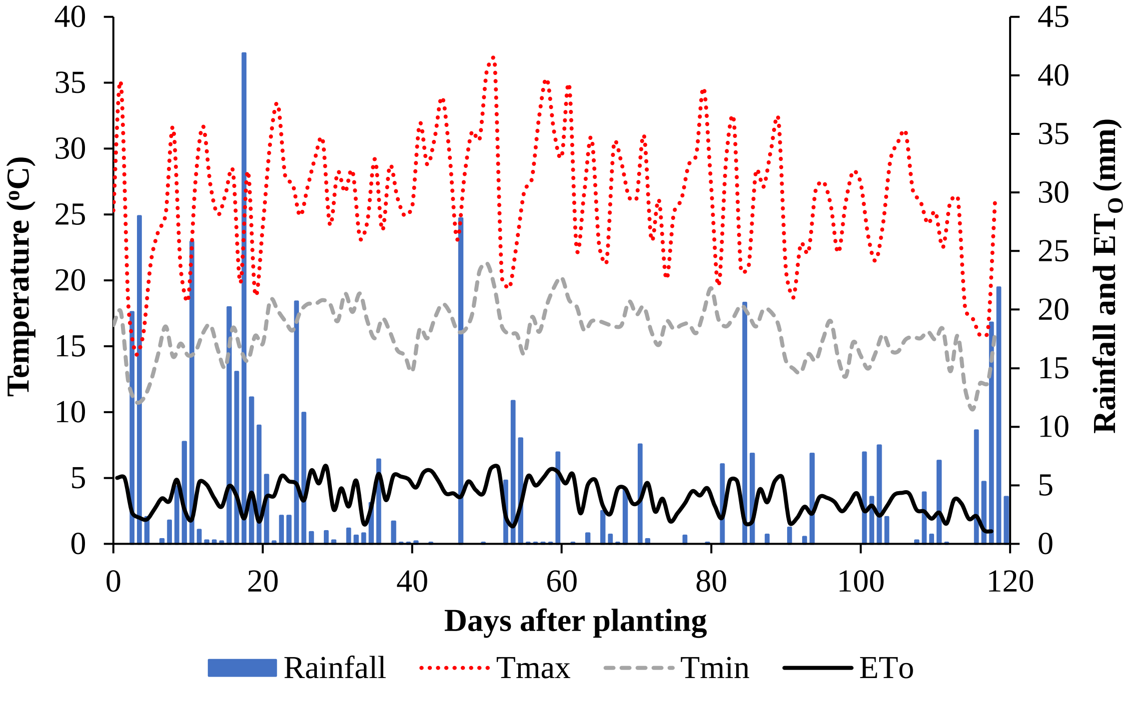

Figure 4.1: Variations in rainfall, reference crop evapotranspiration (ETo) and air temperature (minimum and maximum) over the 2021/22 growing season at Fountainhill Estate

During the growing season, the daily average minimum and maximum air temperatures at the trial site were 16.0 and 26.2°C, respectively. The daily average temperature (21.1°C) was within the range considered optimum for sweet potato growth (cf. **Section 2.1.1**). For the majority of the growing season, the maximum air temperature did not exceed 35˚C and thus, did not negatively affect crop development and yield.

4.2 Crop health

The chlorophyll content index, stomatal conductance and leaf temperature measured over the growing season are presented and discussed next. These measurements provide valuable indicators of crop health.

4.2.1 Chlorophyll content index

The chlorophyll content index (CCI) (**Figure 4.2**) was measured over the growing season as it can be used to indicate plant health and the plant's ability to capture photosynthetically active radiation (Devnarain et al., 2016; Shelembe, 2020). The CCI can also indicate plant senescence and maturity, as it increases during plant development, then starts to decrease towards (or after) the maturity stage (Shelembe, 2020). The CCI showed an increasing trend until 100 days after planting (DAP), reaching a maximum value of 58.1%. The CCI trend was similar to that obtained by Dladla (2017) who obtained a maximum CCI value of approximately 65%.

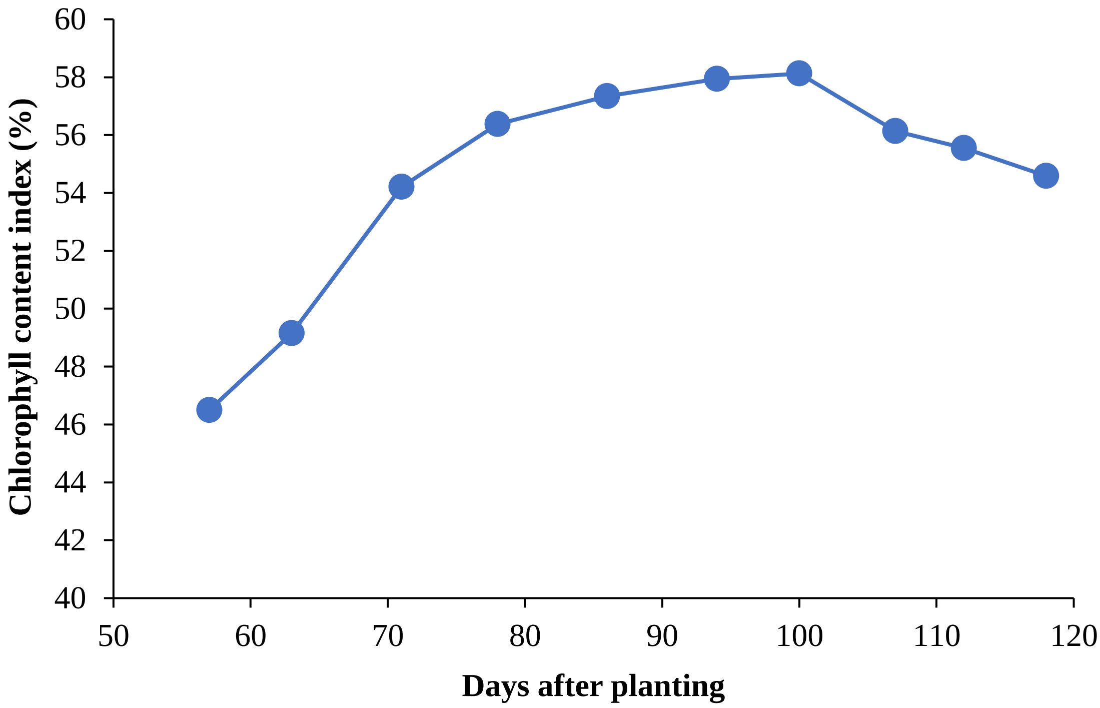

Figure 4.2: Chlorophyll content index of orange-fleshed sweet potato grown under rainfed conditions over the 2021/22 growing season

4.2.2 Stomatal conductance and leaf temperature

The relationship between stomatal conductance (SC) and leaf temperature (LT) is shown in **Figure 4.3**. During the initial/juvenile growth stage (57 to 71 DAP), a decline in SC with increasing leaf temperature was observed. This may indicate a period of water stress that resulted in higher leaf temperatures triggered by stomatal closure. From 71 to 78 DAP, LT decreased from 32.8 to 29.7°C, which was due to cooler and humid weather conditions, which also resulted in reduced transpiration rates.

However, the highest SC of the season (1256 mmol m^{-2} s^{-1}) was measured at 86 DAP. This was due to the warm and less humid conditions that resulted in high transpiration rates. Furthermore, 20.6 mm of rainfall occurred on day 83 (cf. **Figure 4.1** in **Section 4.1**) thus, there was sufficient soil water that resulted in a high transpiration rate (i.e. high SC). Larger SC values (e.g. at 86 DAP) indicate higher transpiration rates, which occurred after 20 mm of rainfall fell on day 83 after planting. Increased transpiration increases the flow of CO_2 into plant leaves, thus implying higher photosynthetic rates and increased plant growth. The decrease in SC after 107 DAP was due to the crop approaching maturity, which caused the leaves to senesce, resulting in a reduced leaf area for transpiration to occur optimally.

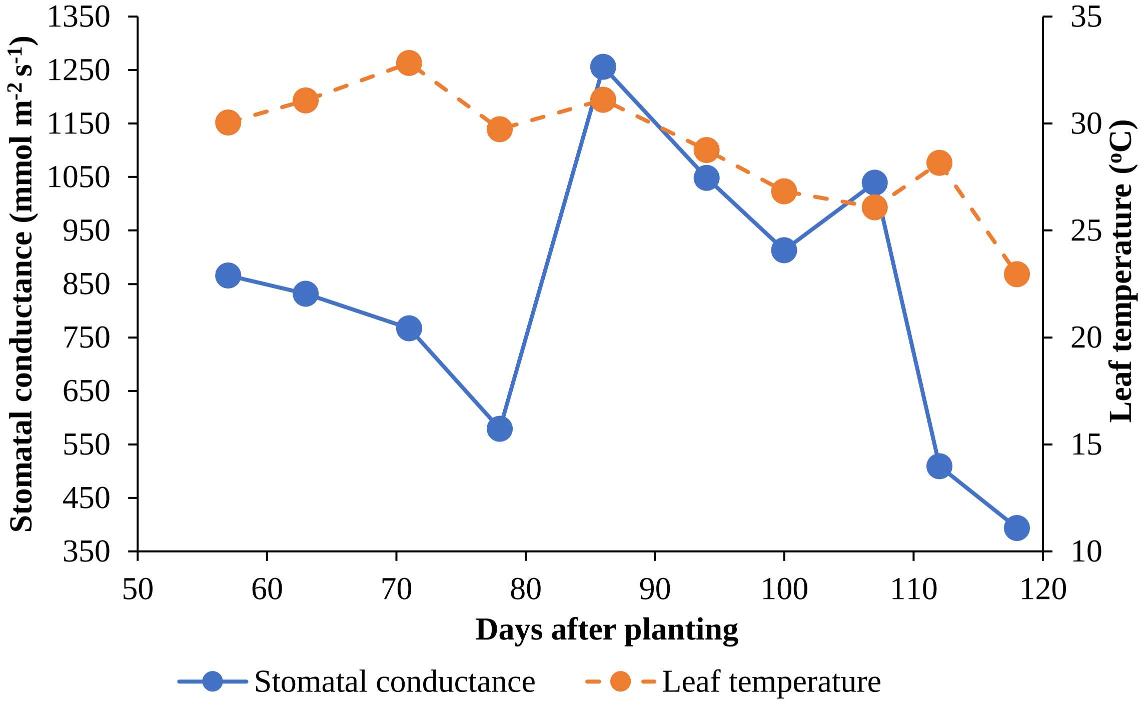

Figure 4.3: Stomatal conductance and leaf temperature of orange-fleshed sweet potato grown under rainfed conditions over the 2021/22 growing season

4.2.3 Summary

In summary, the yellowing of leaves and stunted crop growth, which occurs due to crop water stress, was not observed during the growing season. The above results show no evidence that water stress over a prolonged period occurred during the growing season, especially during critical stages of crop development. The tuber initiation and filling development stages are critical for tuber growth and water stress should be avoided during these stages.

4.3 Crop development

Results related to plant height, leaf number and leaf area index measured over the growing season are presented next. The latter variable was used to estimate canopy cover development.

4.3.1 Plant height

The crop reached its maximum height of 69 cm at 112 DAP (**Figure 4.4**), this equates to an average increase of 4 cm every week from 57 DAP. The maximum plant height (PH) was higher than the 60 cm value reported by Masango (2015), which is probably related to the different cultivars.

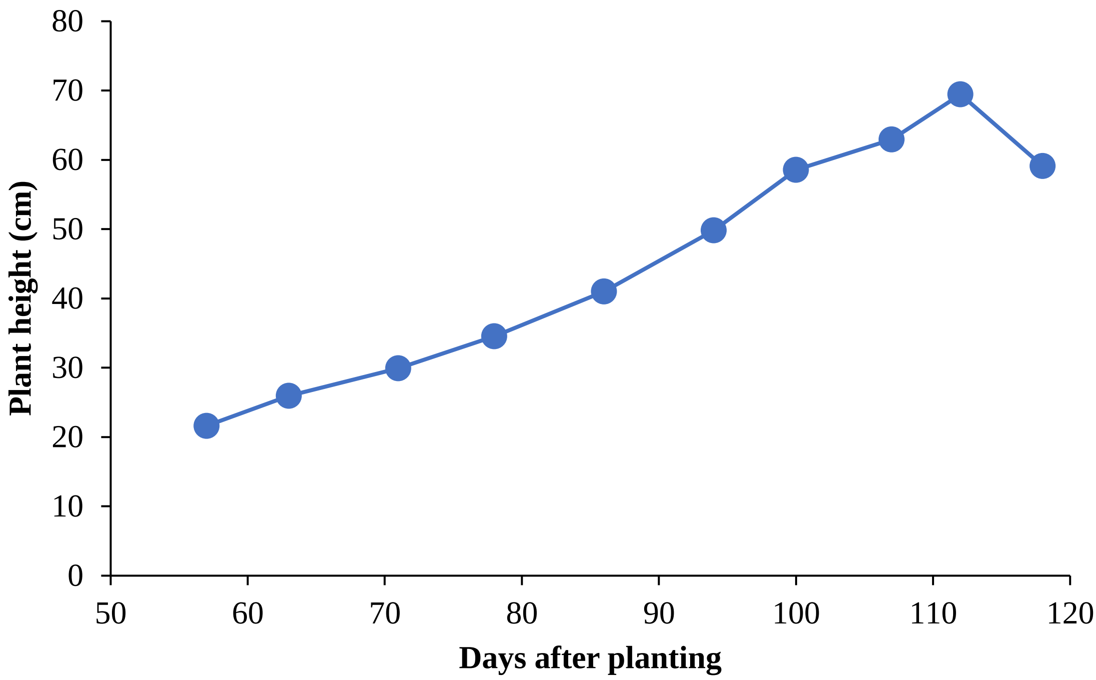

Figure 4.4: Plant height of orange-fleshed sweet potato grown under rainfed conditions over the 2021/22 growing season

4.3.2 Leaf number

From **Figure 4.5**, a similar trend was noted where leaf number (LN) steadily increased over the growing season until 112 DAP, after which it started to decline. From 57 to 112 DAP, LN increased on average by 9 every week, reaching its maximum value of 127. This value is substantially higher than that (~80) reported by Dladla (2017), who also grew sweet potato under peaked ridges at the same experimental site. The difference may have been caused by applying fertiliser in this study, which was not done by Dladla (2017). From 86 to 112 DAP, which represents the vegetative stage, LN increased from 80 to 127. This result is consistent with the increase in LAI seen in **Figure 4.6** (cf. **Section 4.3.3**). The reason for the sudden decrease in the LN was due to the animal damage which had occurred at the site.

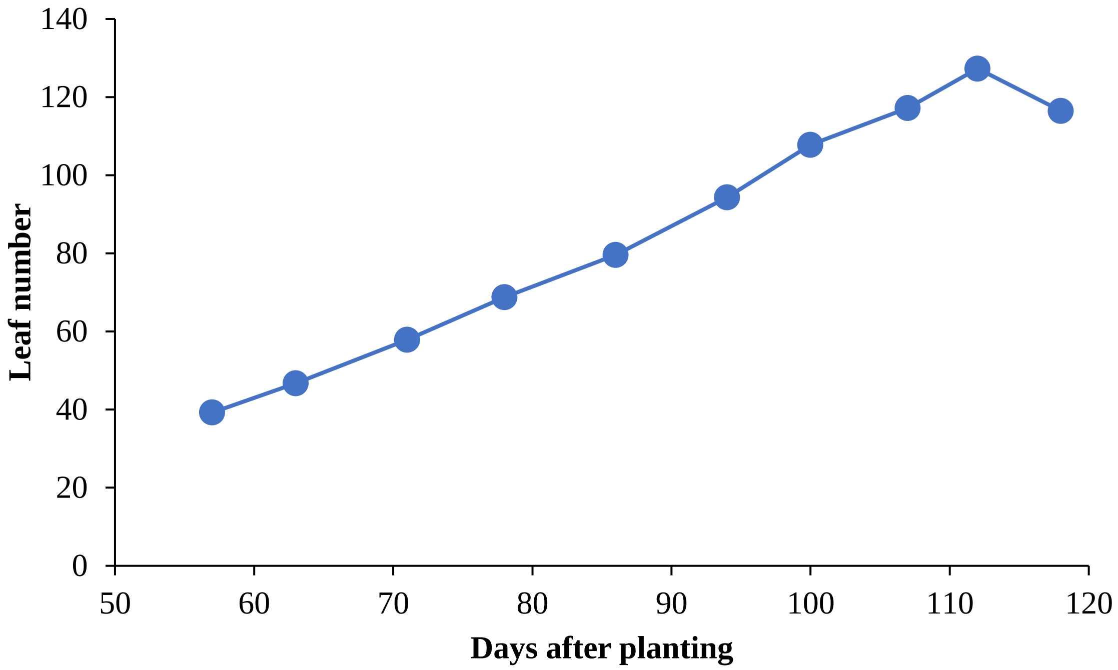

Figure 4.5: Leaf number of orange-fleshed sweet potato grown under rainfed conditions over the 2021/22 growing season

4.3.3 Leaf area index

The measured LAI trend for OFSP over the growing season is shown in **Figure 4.6**. The highest and lowest LAI values observed throughout the measurement period were 3.02 m^2 m^{-2} (at 112 DAP) and 0.49 m^2 m^{-2} (at 57 DAP), respectively. These measured LAI values were comparable to those reported by Nyathi et al. (2016), which ranged from approximately 1.8 to 4 m^2 m^{-2}. Gradual increases in LAI were observed from 71 to 78 DAP and 86 to 94 DAP. This was due to the decline in SC from 71 to 78 DAP (767 to 579 mmol m^{-2} s^{-1}, respectively) and 86 to 94

DAP (1256 to 1048 mmol $m^{-2} s^{-1}$, respectively) (cf. **Figure 4.3** in **Section 4.2.2**). Declining SC values indicate lower transpiration rates, which reduce the flow of CO_2 into plant leaves. This results in reduced photosynthetic rates and therefore, reduced plant growth.

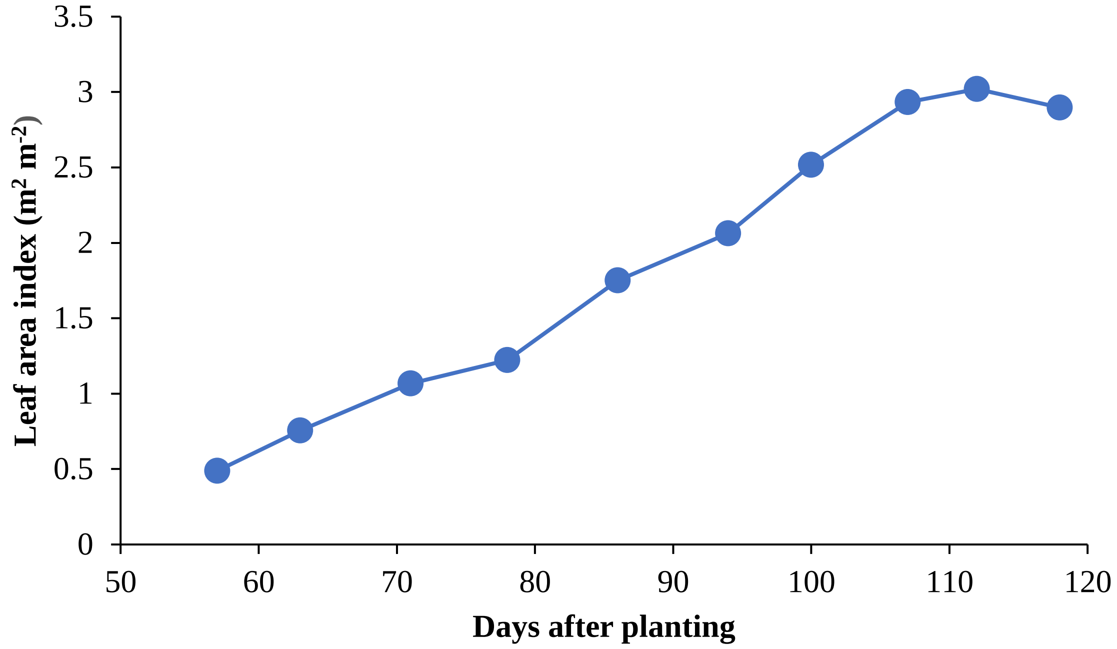

Figure 4.6: Leaf area index of orange-fleshed sweet potato grown under rainfed conditions over the 2021/22 growing season

4.3.4 Canopy cover

As noted in **Section 3.4.4.4**, canopy cover (CC) was estimated from LAI using the Beer-Lambert equation (**Figure 4.7**). As expected, CC followed a trend similar to LAI (cf. **Figure 4.6** in **Section 4.3.3**), since LAI is directly proportional to CC (Mabhaudhi et al., 2014). Maximum CC of 92.3% was reached at 112 DAP, which is an important parameter (CC_X) required by the AquaCrop model.

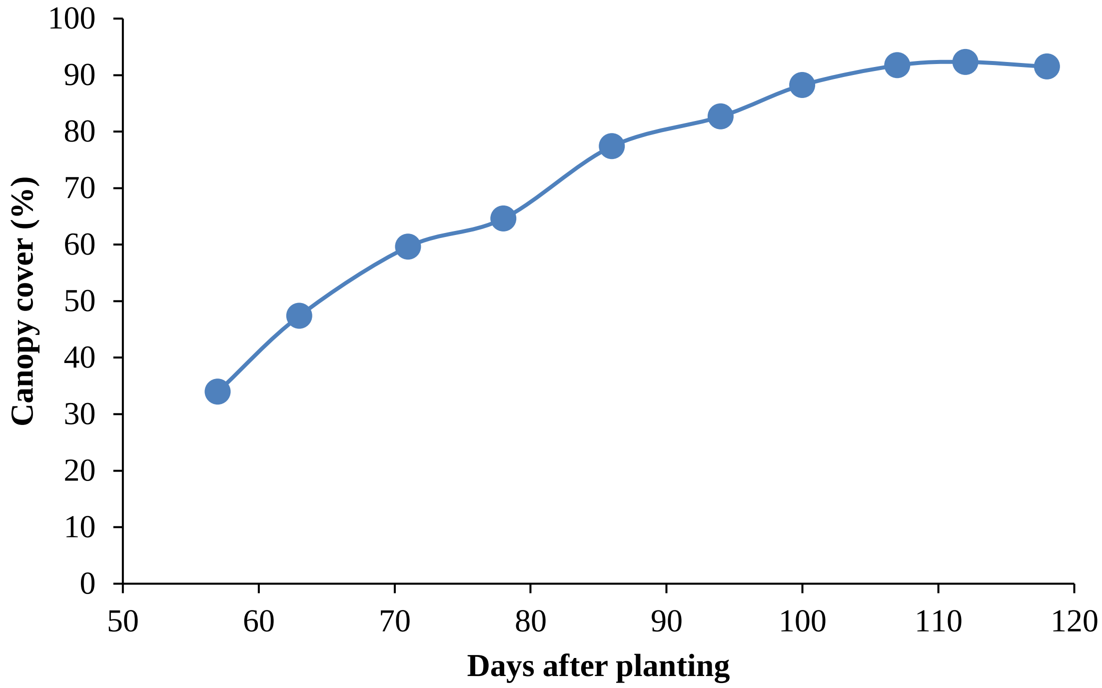

Figure 4.7: Estimated canopy cover of orange-fleshed sweet potato grown under rainfed conditions over the 2021/22 growing season

4.3.5 Total biomass accumulation

The accumulation of fresh biomass, measured weekly over the growing season, is presented in **Figure 4.8**. The decline in fresh above-ground biomass (AGB) after 100 DAP marked the translocation of carbon assimilates from above- to below-ground development, which results in reduced AGB and increased tuber yield. This is similar to findings reported by Al-Jamal et al. (2001), Belehu (2003) and Masango (2015). A plant's growth rate is negatively affected when it experiences a certain degree of water stress, since the growth rate is directly related to the leaf area and transpiration process (Chartzoulakis et al., 1993). Therefore, biomass accumulation is sensitive to water availability. Prolonged periods of water stress, especially at the critical stages of crop development, should be avoided. The lack of fresh AGB accumulation from day 71 to 86 may be attributed to the low average soil water content (10%) near the permanent wilting point during this period (cf. **Figure 4.10** in **Section 4.5.1**). This brief period of water stress caused the crop to reduce its leaf water content to conserve water and maintain a gradient for transpiration, which resulted in a gradual accumulation of biomass.

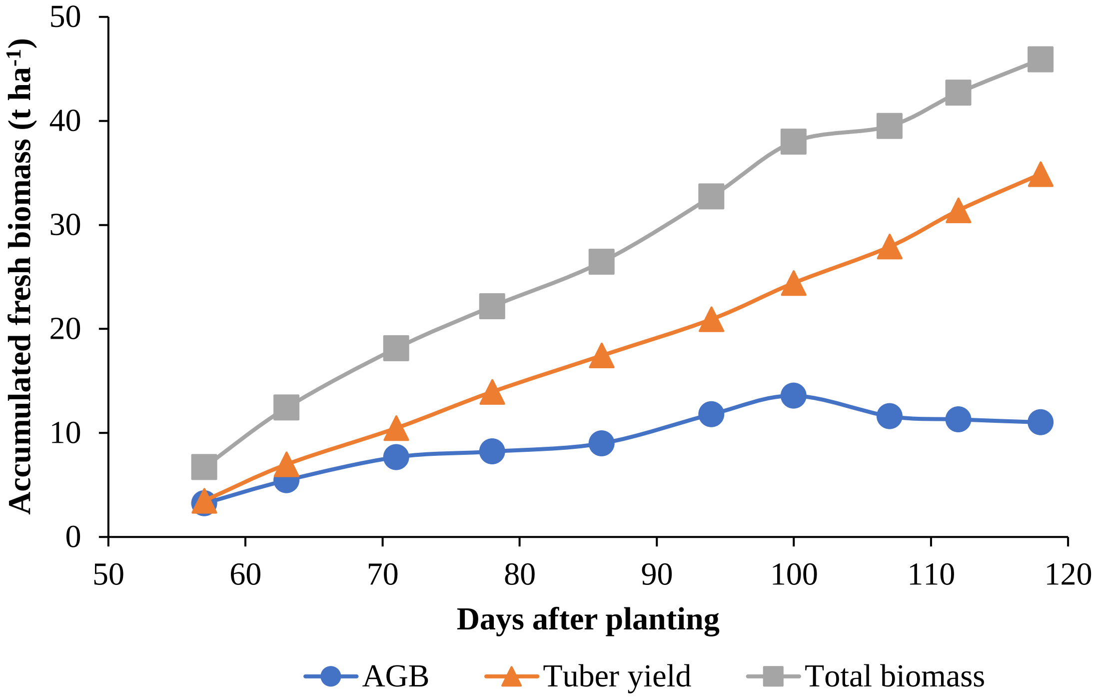

Figure 4.8: Fresh biomass accumulation of orange-fleshed sweet potato grown under rainfed conditions over the 2021/22 growing season

The accumulation of dry biomass is presented in **Figure 4.9**. The difference between the fresh (**Figure 4.8**) and dry biomass accumulation was minimal and substantial during the initial and latter stages of the measurement period, respectively. During the initial stage of crop development, the fresh crop had a low water content therefore, a small amount of water was lost during the oven-drying process. This was influenced by the low soil water content from 57 to 78 days after planting (average of 11%), which was relatively close to PWP (7%) (cf. **Figure 4.10** in **Section 4.5.1**). However, as the crop grew, the tubers and leaves accumulated larger amounts of water from the higher soil water content. Therefore, large differences between fresh and dry biomass accumulation were observed towards the end of the growing season. Masango (2015) found that over a growing season, the dry total biomass of sweet potato exhibits a sigmoidal curve, which was also observed in this study.

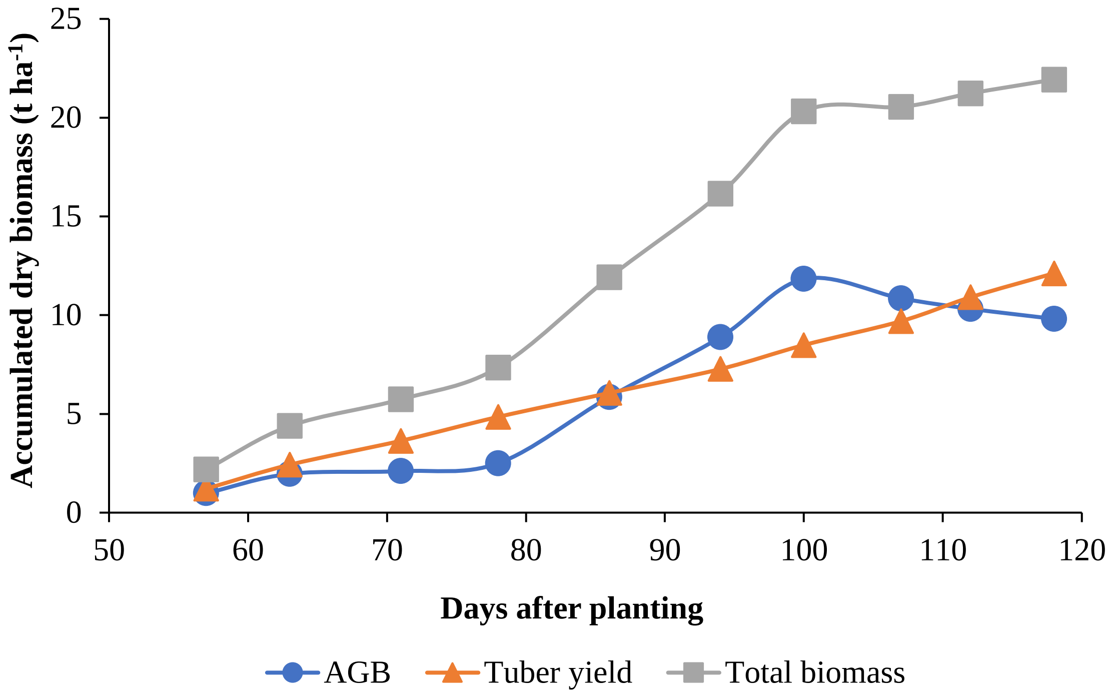

Figure 4.9: Dry biomass accumulation of orange-fleshed sweet potato grown under rainfed conditions over the 2021/22 growing season

4.3.6 Summary

Plant height of OFSP (cf. **Figure 4.4** in **Section 4.3.1**) showed a consistent trend, which was strongly correlated with leaf number (cf. **Figure 4.5** in **Section 4.3.2**) and leaf area index (cf. **Figure 4.6** in **Section 4.3.3**). The period when the crop was producing leaves was directly influenced by the plant's rapid growth in height from 86 to 112 DAP. The observed decrease in plant height, leaf number and leaf area index after 112 DAP was due to the crop approaching the maturity stage and start of leaf senescence. Fresh biomass accumulation was sensitive to soil water stress (cf. **Figure 4.8** in **Section 4.3.5**).

4.4 Final biomass, yield and harvest index

This section presents and discusses tuber yield and biomass accumulation (above-ground and total). The harvest index is also included in this section.

4.4.1 Final tuber yield

A week before harvest, damage was observed along the border rows due to animals (porcupines and bush pigs) gaining access to the experimental trial site by digging under the perimeter fence (cf. **Figure 7.3** in **APPENDIX A**). Despite numerous efforts to strengthen the surrounding fence with shade-cloth netting weighted down with large wooden poles, the animals continued to dig their way into the site, which was made relatively easy by the loamy sand texture. Therefore, the decision was made to prematurely harvest the crop on the 11th of April 2022 (118 DAP), which was 1 to 2 weeks before the desired harvesting date. A total of 30 plants were randomly harvested from two different rows (15 crops in each row). One week later, the experimental trial was completely decimated as a result of the animals continuing to gain entry to the site.

The 30 harvested plants produced 109 tubers, with a fresh and dry yield of 34.89 and 12.12 t ha^{-1}, respectively. Although sweet potato is consumed fresh, it is important to determine dry yield, which is useful for industrial processes producing dried foods (Mulovhedzi, 2017) and comparing observations with simulations from crop models. It is important to note that due to the premature harvest, higher crop yields could have been obtained. Since there is a direct relationship between actual crop evapotranspiration and yield (cf. **Equation 8** in **Section 3.5**), a longer growing season would have resulted in additional transpiration and increased tuber yields.

The dry tuber yield obtained in this study was substantially higher than the figure reported by Masango (2015) and Mulovhedzi (2017), which ranged from 6.5 to 7.6 dry t ha^{-1} and 7.5 to 8.7 dry t ha^{-1}, respectively. However, the dry tuber yield was in the range reported by Nyathi (2019) of 4.4 to 17.0 dry t ha^{-1}. The fresh yield obtained in this study is comparable to values of 25.0 to 31.0 t ha^{-1}, 29.7 to 32.2 t ha^{-1} and 7.6 to 35.5 t ha^{-1} that were reported by Masango (2015), Mulovhedzi (2017) and Dladla et al. (2019), respectively.

These comparisons of yield highlight the importance of studying crops under different management practices across a wide range of agroecological zones. This type of research helps to identify regions where high tuber yields can be produced under rainfed agriculture and where the crop can be grown in a water use efficient manner. However, it also questions the value of comparing yields obtained in different studies, especially when results are obtained in different seasons using different cultivars.

4.4.2 Biomass at harvest

Only the leaves, stems and vines contribute to AGB, while the total biomass includes AGB and tuber yield (Nyathi et al., 2019). The fresh and dry yield of ABG was 11.02 and 9.81 t ha^{-1}, respectively. This produced fresh and dry biomass totals of 45.91 and 21.93 t ha^{-1}, respectively.

The difference in AGB and tuber yields highlights the translocation process mentioned in **Section 4.3.5**.

4.4.3 Harvest index

The harvest index (HI) refers to the ratio of tuber yield to total biomass (Nyathi et al., 2019). As shown in **Table 4.1**, the fresh and dry HI obtained in this study was 76.0 and 55.3%, respectively. These values were comparable to those reported by Yeng et al. (2012), Masango (2015) and Mulovhedzi (2017), which ranged from 41 to 61%, 53 to 59% and 53 to 63%, respectively. Hartemink et al. (2000) stated that high (above-ground) vegetative growth reduces the economic tuber yield, which then lowers the HI. However, for dual-purpose crops such as sweet potato, relatively high HI values are desirable since a portion of the AGB (leaves) is edible.

Table 4.1: Fresh and dry tuber yield, above-ground biomass, total biomass and harvest index of orange-fleshed sweet potato grown under rainfed conditions over the 2021/22 growing season, expressed as a mass basis

Tuber yield		Above-ground biomass		Total biomass		Harvest index	
t ha^{-1}		t ha^{-1}		t ha^{-1}		%	
DM	FM	DM	FM	DM	FM	DM	FM
12.12	34.89	9.81	11.02	21.93	45.91	55.27	76.00

DM = dry mass; FM = fresh mass

4.5 Crop water use

In this study, the total water use of OFSP over the entire growing season was estimated using the soil water balance method, as described in **Section 3.4.6**. As a minimum, this method requires accurate estimates of rainfall and soil water content.

4.5.1 Change in soil water content

The depth-weighted soil water content (SWC) over the 0.60 m profile was calculated from values measured by the CS616 soil moisture probes at three depths. As shown in **Figure 4.10**, the profile PWP and FC values were 7 and 23%, respectively. Profile water content was closer to PWP because the loamy sand soil is unable to retain moisture and has a high drainage rate.

Since the average SWC did not drop to PWP, the crop did not experience severe water stress over the growing season. However, in some instances, even though a relatively large rainfall event occurred, profile water content did not increase as expected. This may be due to infiltrated rainfall that reached the 0.15 m probe, but not the 0.30 and 0.60 m probes. Since the SWC at 0.15 m did not exceed FC, it is unlikely that runoff occurred (cf. **Figure 10.1** in **APPENDIX D**). However, the CS616 soil moisture probes may not have been in adequate contact with the soil, due to its predominant loamy sand texture, which may have affected the measurements.

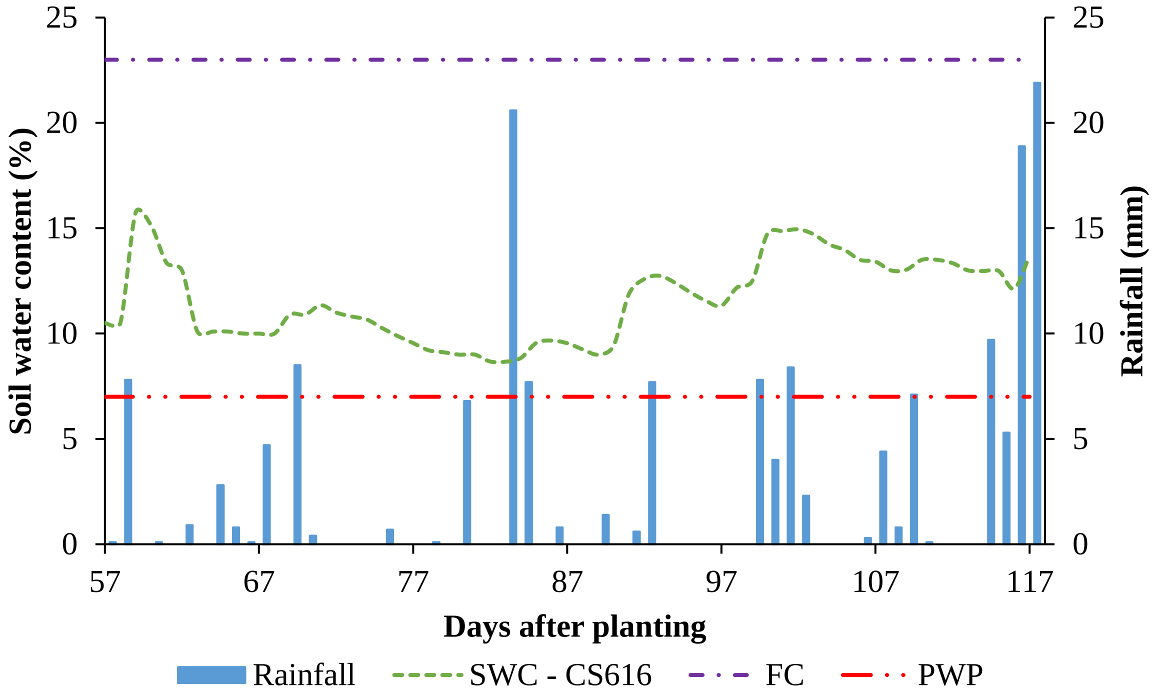

Figure 4.10: Profile water content measured by the CS616 soil moisture probes, together with rainfall, field capacity and permanent wilting point over the 2021/22 growing season at Fountainhill Estate

4.5.2 Actual crop evapotranspiration

Owing to the failure of the soil water sensors (as explained in **Section 3.4.2.1**), a daily soil water balance could not be calculated due to missing data and thus, a seasonal water balance was calculated. From **Table 4.2**, the total rainfall measured over the 118-day growing season was 472.90 mm. The final SWC measured by the CS616 probes was subtracted by the initial SWC measured by the CS650 probes (cf. **Section 3.4.2.1**) to calculate the change in SWC, which was estimated to be 4.77 mm. An accumulated ET_A of 468.13 mm was calculated using the soil water balance equation (cf. **Section 3.4.6**). This value is within the range of 400 to 500 mm that Bok (1998) reported as adequate for maximising the yield of OFSP under rainfed conditions.

Table 4.2: Soil water balance components which enabled the estimation of actual crop evapotranspiration (ET_A) of orange-fleshed sweet potato grown under rainfed conditions over the 2021/22 growing season

Total rainfall	Irrigation	Surface runoff	Drainage	Capillary rise	Change in soil water content	ET_A
mm	**mm**	**mm**	**mm**	**mm**	**mm**	**mm**
472.90	-	0.00	0.00	0.00	4.77	468.13

It is important to note that estimating ET_A using the soil water balance method has various shortcomings that ultimately reduce the accuracy of crop water use estimates (Richard et al., 2011). Firstly, actual crop evapotranspiration cannot be partitioned into soil water evaporation and transpiration. This complicates the estimation of productive water use that excludes soil water evaporation. The average crop canopy cover from day 57 to 118 after planting was 73%, which suggests that canopy development was sufficient to minimise soil water evaporation and to maximise water available for transpiration and crop growth.

Secondly, uncertainties in drainage and capillary rise values further reduce the confidence in estimated crop water use. Richard et al. (2011) stated that detecting errors in drainage is a complex process, since the estimation of these fluxes requires parametric modelling. As mentioned in **Section 3.4.2.1**, it was not possible to purchase additional CS616 probes to assess fluxes in soil water content below the effective rooting zone. Hence, drainage and capillary rise were therefore assumed to be negligible. Due to the sandy soil texture and high K_{SAT} value at the experimental site, drainage was unlikely to be negligible. Therefore, the ET_A value in **Table 4.2** is likely to be over-estimated.

Masango (2015) and Mulovhedzi (2017) conducted OFSP trials in Pretoria (Gauteng) and also assumed drainage and surface runoff to be negligible. Instead of measuring drainage loss, Masango (2015) simulated it using the SWB model. For this study, the profile water content simulated by the SWB model (not AquaCrop) was closer to observed profile water content (cf. **Figure 4.16** in **Section 4.9.3.1**). If drainage is accounted for using the value of 64.20 mm simulated by the SWB model, the estimated ET_A is reduced to 403.93 mm. This highlights the importance of considering drainage when estimating ET_A using the soil water balance equation.

Reddy (2020) stated that where lysimeters or micrometeorological instrumentation are not available (maybe due to budget limitations), the soil water balance method can still be used to provide crop water use estimations, but only for crops grown on small scales. However, values are likely to be over-estimated.

4.6 Crop water productivity

Table 4.3 shows the dry (2.59 kg m^{-3}) and fresh (7.45 kg m^{-3}) CWP values calculated from tuber yield, which are similar to values obtained from other studies. For example, Masango (2015) obtained a dry and fresh tuber CWP of 2.55 and 9.82 kg m^{-3}, respectively. Mulovhedzi (2017) obtained relatively similar values of 2.41 kg m^{-3} (dry) and 8.92 kg m^{-3} (fresh). Under conditions of supplemental irrigation, full fertilisation and no leaf harvesting, Nyathi (2019) obtained dry CWP tuber values ranging from 2.38 to 2.78 kg m^{-3}. Nyathi et al. (2016) highlighted the large variation in CWP values for OFSP obtained from different agroecological zones in South Africa. As mentioned before (cf. **Section 4.4.1**), the value of comparing yield and CWP values obtained in different studies is questionable.

Table 4.3: Crop water productivity of orange-fleshed sweet potato grown under rainfed conditions over the 2021/22 growing season

Water use	Tuber yield		CWP	
m^3 ha^{-1}	kg ha^{-1}		kg m^{-3}	
	DM	FM	DM	FM
4681.3	12 120	34 890	2.59	7.45

CWP = crop water productivity; DM = dry mass; FM = fresh mass

Crop water productivity (CWP) can be improved by increasing yield and/or decreasing ET_A. For example, growing OFSP in areas with no water stress and high evaporative demand (i.e. non-limiting conditions) and in soils that promote root expansion, tuber development and AGB accumulation, will likely maximise both crop yield and CWP. Furthermore, the CWP values obtained in this study could have been higher if harvesting had been delayed by 1 to 2 weeks, which would have likely resulted in a higher tuber yield. The dry and fresh CWP calculated using the ET_A estimated with simulated drainage (i.e. 403.93 mm; cf. **Section 4.5.2**) increased to 3.00 and 8.64 kg m^{-3}, respectively.

Mabhaudhi (2012) reported fresh CWP values for taro tubers that ranged from 0.06 to 0.53 kg m^{-3}, while Shelembe (2020) obtained a fresh CWP of 6.45 kg m^{-3}. The latter value is questionable, since it was calculated from an unusually high fresh yield of 56.54 t ha^{-1} and an applied irrigation amount totalling 870.6 mm (not ET_A). The final yield may have been over-estimated when tuber mass was scaled up to a per hectare basis. Values from Mabhaudhi (2012) were substantially lower when compared to the fresh CWP of OFSP obtained in this study (**Table 4.3**). It is clear that sweet potato is more water use efficient than taro, which is one of the main reasons why sweet potato was studied (and not taro). The high CWP exhibited by OFSP highlights the importance of prioritising the production of this RTC, especially under rainfed agricultural production.

4.7 Nutritional content

4.7.1 Tubers

Table 11.1 (cf. **APPENDIX E**) provides the average NC of dry OFSP tubers. High NC values were observed for K (23.25 g kg^{-1}), N (13.50 g kg^{-1}) and P (3.376 g kg^{-1}), which can be attributed to the application of an organic NPK fertiliser at planting. Hence, the tubers were able to take up and store the applied nutrients. In addition, some of the NCs were substantially higher than those reported in previous studies. For example, Mabhaudhi et al. (2019) reported values for Ca, Mg and Na that ranged from 0.0045 to 0.0048 g kg^{-1}, 0.0009 to 0.0010 g kg^{-1} and 0.0008 to 0.0011 g kg^{-1}, respectively. Furthermore, the Fe and Zn contents were 0.042 and 0.014 g kg^{-1}, respectively, while the Fe and Zn contents determined by Nyathi (2019) ranged from 0.0067 to 0.0236 g kg^{-1} and 0.0024 to 0.0043 g kg^{-1}, respectively. This highlights the large variation in nutrient contents of vegetable crops, which is influenced by numerous factors including plant variety, climatic conditions, environmental conditions (soil type and properties), water availability, harvesting methods and growing season lengths (Chapin, 1980; Uusiku et al., 2010). However, information regarding which of these factors have a major effect on the nutrient concentration of crops remains uncertain (Nyathi, 2019).

4.7.2 Leaves

The NC of dry OFSP leaves is presented in **Table 11.2** (cf. **APPENDIX E**), which showed higher values compared to the tubers for almost all of the elements. In particular, the leaves have much higher NCs (10-30 times) than the tubers for Ca, Mn, Mg and B and the reason for this is unknown. The Mg content in the leaves was high, considering Mg is easily leached from sandy and very acidic soils. As shown in **Table 3.1** in **Section 3.3.3**, the sandy soil at Fountainhill had a very low pH of 4. The availability of molybdenum (Mo) in acidic soils with a pH less than 4.5 is very limited (Kunz et al., 2020). In this study, Mo was low in both the tubers and leaves. Therefore, soil pH at the experimental trial site should have been corrected using agricultural lime to help increase the availability of Mo. As a trace element, Mo is important for humans as it affects the functioning of sulfite oxidase, xanthine and aldehyde oxidase enzymes (Rajagopalan, 1988). These enzymes are essential in processes involving the oxidation of sulfite to sulfate, uric acid production and the oxidation of aldehydes (Rajagopalan, 1988). Furthermore, African soils are typically deficient in Zn, Bo, Fe and Cu (Kihara et al., 2020). Therefore, when aiming to maximise micronutrient availability, foliar plant sprays consisting of these micronutrients should be applied regularly to the growing crop.

Overall, the above results confirm that OFSP is a dual-purpose crop, where both the tubers and leaves exhibit high nutritional value. The results support the finding by Chivenge et al. (2015) that a variety of root and tuber crops are known to be nutrient-dense thus, their consumption can 1) address nutrition insecurity issues, and 2) help to alleviate malnutrition.

4.8 Nutritional water productivity

The NWP was calculated as a product of the CWP and NC (cf. **Equation 9** in **Section 3.5**) and values for both OFSP tubers and leaves are shown in **Table 4.4**. Since CWP is constant, the NWP metric is most sensitive to NC. Leaves exhibited higher NWP values than the tubers, especially for Ca, Mn, B, Mg, Fe and S. As mentioned previously, various factors affect the nutrient content of crops. Therefore, production guidelines for RTCs should emphasise the importance of applying fertilisers and foliar sprays, as well as correcting soil pH to maximise crop yield and nutrient uptake, which strongly influences CWP and NWP values.

The NWP values for K (60.19 g m^{-3}), P (8.74 g m^{-3}), Ca (3.55 g m^{-3}) and Mg (2.61 g m^{-3}) in tubers were substantially higher than those reported in previous studies, due to the high NCs measured for these elements. Mabhaudhi et al. (2019) reported NWP values for Ca, Mg and Na of OFSP tubers (199062.1 cultivar) that ranged from 0.064 to 0.086 g m^{-3}, 0.007 to 0.019 g m^{-3} and 0.007 to 0.022 g m^{-3}, respectively. These NWP values were substantially lower than those obtained in this study. Furthermore, NWP values for Fe (0.11 g m^{-3}) and Zn (0.04 g m^{-3}) in the tubers were comparable to those obtained by Nyathi (2019), which ranged from 0.065 to 0.155 g m^{-3} and 0.016 to 0.036 g m^{-3}, respectively.

Table 4.4: Nutritional water productivity (NWP) of orange-fleshed sweet potato tubers and leaves grown under rainfed conditions over the 2021/22 growing season

Element	NWP (g m^{-3})	
	Tubers	Leaves
C	1099.30	851.85
K	60.19	49.06
N	34.95	78.85
P	8.74	6.56
Ca	3.55	84.51
Mg	2.61	22.67
S	2.07	6.50
β-c	0.51	n.d.
Na	0.16	0.15
Fe	0.11	0.47
Zn	0.04	0.04
Mn	0.03	0.45
B	0.01	0.13
Cu	0.01	0.01
Mo	0.00	0.00

β-c = beta-carotone; n.d. = no data

The NWP for β-carotene content in tubers (0.51 g m^{-3}) was higher than values reported by Mulovhedzi (2017), which ranged from 0.09 to 0.11 g m^{-3} but was similar to the range of 0.43 to 1.88 g m^{-3} given by Mabhaudhi et al. (2019) for the same cultivar. OFSP is well renowned for having a high β-carotene content. Laurie et al. (2012) recommended that breeding programmes should aim to improve NWP in tubers and leaves. This may assist in developing OFSP cultivars that can maintain their nutrient-dense traits under a variety of growing conditions, especially in low input agriculture.

4.9 Modelling crop water use and yield

As noted in **Section 1.2**, Modi and Mabhaudhi (2020) suggested that the water use and yield of RTCs should also be simulated with a crop model. Hence, results obtained from the modelling component of this study are presented in this section. Both the Soil Water Balance and AquaCrop models were run to estimate crop water use and yield of OFSP under rainfed conditions, from which CWP and NWP were derived. These models were partially calibrated using field observations to represent local crop species and growing conditions. The partial calibration of both models was evaluated by comparing simulations to observations using various statistical indicators (cf. **Section 3.6.7**). Where possible, output from both models is shown together to facilitate easier visual comparison.

4.9.1 Crop development

4.9.1.1 Leaf area index

The comparison of the simulated (SWB model) to the observed leaf area index is shown in **Figure 4.11**. The R^2 and d index statistics indicate a strong correlation between simulated and measured data. However, RMSE and NSE suggest the SWB model under-simulated LAI as shown in **Figure 4.11**, especially towards the end of the measurement period. Overall, the SWB model adequately simulated the LAI of OFSP grown at Fountainhill Estate in the 2021/22 season.

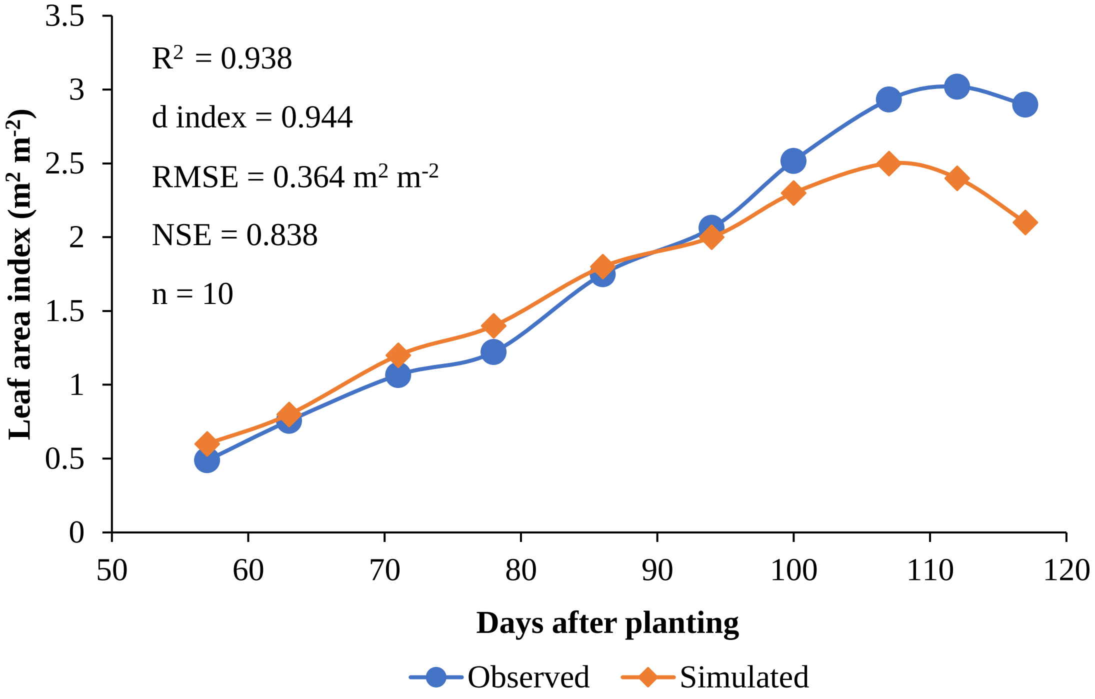

Figure 4.11: Simulation of leaf area index by the SWB model compared to observations for rainfed OFSP obtained at Fountainhill Estate over the 2021/22 season

4.9.1.2 Canopy cover

Figure 4.12 shows the comparison between simulated (AquaCrop model) and estimated CC. The latter was determined from LAI measurements as explained in **Section 3.4.4.4**. Despite a high R^2 and d index, AquaCrop under-simulated CC up to day 86 after planting, as indicated by RMSE and NSE statistics. Overall, AquaCrop's ability to simulate CC development was deemed adequate.

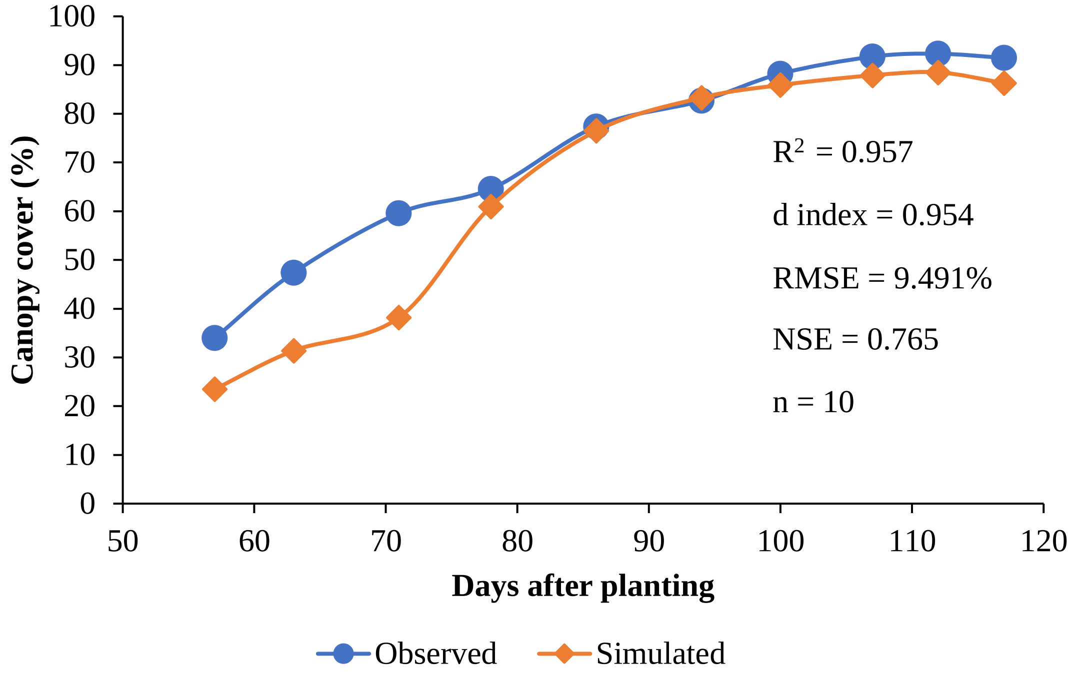

Figure 4.12: Simulation of canopy cover by the AquaCrop model compared to observations for rainfed OFSP obtained at Fountainhill Estate over the 2021/22 season

4.9.1.3 Above-ground biomass accumulation

The comparison between observed and simulated (SWB model) dry AGB is presented in **Figure 4.13**. Despite a reasonable R^2 and d index, the SWB model under-simulated AGB as indicated by the RMSE and NSE statistics. Despite this, the SWB model simulated the final AGB of OFSP well. Masango (2015) also found the SWB model to under-simulate dry AGB. This highlights a shortcoming of the model and thus, fine-tuning crop model parameters related to AGB should be investigated to improve AGB simulations. As shown in **Figure 4.14**, similar results were obtained for AquaCrop, although it performed slightly worse than the SWB model, except for the final AGB value.

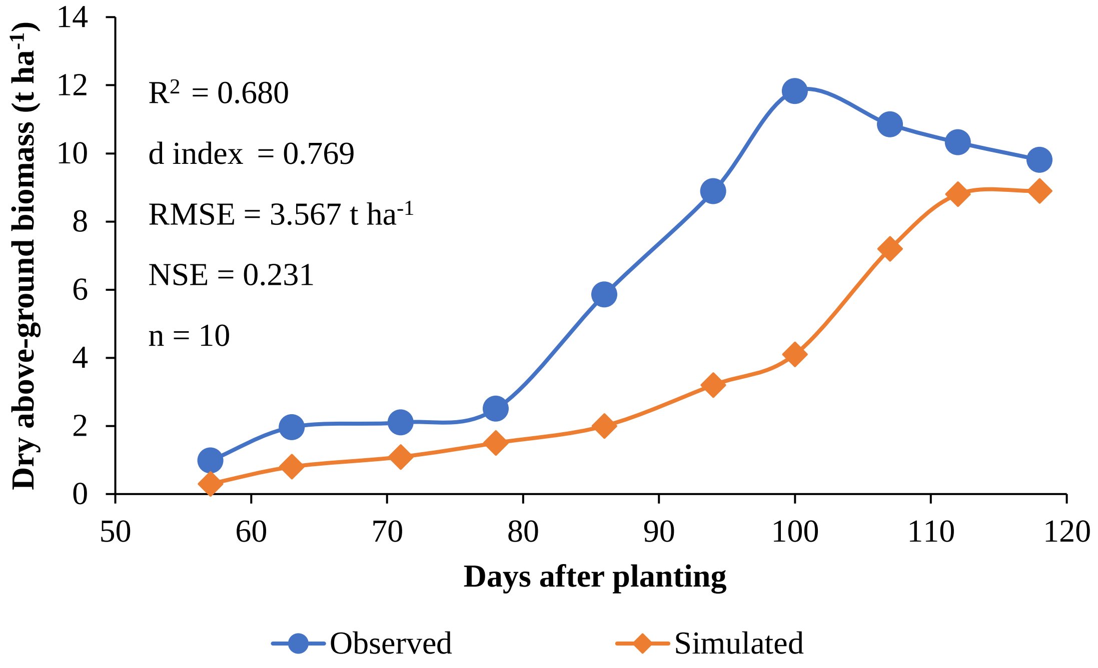

Figure 4.13: Simulation of dry above-ground biomass by the SWB model compared to observations for rainfed OFSP obtained at Fountainhill Estate over the 2021/22 season

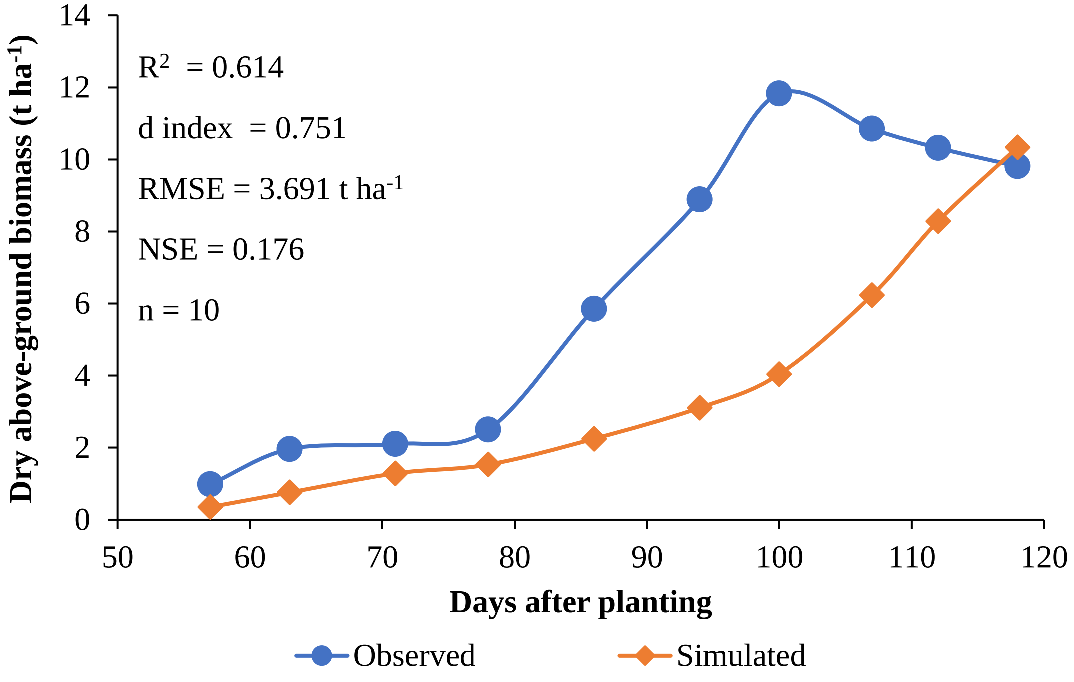

Figure 4.14: Simulation of dry above-ground biomass by the AquaCrop model compared to observations for rainfed OFSP obtained at Fountainhill Estate over the 2021/22 season

4.9.1.4 Tuber formation

The comparison between observed and simulated dry tuber yield is presented in **Figure 4.15**, which shows AquaCrop provided a better simulation when compared to the SWB model. Annandale et al. (2005) stated that the SWB model was originally designed for predicting crop water use and not for accurate yield simulations. They added that various consultants who used the model did not get sufficiently accurate yield and biomass simulations, which may explain the model's poor performance.

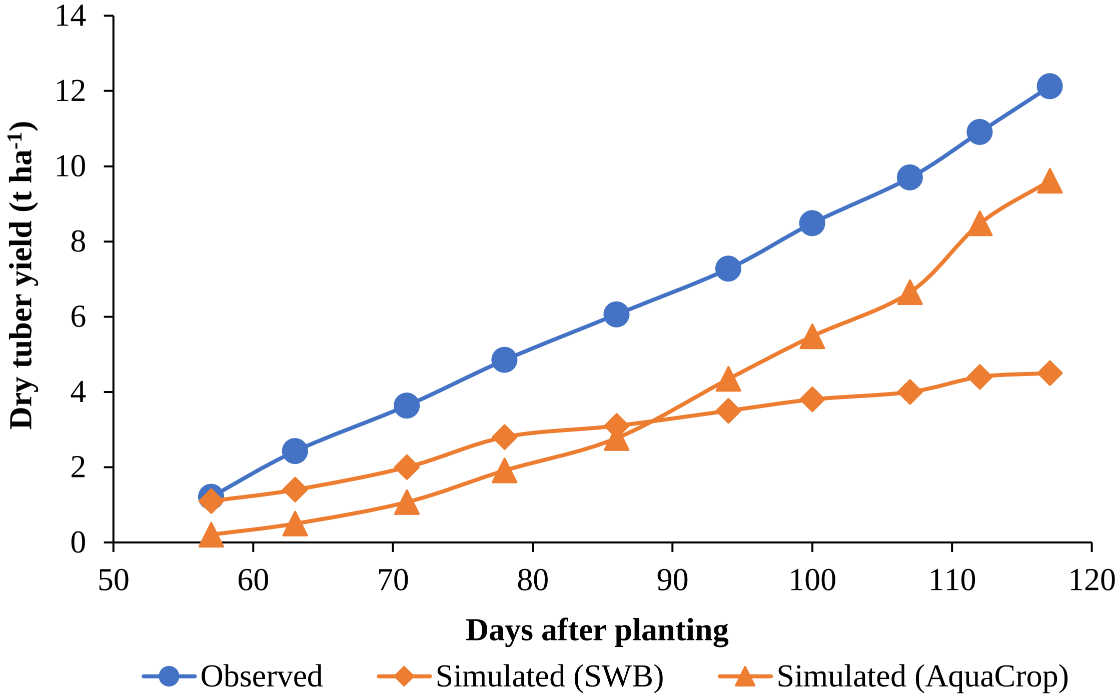

Figure 4.15: Simulation of dry tuber yield by the SWB and AquaCrop model compared to observations for rainfed OFSP obtained at Fountainhill Estate over the 2021/22 season

The statistics of dry tuber yield simulated by the SWB and AquaCrop model are presented in **Table 4.5**. Despite the high RMSE and low NSE indicating model under-simulation, the R^2 and d index were high, suggesting that AquaCrop's ability to simulate dry tuber yield is deemed adequate. However, the negative NSE and high RMSE statistics highlight the SWB model's inability to adequately simulate dry tuber yield.

Table 4.5: Statistics of dry tuber yield simulated by the SWB and AquaCrop model compared to observations for rainfed OFSP obtained at Fountainhill Estate over the 2021/22 season

Statistic	Crop simulation model	
	SWB	AquaCrop
R^2	0.964	0.971
d index	0.459	0.862
RMSE (t ha^{-1})	4.310	2.643
NSE	-0.533	0.423
n	10	

4.9.1.5 Summary

The SWB and AquaCrop models adequately simulated and estimated the LAI and CC of OFSP, respectively. Both model's showed reasonable simulations of the AGB of OFSP, especially towards the end of the season. However, the SWB model poorly simulated dry tuber yield when compared to AquaCrop, which will negatively impact CWP and NWP simulations. Therefore, it is recommended that AquaCrop should be used for simulating tuber yield of OFSP, especially if further improvements can be made regarding model calibration.

4.9.2 Final biomass, yield and harvest index

Both crop simulation models output dry biomass accumulation and tuber yield. The SWB model simulated a substantially lower tuber yield (4.50 dry t ha^{-1}) compared to AGB (8.90 dry t ha^{-1}) (**Table 4.6**). This suggests that the model did not adequately account for the translocation of assimilates from the leaves, vines and stems to the tubers as the crop approached maturity. This process usually results in a reduced rate of biomass accumulation and an increased rate of final tuber yield accumulation. This issue is further highlighted by the under-simulation of HI.

Table 4.6: Observed versus simulated data for final tuber yield, above-ground biomass, total biomass and harvest index for rainfed orange-fleshed sweet potato for the 2021/22 growing season

Method	Tuber Yield	Above-ground biomass	Total Biomass	Harvest index
	dry t ha^{-1}	dry t ha^{-1}	dry t ha^{-1}	%
Observed	12.12	9.81	21.93	55.27
SWB model	4.50	8.90	13.40	33.58
AquaCrop model	9.62	10.34	19.96	48.20

The AquaCrop model also under-simulated dry tuber yield and AGB, but to a lesser extent when compared to the SWB model (**Table 4.6**). Both models were able to adequately simulate the final AGB accumulation for OFSP. AquaCrop simulations of dry tuber yield and AGB (9.62 and 10.34 t ha^{-1}, respectively) production were substantially higher than simulations (2.36 and 3.80 t ha^{-1}, respectively) obtained by Beletse et al. (2013). The HI simulated by AquaCrop was 48.20%, which indicates an almost equal sharing of assimilates between AGB and tubers.

As mentioned in **Section 3.6.3.2**, the AquaCrop parameter file developed by Beletse et al. (2013) for locally grown OFSP could not be sourced. Hence, published crop parameters were used, with missing parameters gleaned from the crop parameter file obtained from Rankine et al. (2015). This non-ideal situation may have affected the accuracy of the AquaCrop model to simulate the crop water use and yield of OFSP. Therefore, calibration and validation of the model for locally grown OFSP should be undertaken in the future to further improve model performance.

4.9.3 Crop water use

4.9.3.1 Change in soil water content

According to Annandale et al. (2005), the SWB model is well suited to simulating crop water use and seasonal SWC. Similarly, AquaCrop provides adequate simulations of crop water use, biomass and yield (Mabhaudhi, 2012). Other studies also reported that AquaCrop is a valuable tool for simulating SWC (e.g. Pereira et al., 2015). However, neither model adequately estimated SWC when compared to measurements from CS616 soil moisture probes. For majority of the measurement period, the AquaCrop model simulated a higher SWC relative to the SWB model (**Figure 4.16**).

The SWB model's initial SWC was set at 18%, which was obtained from the CS650 probes at planting. For AquaCrop, the default option was used, which assumes the initial SWC is at FC (23%). This decision was due to AquaCrop's sensitivity to water stress at emergence (FAO, 2017a). On day 57 after planting, the simulated SWC had decreased to 9 (SWB model) and 21% (AquaCrop).

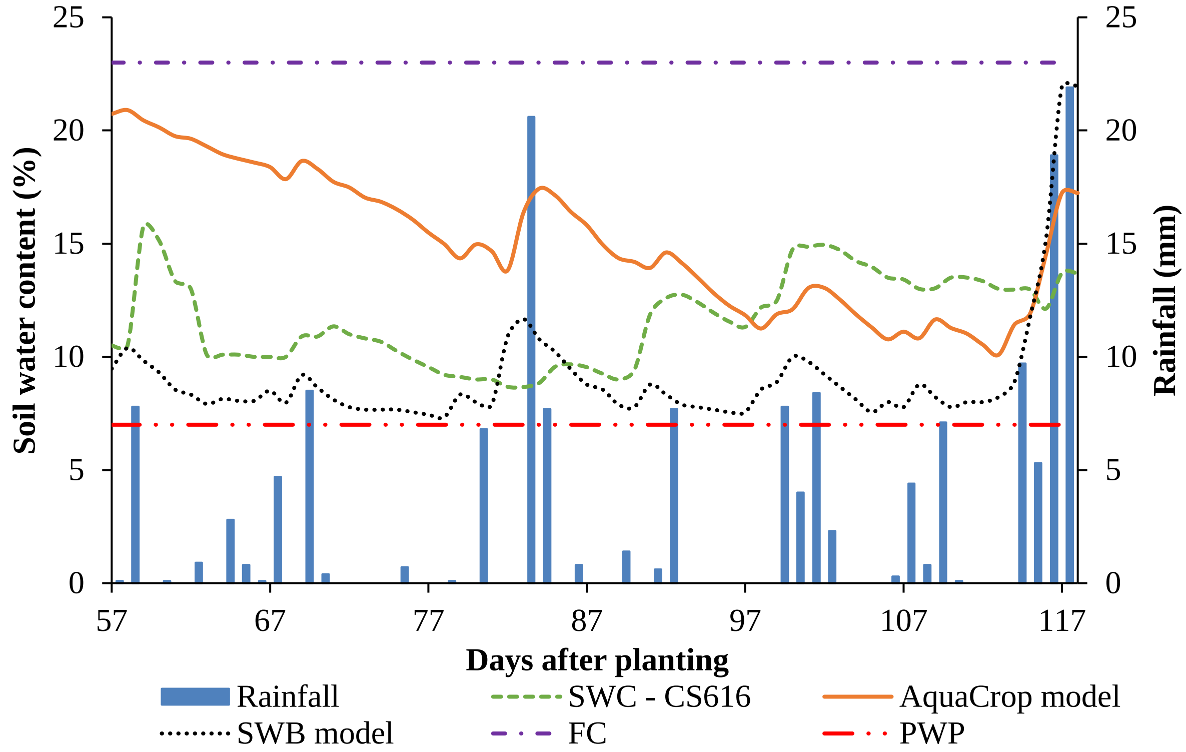

Figure 4.16: Comparison between profile water content measured by CS616 soil water content probes at Fountainhill Estate and simulations by the SWB and AquaCrop model

4.9.3.2 Actual crop evapotranspiration

The SWB model simulated a crop water use of 388.4 mm (**Table 4.7**), with total transpiration (216.3 mm) being higher that soil water evaporation (172.1 mm). The model successfully predicted LAI (cf. **Section 4.9.1.1**), which influences soil water evaporation. The AquaCrop model simulated a crop water use of 376.6 mm (**Table 4.7**), which was relatively similar to that simulated by the SWB model. However, AquaCrop simulated higher soil water evaporation (215.3 mm) compared to transpiration (161.3 mm). This may be attributed to the under-simulation of canopy cover from day 57 to 86 after planting (cf. **Figure 4.12** in **Section 4.9.1.2**).

Table 4.7: Observed and simulated soil water balance components, from which actual crop evapotranspiration was estimated for OFSP grown under rainfed conditions at Fountainhill Estate over the 2021/22 growing season

Variable (mm)	Observed	SWB model	AquaCrop model
Precipitation (P)	472.9		
Irrigation (I)	-	-	-
Runoff (R)	-	65.4	46.9
Drainage (Dr)	-	64.2	97.3
Change in soil water content (ΔS)	4.8	8.3	31.9
Crop water use (ET_A)	468.1	388.4	376.6

Both models simulated surface runoff. However, surface runoff was assumed to be negligible when calculating ET_A empirically (cf. **Section 3.4.6**), because the crop was planted on peaked ridges on a loamy sand soil. The soil has a high K_{SAT} value that suggests the infiltration rate is also high. As mentioned in **Section 4.5.1**, SWC at 0.15 m did not exceed FC, which suggests that runoff was unlikely to occur.

Both models estimated drainage beyond the root zone, which is likely due to the sandy soil texture. However, drainage was assumed to be negligible, which resulted in ET_A being over-estimated. Although the estimation of ET_A could be improved by accounting for drainage (cf. **Section 4.5.2**), it was not possible due to the unavailability of additional CS616 probes as well as the hard sandstone layer found below 60 cm (as mentioned in **Section 3.4.2.1**).

Many crop water use studies (e.g. Ibraimo, 2011; Masango, 2015) conducted at the University of Pretoria use the SWB model to estimate drainage. However, this approach was not taken in this study due to the uncertainty associated with the simulated drainage. As shown in **Table 4.7**, SWB and AquaCrop estimate different drainage amounts. Furthermore, other studies (e.g Ridley et al., 2001; Wilcox et al., 2006) also assumed drainage to be negligible.

4.9.4 Crop water productivity

The low CWP of 1.16 dry kg m^{-3} estimated from SWB model output was largely influenced by the low simulated tuber yield (4 500 dry kg ha^{-1}) (**Table 4.8**). The CWP calculated from AquaCrop simulations (2.55 kg m^{-3}) was substantially higher than that simulated by SWB and closer to the observed CWP, due mainly to the higher estimate of tuber yield. This suggests that AquaCrop is a better predictor for estimating CWP when compared to the SWB model.

Table 4.8: Observed versus estimated crop water productivity (CWP) of rainfed orange-fleshed sweet potato for the 2021/22 growing season

Method	Water use	Tuber yield	CWP
	m^3 ha^{-1}	kg ha^{-1}	kg m^{-3}
Observed	4 681	12 120	2.59
SWB model	3 884	4 500	1.16
AquaCrop	3 766	9 620	2.55

4.9.5 Nutritional water productivity

NWP was estimated as the product of NC and model-derived CWP. AquaCrop provided a better estimate of tuber yield and CWP than the SWB model (cf. **Table 4.8** in **Section 4.9.4**), which explains the results shown in **Table 4.9**. This further highlights AquaCrop's potential to provide more reliable CWP and NWP estimates. For the SWB model, as mentioned in **Section 4.9.4**, it is important to adequately calibrate the crop model to improve yield simulations, as this will result in more accurate estimates of CWP and NWP.

Table 4.9: Observed versus estimated nutritional water productivity (NWP) of rainfed orange-fleshed sweet potato for the 2021/22 growing season

Element	NWP (g m^{-3})		
	Observed	AquaCrop model	SWB model
C	1099.30	1084.61	491.92
K	60.19	59.38	26.93
N	34.95	34.48	15.64
P	8.74	8.62	3.91
Ca	3.55	3.50	1.59
Mg	2.61	2.58	1.17
S	2.07	2.04	0.93
β-c	0.51	0.50	0.23
Na	0.16	0.16	0.07
Fe	0.11	0.11	0.05
Zn	0.04	0.04	0.02
Mn	0.03	0.03	0.01
B	0.01	0.01	0.01
Cu	0.01	0.01	0.00
Mo	0.00	0.00	0.00

5. CONCLUSIONS

This chapter summarises the various approaches used to achieve the aims and objectives of this study. A summary of the main findings pertaining to each objective and recommendations for future research are also included in this chapter.

5.1 Summary of approach

This study aimed to highlight the limited research on the water use and yield of indigenous root and tuber crops, particularly sweet potato and taro. Of these two crops, sweet potato was selected for further study because of its higher water use efficiency under rainfed agricultural production. The orange-fleshed variety was selected (not the white/cream-fleshed variety) due to its high β-carotene content. Therefore, the study aimed to improve knowledge of sweet potato's crop and nutritional water productivity. It is envisaged that the knowledge gained from this study may assist in promoting the commercial production of this crop.

A field trial was established at Fountainhill Estate over the 2021/22 season to measure crop water use and yield under fully fertilised and rainfed conditions. The required fertiliser application rate was based on a soil fertility analysis. A micrometeorological station was installed at the experimental site to measure net radiation and wind speed, as well as minimum and maximum values of air temperature and relative humidity. Measurements were made at 15-minute intervals, from which hourly and daily values were calculated. The FAO ET_O Calculator software utility was used to estimate reference crop evapotranspiration (ET_O), which highlighted issues with data obtained from a nearby Automatic Weather Station (AWS) located at Fountainhill Estate.

From day 57 after planting, weekly measurements of 16 plants were undertaken. These included plant height, leaf number, leaf area index, leaf temperature, stomatal conductance and chlorophyll content index. Canopy cover developed was estimated from leaf area index measurements. Tuber formation and above-ground biomass (AGB) accumulation were also determined weekly via random destructive sampling. The final tuber yield and AGB was measured from 30 plants harvested 118 days after planting. The trial was harvested prematurely due to animals eating the tubers. Phenological growth stages were recorded as the time from transplanting to: recovered plant, maximum rooting depth, start of leaf senescence, start of yield formation and harvest maturity.

The soil water balance method was used to determine crop water use (ET_A). For this approach, precipitation and soil water content were measured and surface runoff, irrigation, capillary rise and drainage were considered negligible. Changes in soil water content were monitored by soil moisture probes installed at three depths, while daily measurements of precipitation were obtained from the AWS located at Fountainhill Estate. Crop water use, tuber yield and AGB obtained after harvest were used to estimate crop water productivity (CWP).

Harvested tuber and foliar samples were sent to a laboratory for analysis of nutrient content (NC), where the following elements were measured: B, Ca, Cu, Fe, K, Mg, Mn, Mo, Na, P and Zn. In addition, total C, N and S were also determined. The β-carotene content of tubers was also measured in a laboratory. The NCs and CWP value were then used to determine nutritional water productivity (NWP).

A multi-disciplinary approach was followed in this study that involved in-field measurements and simulations using two crop simulation models. Crop parameters required by the SWB model were obtained from Masango (2015). For the AquaCrop model, parameter values were obtained from Beletse et al. (2013) and Rankine et al. (2015). Soil parameters required by both models (e.g. saturation, field capacity, permanent wilting point and saturated hydraulic conductivity) were determined from laboratory measurements using the pressure outflow method.

Field observations were used to partially calibrate both models. For example, crop parameters associated with phenological growth stages were adjusted using observations in calendar days, which were then converted to thermal time (growing degree-days). The models were run to estimate crop water use, AGB and tuber yield, from which crop water productivity was estimated. Model performance was assessed by comparing simulations of leaf area index, canopy cover, AGB accumulation and tuber formation to field observations using various statistical indicators. The ability of both models to estimate profile water content was also assessed.

5.2 Summary of main findings

Biomass accumulation and tuber formation are sensitive to water availability. Therefore, prolonged periods of water stress, especially at critical stages of crop development (e.g. tuber initiation and filling), should be avoided. Based on measurements at the trial site, profile water content was closer to permanent wilting point than field capacity. This was due to the high drainage rate of the sandy soil found at the trial site. However, this did not have a detrimental effect on crop development, which suggests that sweet potato can utilise soil water held at higher matric potentials than other crops. Crop water use or actual crop evapotranspiration (ET_A) was over-estimated by the soil water balance method due mainly to drainage being considered negligible.

From the literature review, orange-fleshed sweet potato (OFSP) has a higher CWP when compared to taro. For this reason, the study aimed to improve existing knowledge of sweet potato's crop and nutritional water productivity. This may help to promote the production of this root and tuber crop, especially under rainfed agricultural production.

The leaves of OFSP exhibited higher nutrient content values compared to the tubers for almost all of the analysed elements. For example, the leaves exhibited NCs which were approximately 10 to 30 times higher than the tubers for Ca, Mn, Mg and B. The high β-carotene of the OFSP tubers highlights the crop's potential to alleviate deficiencies of vitamin A, especially in children. This also highlights the dual-purpose nature of this crop, where both the tubers and leaves exhibit high nutritional value. Therefore, promoting the consumption of OFSP can help address nutrition insecurity and to alleviate malnutrition, particularly in rural communities.

The AquaCrop model under-simulated the observed tuber yield, but to a lesser extent than the SWB model. This resulted in the observed CWP being higher than that simulated by both models. The simulation of AGB by the models was comparable to observed values. Furthermore, the AquaCrop-simulated harvest index (HI) was comparable to observations and substantially higher than the SWB-simulated HI. The SWB model's very low simulation of tuber yield negatively impacted the simulated HI. However, the adequate tuber yield and AGB simulation by AquaCrop enabled the model to better estimate the HI.

When compared to field observations, the crop models simulated similar ET_A but different tuber yields. This affected the accuracy of CWP estimates as this metric is sensitive to tuber yield, which then resulted in differences between measured and model-derived NWP values. The AquaCrop model estimated the observed CWP and NWP better than the SWB model. Hence, it is important to adequately calibrate the crop models to improve yield simulations, as this will result in more accurate estimates of CWP and NWP.

5.3 Revisiting the aims and objectives

The main aim of this study was to quantify the yield, water use and nutrient content of sweet potato grown under rainfed conditions, from which crop and nutritional water productivity were determined. Each specific objective was achieved as follows:

1) Establish a field experiment to quantify the crop's water use and yield - the first objective was achieved by conducting an orange-fleshed sweet potato field trial at Fountainhill Estate from December 2021 to April 2022 (**Section 3.1** to **3.3**), from which crop water use and yield were quantified. Results were presented in **Sections 4.4** to **4.5**.

2) Measure the nutrient content of harvested material in a laboratory - this was achieved by analysing the nutrient content of harvested leaves and tubers (**Section 3.5**), with results given in **Section 4.7** and **APPENDIX E**.

3) Estimate both crop and nutritional water productivity - the tuber yield and water use results from **Table 4.3 (Section 4.6**) were used to calculate crop water productivity. This metric, together with the crop's nutrient content (refer to objective 2 above) were used to estimate nutritional water productivity (cf. **Sections 4.6** to **4.8**).

4) Use field observations to partially calibrate two crop models - the fourth objective was achieved by using field-collected data to partially calibrate the Soil Water Balance and AquaCrop models by adjusting various existing crop parameters as suggested by Steduto et al. (2012) (**Section 3.6.4**). The default and adjusted crop parameters used in this study are given in **APPENDIX C**.

5) Simulate the crop's water use and yield under rainfed conditions with optimal fertilisation - the SWB and AquaCrop models were used to achieve the final objective by providing simulations of crop water use (**Table 4.7** in **Section 4.9.3.2**) and tuber yield (**Table 4.6** in **Section 4.9.2**) of orange-fleshed sweet potato, from which crop (**Table 4.8** in **Section 4.9.4**) and nutritional water productivity (**Table 4.9** in **Section 4.9.5**) were determined.

5.4 Recommendations for future research

Based on the findings from this study, the following recommendations for future research are made.

- It is recommended that drainage is measured (not assumed zero or simulated by a model) to improve the confidence in crop water use estimates derived using the soil water balance equation. This is especially true for studies conducted on sandy textured soils.

- The AquaCrop model should be modified to consider water losses from the evaporation of intercepted water.
- It is recommended that the SWB model is modified to account for various levels of soil fertility to improve yield simulations.
- The AquaCrop and SWB model should be calibrated and validated for different OFSP varieties to improve simulations across different agroecological zones.
- The CWP and NWP of other root and tuber crops under rainfed agricultural production should be investigated and compared to values for OFSP.
- Research aimed at enhancing the available knowledge on vine harvesting is needed to better understand its impact on sweet potato yield across different agroecologies.
- Furthermore, the way in which the production of OFSP can be commercialised should be assessed.

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7. APPENDIX A

(a) (b)

Figure 7.1: Vegetative propagation of orange-fleshed sweet potato (199062.1 variety) at (a) the University of KwaZulu-Natal's Ukulinga Research Farm, and (b) Agronomy greenhouse tunnel

Figure 7.2: Crop yield of orange-fleshed sweet potato grown over the 2021/22 growing season

(a) **(b)**

Figure 7.3: Evidence of animal entry (a) and damage (b) to sweet potato grown at the experimental trial at Fountainhill Estate during the 2021/22 season

8. APPENDIX B

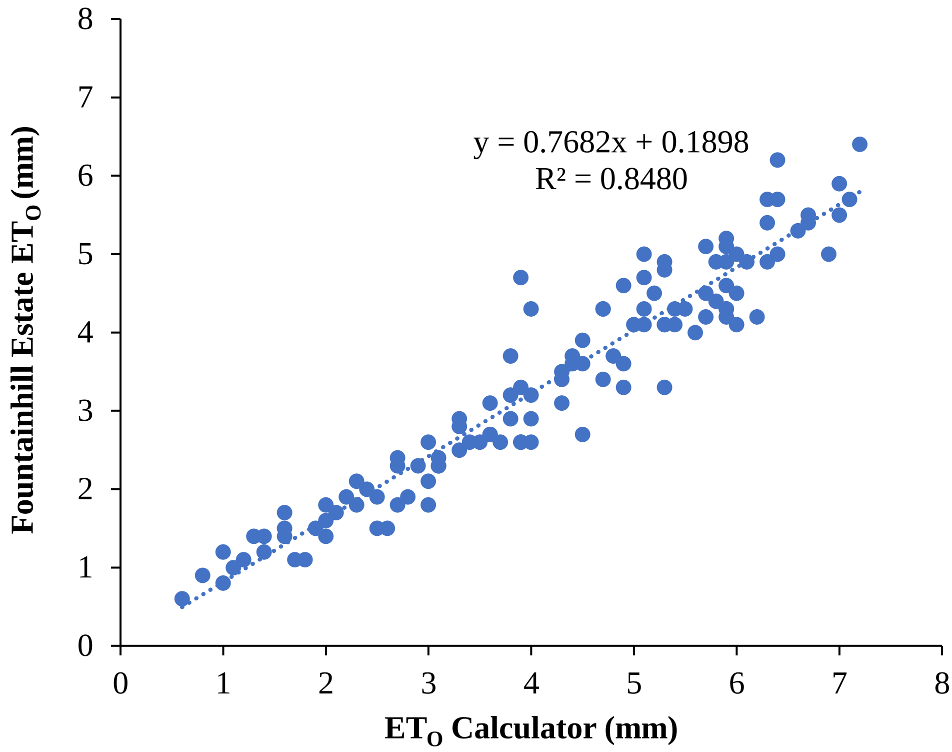

Figure 8.1: Reference crop evapotranspiration (ET_O) measured by the Fountainhill Estate weather station versus ET_O estimated by the ET_O Calculator

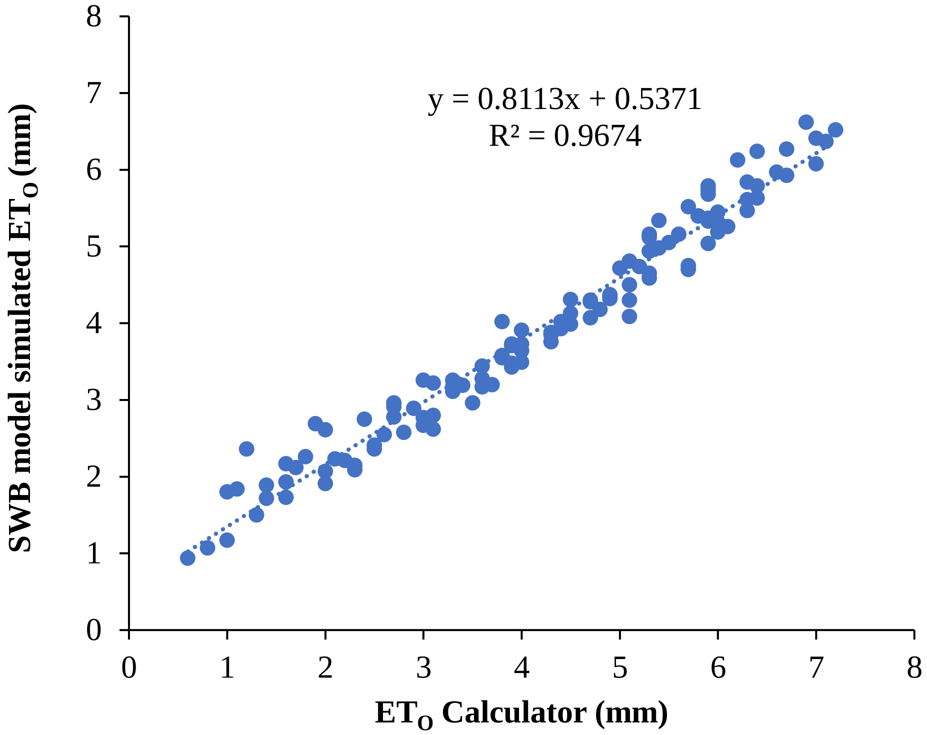

Figure 8.2: Reference crop evapotranspiration (ET_O) simulated by the SWB model versus ET_O estimated by the ET_O Calculator

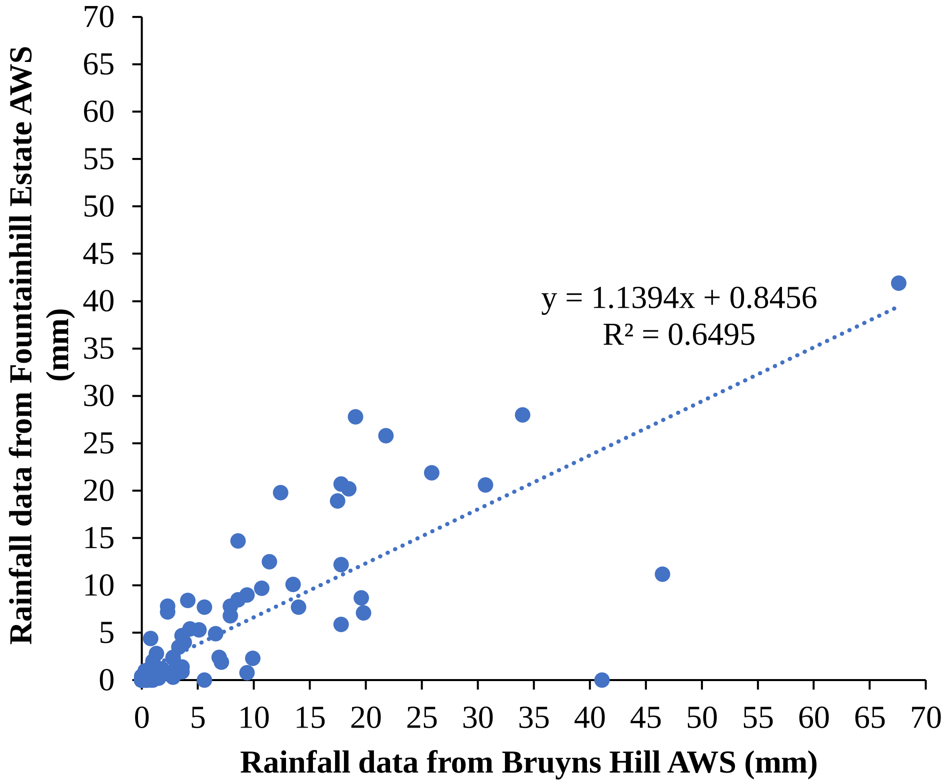

Figure 8.3: Rainfall data from the Fountainhill Estate AWS compared to data from the Bruyns Hill AWS

9. APPENDIX C

For running the SWB model, parameter values developed by Masango (2015) were used in this study (**Table 9.1**). However, certain parameters (as suggested by Steduto et al., 2012) were partially calibrated based on field observations at Fountainhill during the 2021/22 season (shown in bold in **Table 9.1**).

Table 9.1: List of crop parameters used to run the SWB model for sweet potato, with adjusted (i.e. partially calibrated) values highlighted in bold

Input crop growth parameters	Masango (2015)	Partially calibrated
Canopy radiation extinction coefficient	0.85	
Corrected dry matter to water ratio (Pa)	6.5	
Radiation conversion efficiency (kg MJ^{-1})	0.00121	
Base temperature (^{o}C)	8	
Temperature for optimum growth (^{o}C)	28	
Cut-off temperature (^{o}C)	38	**36.8**
Time to emergence (d ^{o}C)	25	**181**
Time to flowering (d ^{o}C)	650	**650**
Time to maturity (d ^{o}C)	1950	**1549**
Transition period (d ^{o}C)	480	**480**
Time to leaf senescence (d ^{o}C)	1650	**1524**
Maximum crop height (m)	0.60	**0.69**
Maximum root depth (m)	1.5	**1.0**
Fraction of total dry matter translocated to the roots	0.45	
Canopy interception storage (mm)	1	
Leaf water potential at maximum transpiration (kPa)	-1500	
Maximum transpiration (mm d^{-1})	8.0	**7.1**
Specific leaf area (m^2 kg^{-1})	9.8	
Leaf-stem partition parameter (m^2 kg^{-1})	1	
Total dry matter at emergence (kg m^{-2})	0.03	
Root fraction	0.15	
Root growth rate (m^2 $kg^{-0.5}$)	3.5	
Stress index	0.9	

For running the AquaCrop model, crop parameters obtained by Beletse et al. (2013) and Rankine et al. (2015) were used in this study (**Table 9.2**). Where possible, values provided by Beletse et al. (2013) were used. However, for parameters not provided by Beletse et al. (2013), values were obtained from Rankine et al. (2015). Field measurements collected in this study were used to partially calibrate the AquaCrop model (as suggested by Steduto et al., 2012) to better represent the (i) cultivar planted at Fountainhill during the 2021/22 season, and (ii) local climate conditions (shown in bold in **Table 9.2**).

Table 9.2: List of important crop parameters used to run the AquaCrop model for sweet potato, with adjusted (i.e. partially calibrated) values highlighted in bold

Crop growth parameter	Beletse et al. (2013)	Rankine et al. (2015)	This study
Base temperature T_B (°C)	8	15	
Cut-off temperature T_{UPPER} (°C)	35	35	**36.8**
Canopy growth coefficient (%/°C-day)	1.155	0.966	**0.006517**
Time to emergence (GDD)	-	77	**181**
Time to start senescence (GDD)	1974	1091	**1524**
Canopy decline coefficient (%/°C-day)	0.143	0.09529	
Growing cycle (GDD)	1967	1294	**1549**
Minimum rooting depth Z_{MIN} (m)	0.25	0.30	
Maximum rooting depth Z_{MAX} (m)	1	1.6	
Shape factor	2	0	
Time from transplanting to maximum rooting depth (growing degree days)	677	772	**874**
Crop transpiration coefficient (K_{cb})	1.5	1.1	**1.0**
Reduction with age (%/day)	0.15	0.15	
Water productivity (g m^{-2})	20	20	
Reference harvest index (%)	90	55	
Building up of HI (growing degree days)	261	872	**122**
Increase (%) of harvest index due to water stress before yield formation	-	8	
Increase (%) of harvest index	5	9	

10. APPENDIX D

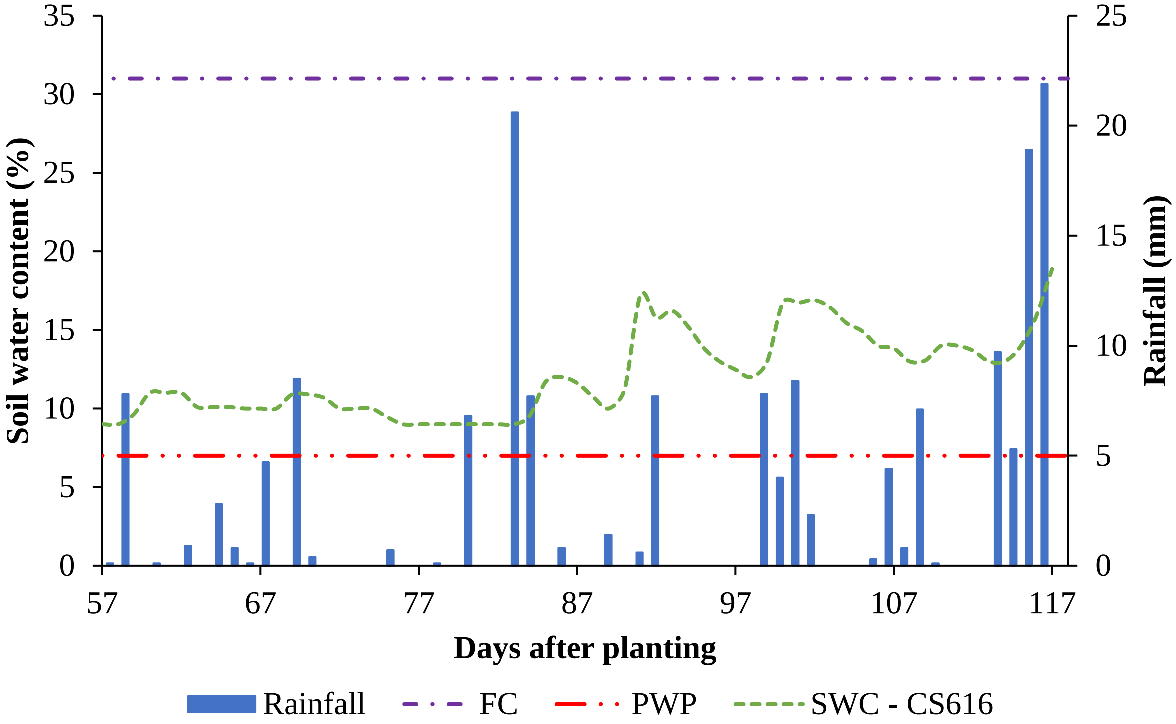

Figure 10.1: Profile water content measured by the CS616 soil moisture probe at 0.15 m soil depth, together with rainfall, field capacity and permanent wilting point over the 2021/22 growing season at Fountainhill Estate

11. APPENDIX E

Table 11.1: Nutrient content of orange-fleshed sweet potato tubers grown under rainfed conditions over the 2021/22 growing season

Nutritional value of OFSP tubers (g kg^{-1})															
	Macronutrients								Micronutrients						
Reps	**C**	**K**	**N**	**P**	**Ca**	**Mg**	**S**	**β-c**	**Na**	**Fe**	**Zn**	**Mn**	**B**	**Cu**	**Mo**
1	433.9	23.66	13.80	3.443	1.359	1.018	0.900	0.200	0.063	0.044	0.015	0.012	0.006	0.003	0.0001
2	417.7	23.90	13.30	3.402	1.391	1.021	0.600	0.200	0.062	0.045	0.015	0.012	0.005	0.003	0.0001
3	422.2	22.18	13.50	3.283	1.362	0.991	0.900	0.190	0.064	0.038	0.013	0.011	0.005	0.003	0.0003
Ave.	**424.6**	**23.25**	**13.50**	**3.376**	**1.370**	**1.010**	**0.800**	**0.200**	**0.063**	**0.042**	**0.014**	**0.011**	**0.006**	**0.003**	**0.0002**
SD	**8.4**	**0.93**	**0.30**	**0.083**	**0.020**	**0.020**	**0.200**	**0.000**	**0.001**	**0.004**	**0.001**	**0.001**	**0.001**	**0.000**	**0.0000**

Reps = replications; Ave = average; SD = standard deviation

Table 11.2: Nutrient content of orange-fleshed sweet potato leaves grown under rainfed conditions over the 2021/22 growing season

Nutritional value of OFSP leaves (g kg^{-1})															
	Macronutrients								Micronutrients						
Reps	**C**	**K**	**N**	**P**	**Ca**	**Mg**	**S**	**β-c**	**Na**	**Fe**	**Zn**	**Mn**	**B**	**Cu**	**Mo**
1	409.5	21.91	34.00	3.740	43.85	10.71	3.100	n.d.	0.070	0.260	0.010	0.110	0.080	0.0055	0.0006
2	398.7	22.98	34.10	2.610	47.19	12.31	3.000	n.d.	0.070	0.260	0.010	0.180	0.070	0.0037	0.0001
3	408.0	26.04	43.00	3.170	34.27	10.26	3.000	n.d.	0.070	0.230	0.030	0.320	0.050	0.0041	0.0001
4	404.4	20.86	34.30	3.330	40.39	10.83	2.900	n.d.	0.070	0.200	0.010	0.140	0.070	0.0040	0.0011
5	411.8	25.27	42.00	2.800	35.92	9.97	3.500	n.d.	0.070	0.170	0.020	0.340	0.050	0.0037	0.0004
Ave.	**406.5**	**23.41**	**37.50**	**3.130**	**40.33**	**10.82**	**3.100**	**n.d.**	**0.070**	**0.230**	**0.020**	**0.220**	**0.060**	**0.0042**	**0.0005**
SD	**5.1**	**2.20**	**4.60**	**0.450**	**5.380**	**0.90**	**0.200**	**n.d.**	**0.000**	**0.040**	**0.010**	**0.110**	**0.010**	**0.0007**	**0.0004**

Reps = replications; Ave = average; SD = standard deviation; n.d. = no data