UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Quantifying water use and nutritional water productivity of two sweet potato (*Ipomoea batatas*) cultivars grown in South Africa

By

Mulovhedzi Ntsieni

Submitted in partial fulfilment of the requirements for the degree
MSc (Agric.) Agronomy
In the Department of Plant and Soil Sciences
University of Pretoria

Supervisor: Dr. M. van der Laan
Co-supervisor: Dr. MK. Fessehazion
Dr. MG. Mengistu

August 2017

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

DECLARATION

I, Mulovhedzi Ntsieni, hereby declare that this dissertation submitted for the degree Master of Science (Agric.) in Agronomy is my own work, and has never been submitted by me at any other university, and that all reference material contained therein has been duly acknowledged

Signed:

Mulovhedzi Ntsieni

Date: August 2017

Place: Pretoria

ACKNOWLEDGEMENTS

I would like to express my greatest gratitude and appreciation to my advisors who have helped and supported me throughout my study. Foremost I would like to express my sincerely gratitude to my advisors Dr Michael van der Laan, Dr Michael Mengistu, and Dr Melake Fessehazion, for their patience, immense knowledge, motivation, enthusiasm, their guidance and insightful advice helped in all the time of research and writing up of the thesis.

To Nadia Ibraimo you have been a great motivation to me, your patience was remarkable. Thank you very much.

Thank you very much to Dr Sunette Laurie for valuable input during the study and Adre Van den Berg for providing technical assistance.

I am also grateful to the team of temporary workers that worked with me at the ARC–VOP farm for their assistance and support throughout my field work.

My gratitude also goes to the financial sponsors of this study the Agricultural Research Council Professional Development Programme and the National Research Foundation.

I am greatly thankful to my best mother Mrs Salphinah Netshivhambe for her generous support and encouragement, my beloved two brothers Mr Samuel and Mr Ndivhuwo Mulovhedzi thank you very much for the words of support, and my only sister Thabelo Mulovhedzi you kept me going, you are my hero.

Lots of thanks to almighty god for seeing me through every mountain and valley, he is the pillar of my strength.

DEDICATION

In loving memory of my late

Dad Mmbangiseni Mulovhedzi and,

Sister Mboniseni Mulovhedzi

You are never gone from my heart

Quantifying water use and nutritional water productivity of two sweet potato (*Ipomoea batatas*) cultivars grown in South Africa

by

Mulovhedzi Ntsieni

Degree: MSc (Agric.) Agronomy

ABSTRACT

The most accurate way of quantifying water use or evapotranspiration (ET) is achieved through direct physical measurements. Therefore, quantifying water use of sweet potato using the eddy covariance (EC) system which is one of the direct methods, and calculating crop growth parameters under optimal crop growing conditions, will improve our understanding and crop management practices. Also water scarcity is becoming more and more of a threat to food and nutritional security. Therefore, it is important to produce higher nutrients per unit of water used in order to alleviate malnutrition and to conserve natural water resources. Thus, it is important to do field trials for this crop in order to measure ET and calculate crop coefficient (K_c) to increase transferability of information generated to other scenarios. This information will help to improve agricultural production and livelihoods in arid and semi-arid areas mainly through improving nutritional water productivity (NWP), and irrigation water management within the sweet potato industry. The aim of this study was to: (a) quantify ET dynamics for sweet potato (*Ipomoea batatas*) in order to determine FAO-type K_c which can be used to estimate crop water use for a range of growing conditions, and (b) to investigate the effects of deficit irrigation on storage root yield, water use efficiency (WUE), nutritional content (NC) nutritional yield (NY) and NWP of commonly cultivated sweet potato cultivars in South Africa (SA) [one orange-flesh (OFSP) ‘Bophelo’ and one white-flesh (WFSP) ‘Blesbok’].

An eddy covariance (EC) system containing energy balance (EB) sensors was installed in a 1.3 ha field with only OFSP variety ‘Bophelo’ in order to quantify the water use. A second trial was composed of 18 plots of 5 m × 4 m (20 m^2), with a 2 m border between plots. Six treatment combinations of OFSP and WFSP and three water levels, termed full irrigation (FI), supplementary irrigation (SI) and rainfed (RF) were arranged in a randomized complete block design (RCBD) with three replications at the Agricultural Research Council–Vegetable and Ornamental Plants (ARC–VOP) Gauteng Province, SA. Daily ET varied between 0.5 to 5.5 mm (linked closely to canopy cover and weather conditions), with total seasonal ET measured at 361 and 347 mm for the 2014/2016 and 2015/2016 seasons, respectively. Averaged values of K_c were 0.46, 0.92 and 0.57 during the initial, middle and late growth stages, respectively. Final storage root yields were 32 t ha^{-1} (2014/2015) and 29 t ha^{-1} (2015/2016), with WUE of 89 and 85 kg ha^{-1} mm^{-1}, respectively. The study was conducted during 2014/2015 and 2015/2016 seasons, from January to May in both seasons.

Storage root yield for both OFSP and WFSP were significantly higher under FI compared to SI and RF treatments, and values recorded under the FI treatment were 35 t ha^{-1} and 39 t ha^{-1} for the OFSP and WFSP cultivars, respectively. The NC for β-carotene, iron (Fe) and zinc (Zn) was

significantly higher under RF conditions compared to SI and FI treatments. For OFSP the β-carotene, Fe and Zn contents measured mean values for the RF were 14.2, 1.5 and 0.8 mg 100 g^{-1}, respectively, while for WFSP, β-carotene, Fe and Zn contents measured mean values for the RF treatment were 1.4, 1.1 and 0.8 mg 100 g^{-1}, respectively.

No significant differences in β-carotene content were recorded under SI, FI and RF treatments for these cultivars. The best crop performance when considering NY (β-carotene, Fe and Zn) was significantly higher under the FI treatment for OFSP. On the other hand, for WFSP, higher β-carotene yield was obtained under SI condition, albeit non-significant; however, Fe and Zn yield was significantly higher under FI treatment. For OFSP, the highest NY (β-carotene, Fe and Zn) recorded mean values were 419 463.0, 63 473.0 and 30 755.0 mg ha^{-1}, respectively, and for WFSP, highest recorded mean values were 51 750.0, 70 480.0 and 32 610.0 mg ha^{-1}, respectively.

Water use efficiency was higher under the FI and SI treatments, and was 81.36 kg ha^{-1} mm^{-1} and 97.24 kg ha^{-1} mm^{-1} for OFSP and WFSP, respectively. The NWP in terms of β-carotene for the OFSP cultivar was highest under the RF treatment and lowest under the SI treatment at 108.5 and 93.9 mg m^{-3}, respectively. But different results were obtained for Fe and Zn WP, for which the highest Fe and Zn WP was recorded for the FI treatment at 14.5 and 7.0 mg m^{-3}. The highest β-carotene, Fe and Zn WP was observed under the RF treatment for the WFSP at 22.2, 19.0 and 12.0 mg m^{-3}.

For the second trial the ET of both cultivars was significantly higher under the FI treatment, and the recorded mean values under FI, SI and RF treatments for OFSP, were 437, 293 and 208 mm, while for WFSP, were 427, 278 and 196 mm. This suggests that soil water stress significantly

affects the sweet potato storage root yield, WP, NC, NY and NWP. The study was conducted during 2015/2016 season.

The development of K_c values for sweet potato can be used to improve irrigation water management for irrigated sweet potato cropping systems in SA using the FAO-56 approach. These results for sweet potato (orange and white-fleshed) yield, WP, NC and NWP from this study can be used to address issues of food and nutritional security in SA.

Keywords: crop coefficients, FAO-56, surface energy balance, eddy covariance, deficit irrigation, β-carotene, evapotranspiration, supplementary irrigation

TABLE OF CONTENTS

CHAPTER 1: INTRODUCTION

CHAPTER 2: LITERATURE REVIEW

CHAPTER 3: MEASURING EVAPOTRANSPIRATION AND DEVELOPING CROP COEFFICIENTS FOR SWEET POTATO (*IPOMOEA BATATAS*) USING THE EDDY COVARIANCE SYSTEM

CHAPTER 4: INFLUENCE OF DIFFERENT IRRIGATION STRATEGIES ON YIELD AND WATER PRODUCTIVITY OF SWEET POTATO (*IPOMOEA BATATAS*)

CHAPTER 5: INFLUENCE OF IRRIGATION STRATEGIES ON THE NUTRITIONAL WATER PRODUCTIVITY OF SWEET POTATO (*IPOMOEA BATATAS*)

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND SYMBOLS

ANOVA	Analysis of variance
AWS	Automatic weather station
CPPMU	Central planning and project monitoring unit
CO_2	Carbon dioxide
Cl-	Chloride
DAP	Days after planting
DAFF	Department of Agriculture Forestry and Fishery
DI	Deficit Irrigation
DM	Dry matter
d	Zero plane displacement height
EC	Eddy covariance
ET	Evapotranspiration
ET_o	Penman-Monteith reference evapotranspiration
FAO	Food and Agriculture Organization
FC	Field capacity
FI	Fractional interception
Fe	Iron
G	Soil heat flux
HI	Harvest Index
H	Sensible heat flux
IRGA	Infrared gas analyzer

K_c	FAO crop factor
K	Potassium
LE	Latent flux of vapourization
LAI	Leaf area index
NWP	Nutritional water productivity
OPEC	Open path eddy covariance
OFSP	Orange fleshed sweet potato
PAR	Photosynthetically active radiation
PAW	Plant available water
R_n	Net radiation
RF	Rainfed treatment
RCBD	Randomized complete block design
RMSE	Root mean square error
R	Runoff
R_s	Solar radiation
SABS	South Africa Bureau of Standards
SRY	Storage root yield
Tx	Daily maximum air temperature
Tn	Daily minimum temperature
T_s	Sonic temperature
TDR	Time domain reflectometry
TDM	Top dry matter
u	Horizontal wind velocity

u_2	Wind speed at 2 m height
v	Vertical wind velocity
WU	Water use
WUE	Water use efficiency
WFSP	White fleshed sweet potato
w	Vertical wind speed
Y_a	Actual crop yield
ΔSWC	Change in soil water content, usually measured continuously or manually with a variety of techniques
ε	Wind direction

CHAPTER ONE

INTRODUCTION

1.1 Background

Globally, sweet potato (*Ipomoea batatas*) is an important staple food crop, and it is mainly grown in tropical climates and parts of the world where temperatures are relatively high (Laurie, 2004). Sweet potato is commonly grown for its edible storage roots which contain high levels of β-carotene, vitamin C, iron (Fe) and zinc (Zn) (Ye et al. 2000; Sirvuman et al. 2006). Sweet potato originated in central and southern America (Laurie, 2004). Currently the area under sweet potato production in South Africa (SA) is about 2000-3500 ha (Laurie, 2004). While white-fleshed sweet potato (WFSP) is the most produced cultivar due to its ability to attain higher marketable yields, its β-carotene levels (the major precursor of vitamin A) are, however, significantly lower compared to orange-fleshed sweet potato (OFSP) cultivar. As a result, OFSP is becoming increasingly popular in SA, especially among smallscale farmers in rural areas. Its consumption can play an important role towards improving human diet and alleviating malnutrition (Bester et al. 1991; Laurie, 2004; Van Jaarsveld et al. 2005; Burri, 2011).

Sweet potato is planted mainly in the rainy season, and is considered a drought tolerant crop (Laurie. 2004, Laurie et al. 2015; Motsa et al. 2014). Few studies have been completed on the water use or evapotranspiration (ET) (Gome and Carr, 2003; Karanja, 2006; Masango, 2014; Nyathi et al. 2016) and nutritional water productivity (NWP) of sweet potato at different water stress levels. However, varying seasonal ET rates have been reported as affected by different factors such as weather conditions and crop management practices (Bok, 1998; Laurie et al. 2009; Beletse et al. 2011; Jovanovic and Israel; 2012; Lewthwaite and Triggs, 2012; Laurie et al. 2012; Beletse, 2013; Prabawardani and Suparno, 2015).

According to Jovanovic and Annandale (2000), often the most accurate way of estimating water use or ET is achieved through direct physical measurements. Therefore, estimating water use of sweet potato using the eddy covariance (EC) system which is one of the direct methods, and calculating crop growth parameters under optimal crop growing conditions, will improve our understanding and crop management practices. Therefore, it is important to do field trials for this crop in order to measure ET and calculate crop coefficient (K_c) to increase transferability of information generated to other scenarios.

Beletse et al. (2013) reported that sweet potato produce higher yields when irrigated optimally and yield decreases with water stress. However, water stress effects on NWP of the most common sweet potato types (white, orange and purple-fleshed), is limited. This information will help to improve agricultural production and livelihoods in arid and semi-arid areas mainly through improving NWP, and irrigation water management within the sweet potato industry (Oweis and Hachum, 2004).

1.2 Problem Statement

With the increased demand for sweet potato by fresh produce consumers and processing industries in SA, there is a need to improve the yields and nutritional value of this crop, including through the use of appropriate irrigation management. Sweet potato has adapted to local conditions very well and therefore has excellent potential in helping address SA’s food insecurity problems. At present there is limited information on the water use and NWP of sweet potato as affected by water stress in SA and globally. It is envisaged that this information will have a significant contribution to better management practices of sweet potato to improve yields, quality and NWP.

1.3 Research aim and objectives

The aim of this study was to: (a) quantify ET dynamics for sweet potato in order to determine FAO-type (K_c) which can be used to estimate crop water use for a range of growing conditions, and (b) to investigate the effects of deficit irrigation on storage root yield, water use efficiency (WUE), nutritional content (NC), nutritional yield (NY) and NWP of commonly cultivated sweet potato cultivars in SA (one OFSP 'Bophelo' and one WFSP 'Blesbok')**.**

The specific objectives of this study are to:

- Measure seasonal water use of sweet potato grown under optimal crop growing conditions using the eddy covariance technique;
- Determine FAO-type sweet potato crop coefficients;
- Quantify the effects of different irrigation levels on sweet potato yield, quality and NWP.

1.4 Hypotheses

1. Increased water stress will decrease sweet potato yield while increasing nutritional content and nutritional water productivity per unit yield.
2. Under water stress conditions, WFSP cultivar 'Blesbok' will produce more total dry matter than OFSP cultivar 'Bophelo' due to lower energy investment in the production of β-carotene and other more complex nutrients.

3. Even under non-limiting water conditions, OFSP cultivar ‘Bophelo’ will produce more nutritious roots than WFSP cultivar ‘Blesbok’.

CHAPTER TWO

LITERATURE REVIEW

2.1 Production of sweet potato *(Ipomoea batatas)*

Sweet potato *(Ipomoea batatas)* is an herbaceous crop of the convolvulceace family, (Shukla, 1976; Hahn, 1977; Jana, 1982; Bourke, 1982). Their roots which store starch are characterized by different sizes, shapes, and colours. The most common colours of sweet potatoes include, purple, yellow, white and oranges (O'Sullivan et al. 1997; DAFF, 2011; Wenold et al. 2012). Both sweet potato roots and leaves are used as food by people (Sirvuwan et al. 2006). Sweet potato has the same amount of carbohydrate as potato, rice, maize and sorghum, and contains about 20 mg 100 g^{-1} of β-carotene (Woolfe, 1992). Sweet potato is also processed in industries to produce different products such as chips, alcohol, flour, butter and baby food (Laurie, 2004; DAFF, 2011).

Sweet potato can survive in tough conditions (van den Berg and Laurie, 2004; Motsa et al. 2015). Beletse et al. (2013) reported that to achieve maximum yield, cultivation practices including; climate and irrigation must be optimum. They grow well in loamy, clay and sandy soil areas with maximum and minimum temperature ranging from 15–30°C (du Plooy, 1991; van den Berg and Laurie, 2004).

Sweet potato is one of the most important root crop worldwide (Horton, 1988). It is ranked seventh food crop after wheat, maize, cassava, potato, rice and barley and third root crops after cassava and Irish potato (FAO, 1996). According to FAO (2000), more than 140 million tons of sweet potato is produced every year with 129 million tons being produced in Asia. In Africa, about 9 million tons of sweet potato is produced annually. However, most of it is grown on smallscale farms especially for use in rural household and for food security (Ewell and Mutaura, 1994).

The South Africa (SA) sweet potato industry is increasing steadily, however, it is still behind other African countries such as Burundi, Rwanda, and Uganda. This is due to the fact that in those countries, sweet potato is used as a staple food (Minde et al. 1999). In 2005, SA produced 51000–65000 tons of sweet potato, with a total value of R 30–35 million (FAO, 2007; DAFF, 2011). Although, most of the sweet potato produced in rural areas by informal sector and smallscale farmers in large quantities is not included in this production figures (Domola, 2003; Laurie, 2004). The area where sweet potato is grown is estimated to be around 2000–3500 ha. Under subsistence levels, with a total yield of 5–10 t ha^{-1}, while under commercial production average yield is around 40 t ha^{-1} (Domola, 2003; Laurie, 2004). The white-flesh sweet potato (WFSP) and orange-flesh sweet potato (OFSP) are the widely produced cultivars in SA. Limpopo (Hoedspruit, Marble Hall, Burgersfot and Livubu), Mpumalanga (Nelspruit), KwaZulu-Natal and Western Cape provinces commonly produce sweet potato due to favourable environmental conditions for the growth of this crop (DAFF, 2011).

2.2 Nutritional value of sweet potato

Sweet potato provides vitamin C and pro-vitamin A, iron (Fe) and zinc (Zn) (Woolfe, 1992). The sweet potato cultivars that are rich in carotenoids are yellow to orange-fleshed and they usually contain high levels of Fe and Zn, they have the same quantity of vitamin A as carrot. The WFSP cultivars have high levels of Fe and Zn, the level of β-carotene are, however, lower. Different researchers have reported different values (Table 2.1) of nutritional content (NC) in both WFSP and OFSP cultivars (Huang et al. 1999; Vimala et al. 2006; Mbwaga, 2007;

Tumiwegamire, 2011; Laurie et al. 2012; Masango, 2014; Motsa et al. 2015; Nyathi et al. 2016). In SA the production of OFSP has increased by 41% in 2009, gaining popularity because it is rich in β-carotene which can help in alleviating the shortage of vitamin A in most children and pregnant women (DAFF, 2011). OFSP can also grow in unfavourable environmental conditions and produce fair amount of yield (Van Jaarsveld et al. 2008).

Table 2.1 Nutritional content [β-carotene, iron (Fe) and zinc (Zn)] in white-flesh (WFSP) and orange-fleshed sweet potato (OFSP) (mg 100 g^{-1})

	B-carotene		**Iron**		**Zinc**	
Source	**WFSP**	**OFSP**	**WFSP**	**OFSP**	**WFSP**	**OFSP**
Laurie et al. (2012)	0.01–0.21	4.25–20.25	0.36–0.84	0.37–0.92	0.37–0.51	0.32–0.59
Nyathi et al. (2016)	–	17.27 to 235.1	–	2.75–10.06	–	0.92–1.68
Masango (2014)	–	10 to 11.95	–	–	–	–
Vimala et al. (2006)	–	13.83	–	–	–	–
Mbwaga, (2007)	–	1–4.59	–	–	–	–
Huang et al. (1999)	<0.1–0.6	6.7–13.1	–	–	–	–
Tumiwegamire, (2011)	0–0.1	23.3–27.2	0.75	0.88–2.84	0.41	0.45–1.44
Wenhold et al. (2012)		5.1–16.5		0.80–1.26		0.56–0.69

Nutritionists in developing countries have gathered information and proof that in adults, and most children there is a deficiency of essential micronutrients and vitamins in the food that they eat every day (United Nations, 1997). The shortage of enough vitamin A, Fe and Zn is a common problem, mainly in South Asia and Southern Africa. Thus, the shortage of food and lack of vitamin and micronutrients in children has placed OFSP cultivar in a recognizable state because it can help in improving livelihoods for poor in rural areas (Rono et al. 2006). Hagenimana and Low (2000) indicated OFSP was a good source of β-carotene, Fe and Zn and that can reduce malnutrition. This OFSP can contribute to food security while improving the consumption of food that is rich in vitamin A, Fe and Zn (CPPMU, 2010). Boiled roots can provide enough vitamin A per day for young children (Ye et al. 2000).

2.3 Water use or requirements of sweet potato

There is shortage of information on the exact water requirement for sweet potato. However, it is estimated that sweet potato requires about 150–1000 mm of water in a growing season under SA conditions with semi-arid climate, and unreliable rainfall (Bok et al. 2000; Allemann, 2004; Laurie et al. 2009; Beletse et al. 2011; Masango, 2014; Nyathi et al. 2016). Water requirement of sweet potato at the beginning of a season is estimated to be 15–25 mm in a week, 25–50 mm per week one months after planting, and water needs decreased to about 20 mm per week late in the season (Allemann, 2004). However, deficit irrigation is important, particularly during different growth stages of the season as high soil water in early stage causes the growth of roots to be slow and late in the season it causes rotting of roots (Allemann, 2004; DAFF, 2011).

2.4 Effects of water stress on yield, nutritional value, nutritional yield, water productivity and nutritional water productivity of sweet potato

2.4.1 Crop yield

Shortage of water is the main cause of sweet potato yield reduction in both small and large scale farms (Allemann, 2004; Kapinga et al. 2005) and as such practicing deficit irrigation is the only way that can increase food security and save water at the same time. Cattivelli et al. (2008) reported that in arid and semi-arid regions water is the main limiting factor of sweet potato production. To achieve a high yield of sweet potato, the cultivation practices such as soil, weather condition and irrigation must be optimum (Beletse et al. 2013) and furthermore, the soil water should be stable during the early, middle, and late growth stages.

Water stress reduced the yield of sweet potato as reported by various authors (Lana and Peterson, 1956; Smittle et al. 1990; Laurie et al. 2009; Laurie et al. 2012; Beletse, 2013; Felix, 2013; Masango 2014). According to Smittle et al. (1990), the highest marketable yield was observed when sweet potato was irrigated at 25 kPa soil water tension throughout growing season, and yield was reduced by 26.10% when the crop was irrigated at 100 kPa throughout growing season. These results were similar to those reported by Lana and Peterson (1956) where sweet potato yield responded well to irrigation application at 22–25% of field capacity. Sweet potato cultivars responds differently to different irrigation levels (Gomes and Carr, 2001; Lewthwaite and Triggs, 2012; Beletse et al. 2013; Masango, 2014). Therefore, it is important to quantify water use of these cultivars in order to optimally irrigate them. The availability of irrigation water is highly important as it can increase sweet potato yield and quality of smallscale farmers to feed ever increasing population (Postel, 1998). Pery et al. (2009) stated that the purpose of irrigation is to satisfy crop water requirement. Bekele and Tilahun (2007) stated that research is required to study and understand to increase efficiency of sweet potato water usage in order to conserve water resource and improve the quality of this crop.

2.4.2 Quality, nutritional value and nutritional yield

In literature, it has been reported that different irrigation levels affect quality of sweet potato in terms of root size, colour, quality and appearance. Under water stressed conditions sweet potato produces smaller roots in size, colour is also affected depending on environmental conditions (Thomson et al. 1992; Laurie and Niederwieser, 2004). The physical appearance in terms of the shape of storage roots is also affected as roots will struggle to expand to their potential size under unfavourable soil conditions. It has been reported that fructose content in sweet potato decreased with increased amount of irrigation, flavour, texture reached their highest values when the crop is fully irrigated and that irrigation reduces dry matter percentage of storage roots (Constantia et al. 1974; Hammett et al. 1982; Thomson et al. 1992; Laurie and Niederwieser, 2004). Under high water application; shoot development, vine length and leaf and roots size increases. Therefore, more energy is partitioned to aboveground; thereby, decreasing fructose and other nutrients content as well as dry matter percentage in the storage roots (Laurie et al. 2009; Beletse et al. 2013; Yooyongwech et al. 2014; Gajanayake, 2014). Globally, few studies have been conducted to quantify the effects of deficit irrigation on the nutritional yield (NY) of sweet potato. Bumgarner et al. (2012) and Luoh et al. (2014) reported that NY [storage roots yield × nutrients content (NC)] can be defined as the amount of nutrients in the edible portion of the crop. Lower storage root growth due to water stress may result in lower NY due to the fact that, water is the main transporter of plants nutrients, therefore water stress can cause a decrease in leaf area, restrict root extension, stomatal closure and reduce photosynthetic activity (Luoh et al. 2014).

Different studies have been conducted around the world to study the response of sweet potato to different water regimes and if sweet potato can produce yield under drought conditions. (Smittle et al. 1990; Thomson et al. 1992; Gomes and Carr, 2000; Laurie et al. 2012; Lewthwaite and Triggs, 2012; Felix et al. 2012; Beletse et al. 2013; Masango, 2014; Motsa et al. 2015). For example, Lewthwaite and Triggs (2012) reported that sweet potato variety Toka Toka gold showed a 77% increase in marketable storage root yield under dryland compared to the well-watered conditions. Laurie et al. (2012) have reported that sweet potato yield was high when irrigated at 100% field capacity (FC) as compared to 60% and 30% FC, where the lowest yield was obtained from 30% FC treatment.

Table 2.2: Sweet potato yield and water productivity under different irrigation treatments.

Source	**Treatments**	**Yield (t ha^{-1})**	**WUE (kg ha^{-1} mm^{-1})**
Laurie et al. (2009)	30%, 60%, and 100% Fc	16.0, 31.8 and 64.4	8.12, 33.44 and 97.50
Beletse et al. (2013)	(Scinarios) 0 and 400 (mm) irrigation	2.36 and 13.9	3.27 and 3.52
Masango (2014)	Ttw, Ow, Otw and dryland	31, 26.5, 25.5 and 29.2	65, 73, 80 and 98
Lewthwaite and Triggs, (2012)	well-watered and rain-fed condition	12 to 31 and 4–29	–
Smittle et al. (1990)	25, 50 and 100 kPa	47.4, 41.7 and 35.1	–
Thomson et al. (1992)	rain-fed and well-watered	26.7 and 32.8	–
Laurie et al. (2012)	100% FC, 60% and 30% irrigation levels	31.9, 24.6 and 10.3	54.0, 69.3 and 58.2
Gomes and Carr, (2001)	rainfed and full irrigation	6.4–14.5 and 32.7–36.7	12.5 and 19.0

2.5 Crop coefficients

Crop coefficient (K_c) is a ratio between the specific crop ET under standard conditions (well fertilized crops, a disease free, grown in a large fields, under optimum soil water conditions and achieving full production under given climate conditions) as defined by FAO-56 (Allen et al. 1998). Crop type, climate, soil evaporation, and crop growth stages are factors that affect K_c (Smith et al. 1991; Aghadis, 2010). Crop coefficient was first introduced by Jensen in 1968 for the purpose of irrigation scheduling, and is calculated using Equation 2.1 (Jensen, 1968; Jensen 1969; Jensen et al. 1970; Jensen et al. 1971):

$$ET_c = K_c \times ET_o \qquad (2.1)$$

Where ET_c is crop water requirement and ET_o is reference ET. Since actual sweet potato field production is generally well managed, K_c under standard condition will be considered, factors determining K_c for sweet potato consist of climate condition and crop growth stages. As the crop develops the crop height, ground cover, and leaf area changes due to differences in ET during different growth stages. The K_c for a given crop differs over the growing period, therefore, the growing period of sweet potato can be divided into four different growing stages: initial, crop development, middle, and late stages. Initial 30 days, crop development 30 days middle 60 days and late stage 30 days (Son Hong Vu et al. 2005).

In order to have an effective irrigation management strategy, it is highly important to estimate ET accurately. Knowledge of K_c is important for the estimation of ET_c it helps in determining the water requirement of crops according to their growing stages, and environmental factors. If K_c is known for a given crop the ET_c can be calculated from ET_o. Previous studies have found that K_c for the same crop may differ from place to place based on factors such as weather variables (Allen et al. 1998; Kang et al. 2003). According to Doorenboss and Pruitt (1977) and

Kang et al. (2003) researchers should give special importance to the need to develop regional K_c for accurate estimation of water requirement under a specific climate. Studies over the years have developed K_c for most crops; however, the value needs to be adjusted for different growing conditions. Crop coefficient of OFSP still needs to be developed under SA conditions.

2.6 Crop evapotranspiration estimation

Allen et al. (1998) stated that ET refers to the water loss from the soil surface which is evaporation (Es) and through the leaf stomata pores which is transpiration (T), the combination of which is evapotranspiration (ET). Great advancement has been made over the past decade on improving the understanding of how weather variables affect the rate of ET under different climatic conditions. Crop evapotranspiration of crops depends on soil water availability, and weather condition of an area and vegetative characteristics (Jovanovic and Israel, 2012). Therefore, different approaches must be implemented in order to study the challenges presented by water scarcity in the modern agriculture crop production system (Maclown, 1996). There are a variety of methods and models (direct and indirect) to measure crop ET.

2.6.1 Soil water balance

The soil water balance (SWB) model is irrigation scheduling and generic crop model that simulate crop grow, and water balance from specific crop grow parameters collected from the field (Annandale et al. 1999; Annandale et al. 2007). It is an indirect method to estimate crop ET, where ET is estimated as a residual term in the SWB Equation (Ranna and Katerji 2000):

$$ET = P + I + U - R - D - \Delta S \qquad (2.2)$$

Where ET is evapotranspiration, P is precipitation, I is irrigation, U is upward capillary rises into the root zone, R is runoff, Dis deep percolation beyond the root zone and ΔS is change in root zone soil water storage. According to Ranna and Katerji, (2000) SWB is applicable to smallscale farmers as well as largescale farmers, and it can be applied throughout the season. Previous studies by different researchers play a big role as the reference that this model can simulate soil water balance components and crop water requirement with acceptable accuracy (Jovanovic and Annandale, 2000, Annandale et al. 2002, Beletse et al. 2008). In order to run SWB model there in certain data that need to be collected and used as input for the model, data such as planting dates, latitude, altitude, rainfall amount as well as daily weather variables such as maximum, and minimum temperature, maximum, and minimum relative humidity, and total solar radiation (Jovanovic and Annandale, 1999).

The availability of water in the agro-ecological system is an important parameter mainly for most physical, and physiological process in soil plant, and atmosphere continuum system (Rivington et al. 2002). Therefore, estimating water use by measuring the change in soil water content has been used for nearly a century. Up to early 1960 the main methodology to determine soil water content was by soil sampling and gravimetric and at the beginning of 1960, the neutron probe water meter began to be the main methodology to measure soil water content and replaced the gravimetric procedures. Currently, a new variety of methodology to measure soil water content has been developed (Allen et al. 2011).

2.6.2 Micrometeorological methods

These methods are gaining popularity in most agricultural researchers because researchers believe that they can measure ET accurately since they can be installed in the field (Meyers and Baldocchi, 2005).

They can be applied in semi-continuous basis, and still make the information about vertical fluxes that occur in the range of meters to several kilometers to be available, relying on the surface roughness, it also depends on the height of instrument (Meyers and Baldocchi, 2005). There are different types of micrometeorological methods such as eddy covariance (EC), mass balance, accumulation, and flux gradient, and the use of these methods depends on the surface type, and size of an area that will be measured (Jarmain et al. 2009). However, technologies such as these have never been utilized for OFSP ET in SA. Which might be due to the fact that these techniques used to measure ET are expensive and are not easy to operate.

2.6.2.1 Surface renewal method

The surface renewal (SR) method, is a new method for estimating sensible heat (*H*) mainly comparing to other method for measuring ET such as EC and BR methods (Spano et al. 2000; Castellvi, 2004; Castellvi, 2006). The SR method has been examined by (Savage et al. 2004; Mengistu, 2008). This method is mainly based on the idea that an air parcel near a surface is renewed by an air parcel from above (Paw U et al. 1995). The SR method require knowledge of the measurement height, the rate of change in air temperature and weighting factor (Jarmain et al. 2009). This is temperature based aerodynamic method that involve high frequency measurement of a single air temperature from which sensible heat is calculated and latent heat (*LE)* is determined using the energy balance equation. The theory of heat exchange between the atmosphere and a surface using SR is described in detail in (Paw U et al. 1995; Snyder et al. 1996; Paw U et al. 2005). Therefore, the exchange of heat energy between the atmosphere and SR is described as:

$$H = \alpha \, \rho_a \, c_p \, z \frac{a}{\tau} \tag{2.3}$$

Where α is a weighting factor, *a* is amplitude of the air temperature ramps; and τ is the total ramping period. The advantage of this technique is that, it is simple to operate and it is not expensive compering to other techniques such as EC (Mengistu, 2008). Thus, the disadvantage of the SR method is that high frequency air temperature measurement are required, necessitating the use of expensive data logging equipment. Furthermore, sensor are fragile and easily damaged and prone to error due to dirt and cobwebs (Jarmain et al. 2009) The SR has been used in SA and has also been evaluated in detail for a range of canopies and above water by (Savage et al. 2004; Mengistu and Savage, 2007; Mengistu, 2008)

2.6.2.2 Scintillometer method

A scintillometer method is used to measure path-weighted *H* with a transmitter and a receiver at each end of the path of a radiation beam (Jarmain et al. 2009). An optical instrument that consists of a transmitter that emits a beam of light and a receiver that can measure the amount of scintillations over a horizontal path (Mengistu and Savage, 2010). This technology measures the intensity fluctuation of a visible radiation beam after it has been propagated above plant canopy of interest (Thiermann, 1992; Savage et al. 2010). There are different types of scintillometer for instance there is surface layer scintillometer (SLS) that measures over horizontal distance between 50 and 350 m, with measurement frequency of 1 khz, and there is large aperture scintillometer (LAS) that measures over distance between 0.25 and 5 km, with measurement frequency of 8 Hz and it employ near-infrared radiation beam (Jarmain et al. 2009; Savage et al. 2010). Jarmain et al. (2009) reported that the main key to the implementation of the surface and large scintillometer method is the interaction between eddy size, beam distance, beam wavelength, aperture diameter and for some of the estimates also effective bean height, air temperature and atmospheric pressure. Therefore, measurement of net radiation flux (R_n) and ground heat flux (G) allows latent heat (LE) to be estimated using the shorten energy balance equation number. The main advantage of this method is that no corrections are applied to the LAS and SLS data other than the use of Monin-Obukhov similarity theory and a possible correction for the influence of water vapour pressure on beam transmission through the Bowen ration (Jarmain et al. 2009). Therefore, the main disadvantage of this technique is that it cannot differentiate between the upward and downward direction of H without additional estimates of atmospheric stability, and this can only be corrected by using a pair of fine-wire thermocouples to measure air temperature at two vertical positions in order to determine the direction of H. This technique has been used in South Africa to estimate H and LE for a long period of time for a mixed grassland community (Savege et al. 2005; Savage et al. 2010).

2.6.2.3 Surface energy balance method

The application of the surface energy balance which is indirect method of determining ET, is highly important to many of the methods used to measure ET (Jarmain et al. 2009). Each term of energy balance is measured independently and therefore, has a different spatial representation (Jarmain et al. 2009). Meyers and Baldocchi (2005) reported that the important facts about this method is that the fetch of surface energy balance measurement components is small; therefore, the available R_n is exactly made of H, LE and G.

According to Gillies et al. (1997) energy balance methods normally estimate LE by measuring the H, using the difference between air temperature, and the land surface temperature, estimated by remote sensing (Moran et al. 1994; Inoue, 2003). This estimate of H flux is joined together with an estimate of available energy (R_n - G) to measure ET as a residual (Nagler et al. 2005). Therefore, energy balance method has the advantage of being physical base, so this method can be used to measure ET under different ecosystems and different climate conditions (Pamela et al. 2005). The limitation of this method is that it neglect energy that is stored in the vegetation, the air below the sensors and also energy required for photosynthesis (Bastiaansen et al. 1998; Scott et al. 2004).

2.6.2.4 Eddy covariance method and instruments used in eddy covariance

The EC system is most common and preferred by researchers because it measures the ET directly and it is noninvasive (Meyers and Baldocchi, 2005; jarmain et al. 2009). Currently, EC system has emerged as an accurate technique to estimate crop ET (Running et al. 1999; Canadell et al. 2000; Geider et al. 2001; Wang et al. 2008). Provided by the fast sensors, EC system measure the surface layer fluxes of trace gases such as [water vapour (H_2O) and carbon dioxide (CO_2)] and heat directly (Massmam, 2000). Latent heat flux, and *H* are affected by turbulent transport (Ham and Heilman, 2003).

Estimating ET of sweet potato using EC system will contribute important knowledge on the amount of water that this crop requires in a growing season in order to satisfy atmospheric demand. According to Jovanovic and Annandale (2000) the most suitable way of estimating crop water use is achieved by direct measurement. According to Wang et al. (2008) different aspect that makes EC special on estimating crop ET include the area sampled with EC system which is called footprint and ranges between 100 m to several Km's. Eddy covariance system produces a direct measurement of CO_2, and water vapour between terrestrial surface, and atmosphere, which is achieved by interpreting covariance measurement of vertical wind (Baldocchi et al. 1988; Verman et al. 1990; Lewchon, 1995). Eddy covariance system is mostly used to estimate fluxes of water, gas, and energy between land, and atmosphere (Baldocchi et al. 2001).

Eddy covariance system has been used by many researchers, mainly because the way its system works is fairly simple, and EC system sensors are fast with measurements frequency of 10 Hz, comparing to other method (Jarmain et al. 2009). It is important to carefully consider how ET rate can be measured accurately with dependable accuracy for different surface type (Savage et al. 2004; Savage, 2009). There are different methods used to measure ET rate (Savage et al. 2010); however, as mentioned by Drexler et al. (2004) in their review, there are very few ET estimation methods that work well for an hourly time-step, such as almost all of the methods for ET estimation except for EC system, from which direct measurements of *H* and *LE* at a point are obtained (Savage, 2010).

Method such as EC system measure ET, normally on a frequency of 10 Hz, of two atmospheric variables, vertical wind speed and water vapour pressure. From which *LE* is calculated directly by EC following many corrections, one such as spike removal, similarly using EC, *H* is calculated from the covariance of vertical wind speed, and air temperature measurements over a specified time interval usually hourly or half-hourly (Savage et al. 2010). The EC system is simple to carry around, and much less invasive, compared to the use of lysimeter, and other methods. Different studies of ET estimation has been conducted around SA, and also around the world using EC system (Savage et al. 2010).

Pakoktom et al. (2013) used EC system to estimate ET of sugarcane (*Saccharum officinarum*) and they reported that ET of sugarcane depends on daily time and growing stages, and total ET was 682 mm over a growing season. Evapotranspiration can be measured using different methods which do not interfere with the process of gas exchange between the surface source, and the atmosphere (Pakoktom et al. 2013). Therefore, the EC system has been used to measure water flux in different areas, and many studies have been published (Savage et al. 1997; Savage et al. 2004; Savage, 2008; Ezzahar et al. 2009; Pakotmom et al, 2013). The EC system uses infrared gas analyser that allows for the estimation of transpiration rate at canopy or leaf level

(Jarmain et al. 2009) Aerodynamic methods, such as EC, involve the measurement of at least two atmospheric variable and a theoretical frame work, and assumptions that allow for the direct calculation of *LE* (Savage et al. 1997; Savage et al. 2004).

Based on the study by Swinbank (1951), EC measurements allows a complete point estimation of *H*, and *LE* at a defined height above the canopy. The calculation of fluxes *H*, using EC system is based on the covariance between vertical wind speed (W) and a scalar property such as air temperature. The covariance between W and temperatures (T) is expressed as ($W-W$) ($T-T$). If the covariances are very small, the *H* is small. The EC system may also be used to directly measure *LE* from covariance between *W* and absolute humidity (kg m^{-3}). Sensible heat may be measured using a three-dimensional sonic anemometer. This instrument gives measurement of three components of vertical wind speed (*W, V* and *U*) as well as estimate of air temperature using sonic temperature (T_s) corrected for the influence of water vapour pressure on the speed of sound (Schotanus et al. 1983) and the *H* is determined using Equation (2.2):

$$H = paCp\,(W - W)\,(T_s - T_s) \tag{2.4}$$

The main disadvantage of EC system is that energy balance is usually not close, which create a major problem for achieving progress in the general knowledge of crop ET variability (Texeira and Bastiaanssen, 2009).The EC method has been used successfully in SA to estimate evaporation from mixed grass land communities for an extended period by (Savage et al. 1997; Savage et al. 2004; Savage, 2008).

2.7 The surface energy balance

2.7.1 Energy balance closure

Energy balance closure, a formulation of the first law of thermodynamics, requires that the sum of estimated LE and H heat flux be equivalent to the sum of R_n and G as well as the storage fluxes from any other energy sinks or sources such as photosynthesis and change in the above ground biomass heat storage (Q) (Li et al. 2005; Masseroni, 2014). Computing energy balance closure has been widely accepted as an important reference for evaluating EC data and when energy imbalances occur, it shows that there may be bias in both turbulent fluxes and available energy, therefore, the data cannot be accurate (Aubinet et al. 2000; Twine et al. 2000; Wilson et al. 2002; Li et al. 2005; Liu et al. 2006). Energy balance closure can be written as Equation 2.4:

$$LE + H = R_n - G - Q \qquad (2.5)$$

The surface energy balance is closed when the energy flux into a system is equal to the energy flux leaving the system, plus any energy storage change in the system. Energy balance closure is closely connected to the evaluation of LE and H fluxes and, not other scalar fluxes (Wilson et al. 2002).

2.7.2 Energy balance closure ratios

The energy balance closure ration is one of the methods that are used to evaluate energy balance closure (Mahrt, 1998; Gu et al. 1999). An energy balance closure ratio (EBCR) can be defined as the ratio of turbulent energy to available energy and can be determined using Equation 2.5 (Wilson et al. 2002):

$$EBCR = \frac{H + LE}{R_n - G - Q} \tag{2.6}$$

When systematic imbalances occur they may reveal errors in H and LE measurements (Twine et al. 2000).

2.7.3 Energy balance closure errors

Energy balance closure error has various possible sources (Wilson et al. 2002). In literature various hypotheses for energy balance closure error can be found (Eder et al. 2014). The reasons that caused energy imbalance between $H + LE$ and $R_n - G$ in EC measurement, are mainly due to errors which may be caused by dirt on the sonic transducers, noise in the measurement system, lack of steady state conditions, consumption of net radiation by photosynthesis, neglected energy sinks, heat storage in the top soil, mismatch in footprint, and malfunctions of sensors during rainfall conditions (Paw et al. 2000; Baldocchi et al. 2001; Scott et al. 2003; Papale et al. 2006; Castellvi et al. 2008; Ezzahar et al. 2009; Teixeira and Bastiaanssen, 2010).

2.8 Methods for improving evapotranspiration, yield, quality and nutritional water productivity of sweet potato

Different methods for improving yield, quality, and nutritional water productivity (NWP) of sweet potato are available, from fully rainfed (RF) or dryland to fully irrigation (FI) farming system, including supplementary irrigation (SI), soil fertility maintenance, and deficit irrigation. Currently, there is wide range of irrigation techniques such as drips and also pressured system. Therefore, agricultural production and livelihoods in arid and semi-arid areas can be sustained by improving sweet potato NWP, quality, and yield (Oweis and Hachum, 2004).

Generally, rainfall distribution is uneven throughout SA, with other parts being wetter than others (Kapinga et al. 2005). Considering the overall prediction that present rainfall is expected to be reduced by 5 to 10%, together with a rise in temperature of about 1 to 3ºC (Kiker, 2000), therefore methods for improving irrigation management, quality, yield and NWP of sweet potato in SA is highly important (Kiker, 2000). Consequently, there is a need to implement agricultural practices that will help to conserve water resource while maximizing crop ET, yield, quality and NWP, because agricultural products that ranged between 20-40% is produced under irrigated agriculture worldwide (Howell, 2001). This can be done by (a) accurately or directly measuring ET and (b) improving water productivity (WP) and nutritional productivity (NP) per mm of water.

2.8.1 Improving the measurement of evapotranspiration

To improve yield and irrigation management under sweet potato production industry, there is a need to estimate ET directly using ET measuring methodology such as EC explained in this chapter (section 2.6). It is important to accurately estimate ET as it will allow the development of accurate K_c that can be used to improve irrigation management and water allocation in water scarce region under sweet potato production (Allen, 2011).

2.8.2 Improving water use efficiency and nutritional water productivity

In order to alleviate malnutrition and food insecurity in SA, there is a need to accurately quantify the effects of DI on nutritional content (NC), WP and NWP of OFSP and WFSP cultivars (Thomson et al. 1992). Water productivity can be defined differently, depending on area of expertise for example to agronomist is yield per unit of water used (kg m^{-3}), while to food nutritionists is more nutrients per water used (mg m^{-3}) (van Dame and Malik 2003; Wenold et al. 2012; Nyathi et al, 2016). Nutritional water productivity is a new idea which connects water use and NC of crops, therefore studying NWP of sweet potato can help in alleviating malnutrition and food insecurity in SA as it contains high level of β-carotene, Fe, Zn and can produce high yield under unfavourable conditions with limited farming inputs (Renaut and Wallender, 2000; Nyathi et al, 2016). However so far there are few detailed studies on NWP of OFSP and WFSP cultivars.

CHAPTER THREE

Measuring evapotranspiration and developing crop coefficients for sweet potato *(Ipomoea batatas)* using the eddy covariance system

3.1 Introduction

South Africa (SA) is mainly characterised by arid (western portion of the country) and semi-arid (eastern portion of the country) climates, therefore, in many areas of the country irrigation is important for crop production (MacCarty et al. 2001; Bannie and Hansley, 2001). Jovanovic and Sticks (2012) stated that drought and poor irrigation water management are some of the main factors that affect world food production. Therefore, the objective of this chapter was to measure seasonal water use of sweet potato *(Ipomoea batatas)* grown under optimal crop growing conditions using the eddy covariance (EC) system and to determine FAO-type sweet potato crop coefficients (K_c). Sweet potato is commonly grown for its edible storage roots which contain high levels of β-carotene. However, few studies have been completed regarding the water use of sweet potato crop under South African conditions. Crop water use can be estimated using different methods, one such method is the use of reference evapotranspiration (ET_o) data. Therefore, quantifying sweet potato water use directly using the eddy covariance (EC) system for estimating ET under optimal management conditions will contribute useful information on the irrigation water management of this crop. Evapotranspiration (ET) of sweet potato is highly variable as affected by a number of factors, one such factor is the environmental condition (Bok et al. 2000; Gomes and Carr 2003; Laurie et al. 2009; Beletse et al. 2011; Masango, 2014; Nyathi et al. 2016). Therefore, the ET estimates from the EC system can be used to extrapolate water use for various climates by determining crop coefficients (K_c) using FAO-56 (Allen et al. 1998) methodology, which will assist in improving water resource planning and irrigation water management of sweet potato production.

3.2 Materials and Methods

3.2.1 Site description and agronomic practices

The study was conducted at the Roodeplaat Experimental Farm of the Agricultural Research Council, Vegetable and Ornamental Plants (ARC–VOP) (25°35’N, 28°21’E, 1164 m above sea level) in Gauteng Province, South Africa. The study was conducted over two growing seasons, the 2014/2015 and 2015/2016 summer (January to May) seasons. The region experiences summer rainfall, with an average of about 650 mm per annum (Jovanovic and Annandale, 1999). The study area has a humid subtropical climate with average daily air temperatures range from 8–34°C in summer and 4–23°C in winter (Beletse et al. 2013).

Prior to commencement of the trial, soil samples were collected to determine the soil physical properties. Soil samples were also collected at the beginning of each growth season to determine the fertility status (Table 3.1). The soil of the site is classified as a Hutton soil form (Soil Classification Working Group, 1991) with a loamy textural (54.0–59.4% sand, 12–14.8% silt and 22.7–34.1% clay).

Table 3.1: Soil chemical analysis results for both growing seasons (2014/2015 and 2015/2016)

Chemical elements	**Units**	**2014/2015**	**2015/2016**
Phosphorous (P)-Bray 1	mg kg^{-1}	21.1	32.6
Potassium (K)	mg kg^{-1}	238.9	185.0
Calcium (Ca)	mg kg^{-1}	1556.2	1215.3
Magnesium (Mg)	mg kg^{-1}	546.5	413.2
Sodium (Na)	mg kg^{-1}	17.8	32.7
Iron (Fe)	mg kg^{-1}	6.4	–
Zinc (Zn)	mg kg^{-1}	7.48	–
Ammonium-nitrogen (NO_4-N)	mg kg^{-1}	–	1.92
Nitrogen (N)	%	0.043	–
Nitrate-nitrogen (NO_3-N)	mg kg^{-1}	1.41	4.86
pH (H_2O)	–	7.18	6.98

Fertiliser was applied based on the soil analysis test results. At planting, 216 kg N [limestone ammonium nitrate (LAN) 28%] ha^{-1}, 75 kg P [superphosphate, (10.5%)] ha^{-1} and 216 kg K (potassium) ha^{-1} in the first season; and 180 kg N ha^{-1}, 53 kg P ha^{-1} and 180 kg K ha^{-1} in the second season were broadcasted and incorporated. Top dressings of 100 kg N ha^{-1} and 200 kg ha^{-1} K in the first season and 100 kg N ha^{-1} and 150 kg K ha^{-1} in the second season were applied 21 days after planting. The fertiliser forms used were 1:0:1 (36%) and superphosphate (10.5%) at planting, and limestone ammonium nitrate (LAN-28%) and potassium chloride (KCl) (50%) for top dressing.

The trial size was 130 m × 100 m (13 000 m^2). The plot was planted with orange-fleshed sweet potato (OFSP) cultivar ‘Bophelo’ cuttings. This cultivar was chosen due to its superior nutritional value and linked potential in alleviating malnutrition as discussed in the Chapter 2 (section 2.2).

The cultivar is also becoming popular among South African farmers. In both seasons, 0.3 m OFSP cuttings with seven nodes, were manually planted at a planting density of 35 507 plants ha^{-1} on ridges apart 1.4 m. For each ridge, two rows of plants were planted at a spacing of 0.4 m between plants.

Dragline sprinkler was used to irrigate the trial. Neutron probe access tubes as well as Chameleon moisture sensors (www.via.farm) (CSIRO, Canberra, Australia) (Stirzaker et al. 2017) were installed at six sites in the field for irrigation scheduling. A volume of 20 mm irrigation was applied immediately after the cuttings were planted, in order to refill the soil profile back to field capacity. Neutron probe measurement were recorded once per week to determine the water depletion levels before irrigating to field capacity, and the crop was irrigated once a week to field capacity to ensure that more than 50% of PAW was never depleted. The field capacity of the trial site is 250 mm, while, the permanent wilting point is 130 mm. Weeds were controlled manually between rows and ridges before the ground was full covered by the crop canopy. The crop was grown under water and nutrient non-limiting conditions, and it did not show any sign of nutrients deficiencies, damage or diseases during both growing seasons.

3.2.2 Eddy covariance system setup

The trial was conducted to measure the ET of OFSP cultivar ‘Bophelo’ in two growing seasons using the EC system. The EC 150 (Campbell Scientific Inc., Logan, Utah, USA) was used to estimate ET directly, and indirectly using the shortened energy balance equation. Three dimensional wind velocity and temperature fluctuations were measured using the CSAT3 (Campbell Scientific Inc., Logan, Utah, USA) sonic anemometer. Water vapour concentration was measured using a fast-response EC 150 CO_2 / H_2O open-path gas analyser (Campbell

Scientific. Inc., Logan, Utah, USA) as part of the EC system. All EC data were logged at an interval of 30 minutes, with subsequent storage in a CR5000 data logger (Campbell Scientific Inc., Logan, Utah USA). The sensors measured the water content of the air, the vertical component of wind speed, and air temperature at 10 Hz. The flux of water and H were statistically calculated every 30 minutes (Nagler et al. 2005).

The EC system estimates sensible heat fluxes (H) based on measurement in the turbulent boundary layer above the canopy (Rana and Katerji, 2000). The air flow is assumed to be made up of a large number of eddies, each having three-dimensional components (horizontal and vertical) (Burba and Anderson, 2010). In this study the energy balance method was used to validate the direct ET estimates from the EC system by assessing the surface energy balance closure. Assessing energy balance closure is the main method used to assess the accuracy of the EC system measurements (Twine et al. 2000; Ezzahar et al. 2009). Energy balance at the land surface is described by the Equation 3.1 as defined by (Twine et al. 2000; Nagler et al. 2005):

$$R_n - G = LE + H \tag{3.1}$$

Where, R_n is the net radiation measured above the canopy, G is soil heat flux, LE is latent heat of vaporization (evaporation multiplied by the latent heat of vaporization), H is sensible heat flux. Therefore, in this study additional sensors for measuring remaining components of the energy balance were used. All sensors were installed in a tower situated around the middle of the plot and the distance from the tower to the edges of the field was 50 to north, 50 south, 60 west and 70 m east; this was done to obtain enough fetch for the EC measurements NR-Lite net radiometer (Kipp and Zonen, delft, The Netherlands) was installed at a height of 1.8 m above the soil to measure net irradiance. Four soil heat flux plates (HFT-S, REBS, Seattle, WA) were installed at a depth of 0.08 m below the soil surface and thermocouple soil temperature averaging probes were installed at the depths of 0.02 and 0.06 m to measure the heat stored above soil heat flux plates. Volumetric soil water content for the top 0.20 m soil was measured using CS616 time domain reflectometer (TDR). Estimates of the turbulent fluxes ($\lambda E + H$) from the EC system were subsequently compared to available energy ($R_n - G$) estimates using energy balance method in order to determine the energy balance closure.

3.2.3 Data collection

3.2.3.1 Crop growth analysis

During both growing seasons, fractional interception (FI) of photosynthetically active radiation (PAR), leaf area index (LAI), were measured non-destructively using a Decagon Sunfleck ceptometer (Decagon, Pullman, Washington, USA) in order to monitor canopy development and the relationship between canopy development and ET. During the measurement, one reading was taken above the canopy of a selected sampling area and four readings were taken below the canopy. The measurements were taken during clear sunny days between 12:00 and 14:00 pm. Leaf area index was also measured destructively (destructive sampling was done at least 20 m away from the tower) using an LAI 3100 belt driven leaf area meter (LI-COR Inc., Lincoln, Nebraska, USA) and was calculated using Equation 3.2:

$$\text{LAI } (\text{m}^2\text{m}^{-2}) = \frac{Measured\ total\ leaf\ area}{Sampled\ ground\ area} \tag{3.2}$$

Fractional interception was calculated using Equation 3.3:

$$\text{FI} = 1 - \frac{I_o}{I_t} \times 100\% \tag{3.3}$$

Where FI is fractional interception, I_o is the measured PAR on the surface of the ground, I_t is the radiant flux density on top of the canopy.

Plant growth analysis (fresh mass and dry matter) was measured at three week intervals throughout the growing season, and was done by sampling the above-ground and harvestable storage root plant material of six plants from each sampling area. Samples were separated into stems, leaves and storage roots, for fresh mass determination. Separated sample (stems, leaves and storage roots) were then oven dried at 50°C to a constant mass for dry matter determination.

3.2.3.2 Daily crop evapotranspiration

Daily ET (mm day^{-1}) measurements were calculated from data collected from the EC system using Equation 3.4:

$$\text{ET (mm day}^{-1}\text{)} = LE \times \frac{1800}{\lambda} \qquad (3.4)$$

Where ET is daily evapotranspiration, *LE* is the latent heat measured using the EC system, and 1800 is the conversion of seconds to 30 minute intervals, λ is specific latent heat of vaporization of water per unit mass (2454 000 J kg^{-1}).

3.2.3.3 Determining the surface energy balance closure and EC data processing

The surface energy balance closure for the EC system measurements was determined for the two growing seasons of sweet potato at the half-hourly time scale using Equation 3.1. The surface energy balance closure was analysed by plotting the sum between $H + LE$ (turbulent fluxes) against the $R_n - G$ (available energy) for the summed half hourly fluxes daytime data set in days of the season where the fluxes were available from sunrise to sunset. Stannard et al.

(1994) stated that if all components of energy balance are measured with accuracy, independently, and sum to zero, it shows that the EC measurements are good, and the energy balance equation is satisfied.

There are few reasons that causes lack of energy balance closure, that mainly lead to underestimation of turbulent fluxes by EC system. Thus, there is need for post data processing in order to improve turbulent fluxes measured with EC system (Twine et al. 2000; Scott et al. 2004; Lee et al. 2004; Papale et al. 2006). Therefore, in this study during irregular periods when there were missing data, linear interpolation was used, however, in rare occasion when more than 25% of the data were missing on an individual day, the daily ET was estimated as being the average daily ET for the three days before and three days after the day with missing data (Scott et al. 2004). The spikes, that might have resulted from mechanical or electronical malfunction of sensors were also removed (Mauder and Foken, 2004), therefore, in this study spikes were filtered following procedure proposed by Vickers and Mahrt (1997), and Hojstrup (1993).

3.2.3.4 Water use efficiency

Water use was estimated as the total water use of the crop from planting date to harvest. It is expressed as the evapotranspiration in mm for the growing period estimated using the eddy covariance method. Water use efficiency (WUE) was determined as the ratio of storage root yield (fresh mass basis) in kg ha^{-1} to seasonal water use (mm). In this study the WUE was calculated at final harvest according to Equation 3.5, as defined by Howell et al. (1992) and Scott et al. (2003):

$$\text{WUE (Kg ha}^{-1}\text{ mm}^{-1}) = \frac{SRY}{ET} \qquad (3.5)$$

Where, *SRY* is storage root yield (fresh mass) in (kg ha^{-1}) and *ET* is evapotranspiration (mm).

3.2.3.5 Crop coefficient

Crop coefficients (K_c) for sweet potato grown under optimum management condition were developed for the summer season using the FAO single crop coefficient method (Allen et al. 1998). In this study the reverse calculation of the determined K_c was done, in order to verify that the recommended K_c actually return the similar values to those on which the determination of coefficient are based. K_c was calculated using Equation 3.6, and the reverse calculation of the determined K_c was done using Equation 3.7:

$$K_c = \frac{ET}{ETo} \qquad (3.6)$$

$$ET_c = ET_o \times developed\ K_c \qquad (3.7)$$

Where, ET_c is crop water requirement (mm) and ET_o is reference evapotranspiration (mm).

ET was determined from *ET* measurements of the EC system, and ET_o was calculated according to the FAO Penman-Monteith equation 3.7 (Allen et al. 1998) using daily weather data:

$$ET_o = \frac{0.408\Delta(Rn-G)+\gamma\frac{900}{T+273}u2\left(e_{a-e_d}\right)}{\Delta+\gamma(1+0.34u_2)} \qquad (3.8)$$

3.2.3.6 Soil water content, rainfall and irrigation

Soil water content was measured using a neutron probe water meter model 503DR CPN Hydroprobe (Campbell Pacific nuclear Inc., California, USA), calibrated for the specific soil on the site with measurements at the wet and dry spot. The wet spot was established by ponding water on the soil until the complete profile was saturated and left to drain for 48 hours to reach field capacity (FC). The dry spot was established by leaving the soil for a period of around five months to dry out. The gravimetric method was used to determine soil water content (SWC) from the wet and dry spots a number of times, simultaneously taking counts at 0.2 m intervals of a 1 m soil profile with the Hydroprobe. Volumetric SWC was calculated by multiplying gravimetric SWC with soil bulk density, which was calculated as follows:

$$\text{Bulk density} = \frac{Ms}{Vsoil} \tag{3.9}$$

Where Ms is the mass of dry soil and Vsoil is the volume of the dry soil. A linear relationship was established between counts and volumetric SWC. Five neutron probe access tubes were installed in the field to a depth of 1 m. Soil water content was measured at 0.2 m increments by lowering the sensor through the access tubes once a week to determine the water depletion level prior to irrigation. For the second season the plan was also to use neutron probe for measuring the profile soil water content and for irrigation scheduling. However, the neutron probe was out of order and the Chameleon soil moisture sensors were used for irrigation scheduling instead. Chameleon soil moisture sensors were also installed at depths of 0.15, 0.30, 0.45, and 0.60 m, and soil tension was monitored twice a week in order to check whether the crop was optimally irrigated. Chameleon sensors give output of three different colours which correspond to the sensors measured tension, namely blue (wet soil, < 25 kPa), green (moist, 25 to 50 kPa), and red (dry soil, > 60 kPa). Rainfall amount and intensity was recorded with TE 525 tipping bucket rain gauges (Texas Electronics, Inc., Dallas, TX, USA) connected to a

CR10X (Campbell scientific, Utah, USA) data logger and actual irrigation applied was measured using manual rain gauges that were placed in the field.

3.2.3.7 Weather data

Weather data was obtained from an automatic weather station which was located at about 500 m from the trial site in Roodeplaat, Pretoria. . The data was recorded and averaged hourly using a CR10X data logger (Campbell Scientific, Inc., Utah, USA), and the following meteorological variables were recorded:

- Daily maximum and minimum relative humidity and temperatures using a CS-500 Vaisala temperature and relative humidity probe (Campbell, Scientific. Inc., Logan. Utah. USA);
- Total daily solar radiation using LI-200 Pyranometer (LI-COR Inc., Lincoln, Nebraska, USA);
- Wind speed and direction were measured using 03002 Wind Sentry (RM Young, Michigan, USA).

3.2.3.8 Final storage yield

Fresh utilizable yield was determined according to the United State Department of Agricultural Marketing Services (1981), and dry matter yield were determined at final harvest by weighing the storage roots of eight selected plants in the field.

3.3 Results and discussion

3.3.1 Weather data variability and profile soil water content during the study period

Generally, weather variables (maximum and minimum temperatures, rain-fall) during growing season one (2014/2015) were lower than during growing season two (2015/2016) (Table 3.2). According to Du Plooy (1989), the optimal temperatures for above-ground and for storage root development differs, and it was reported that sweet potato grows well in temperatures ranged between 15 and 30°C (Laurie and Niederwieser, 2004). Therefore, temperatures during both growing seasons were favourable for sweet potato growth. During season one and two averaged maximum temperatures were 29.46 and 29.18°C, respectively; while, the minimum temperatures were 12.82 and 13.86°C, respectively, with the lowest minimum temperature recorded during May in both seasons, and was less than 8°C . Rainfall during growing season two was higher than growing season one, but not well distributed with most of the rain being received in March. Long-term average rainfall was higher when compared to both growing seasons. The average long-term atmospheric evaporative demand (VPD) was lower than the respective VPDs for the two growing seasons (Table 3.2). The seasonal change of soil water content in response to rainfall received and irrigation applied is shown in Figure 3.1 for the first season and in Table 3.3 for the second season. Irrigation applied and rainfall received during first growing season is shown in (Figure 3.2) and (Figure 3.3) for second growing season. In this study the applied irrigation water and rainfall received during the first season was lower than during the second season, 481 mm and 585 mm, respectively. However, the available of soil water in excess of demand may lead to some water being lost through deep percolation, runoff and yield might even be reduced due to water logging and the leaching of nutrients.

Table 3.2: Monthly average maximum (Tx) and minimum (Tn) temperatures, and total monthly rainfall and reference evapotranspiration (ET_o) of 2014/2015 and 2015/2016 growing seasons with averaged ET_o over the long term (2009 to 2013)

Years	**Month**	**Mean Tx (°C)**	**Mean Tn (°C)**	**Total precipitation (mm)**	**Total ET_o (mm)**
(2009 - 2013)	January	29.4	17.5	93.2	94.7
	February	30.4	16.2	67.0	139.6
	March	29.6	14.5	82.3	133.1
	April	25.8	10.3	78.3	99.3
	May	25.2	8.5	15.1	26.0
2014/2015	January	30.2	16.5	114.6	113.9
	February	31.9	16.0	32.5	151.6
	March	30.2	14.7	71.0	135.5
	April	27.4	10.8	43.0	101.5
	May	27.6	6.1	0.0	30.5
2015/2016	January	31.7	17.6	95.5	94.5
	February	32.5	17.8	49.5	152.8
	March	29.4	15.6	204.5	129.2
	April	28.4	11.8	3.3	112.1
	May	23.9	6.54	0.0	26.8

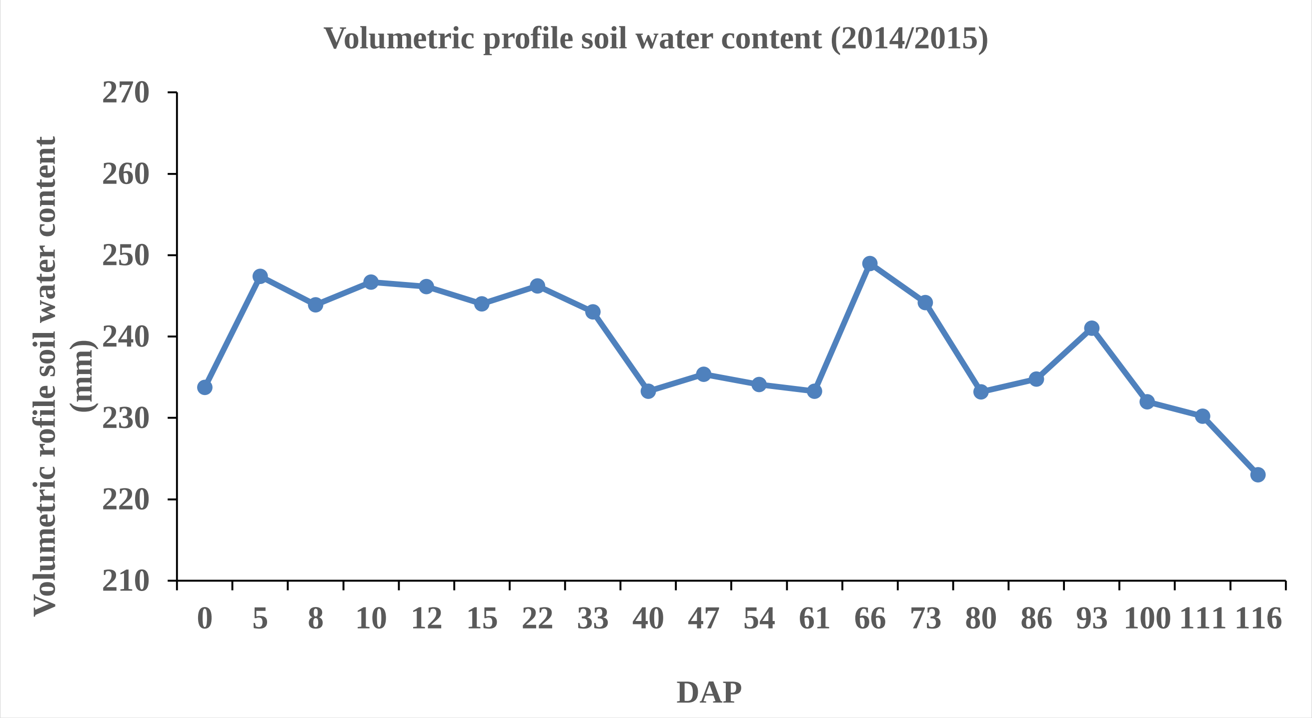


Figure 3.1: Profile soil water content measured using neutron probe water meter model 503DR CPN Hydroprobe during growing season one (2014/2015) (DAP = days after planting). Field capacity = 250 mm and permanent wilting point = 130 mm

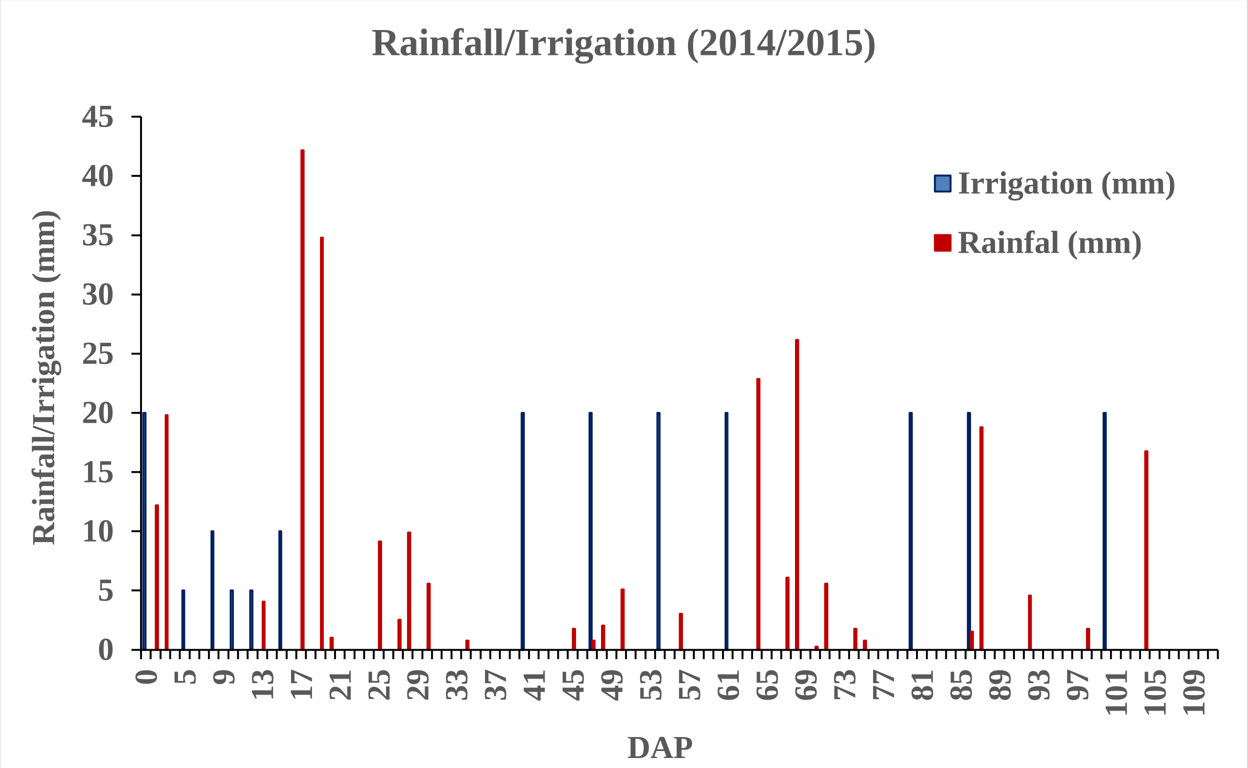


Figure 3.2: Rainfall amount and irrigation applied for growing season one (2014/2015) (DAP = days after planting)

Table 3.3: Chameleon response pattern during growing season two (2015/2016). Chameleon sensors give output of three different colours which correspond to measured tension, namely blue (wet soil, < 25 kPa), green (moist, 25 to 50 kPa), and red (dry soil, > 60 kPa).

Depth	**7-Jan**	**11-Jan**	**12-Jan**	**15-Jan**	**18-Jan**	**22-Jan**	**25-Jan**	**01-Feb**	**08-Feb**	**12-Feb**	**15-Feb**	**22-Feb**	**29-Feb**	**07-Mar**	**15-Mar**	**21-Mar**	**25-Mar**	**29-Mar**	**04-Apr**	**15-Apr**	**25-May**	**03-May**
0.15	G	**B**	**B**	**B**	**B**	**G**	**G**	**G**	**B**	**B**	**G**	**B**	**B**	**G**	**B**	**G**	**G**	**B**	**G**	**G**	**G**	**G**
0.30	B	**B**	**B**	**B**	**B**	**B**	**B**	**G**	**B**	**B**	**G**	**G**	**B**	**G**	**B**	**B**	**G**	**G**	**G**	**G**	**G**	**B**
0.45	B	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**G**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**G**	**G**
0.60	B	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**G**	**B**	**G**	**B**	**B**	**G**	**B**	**G**	**B**	**B**	**G**

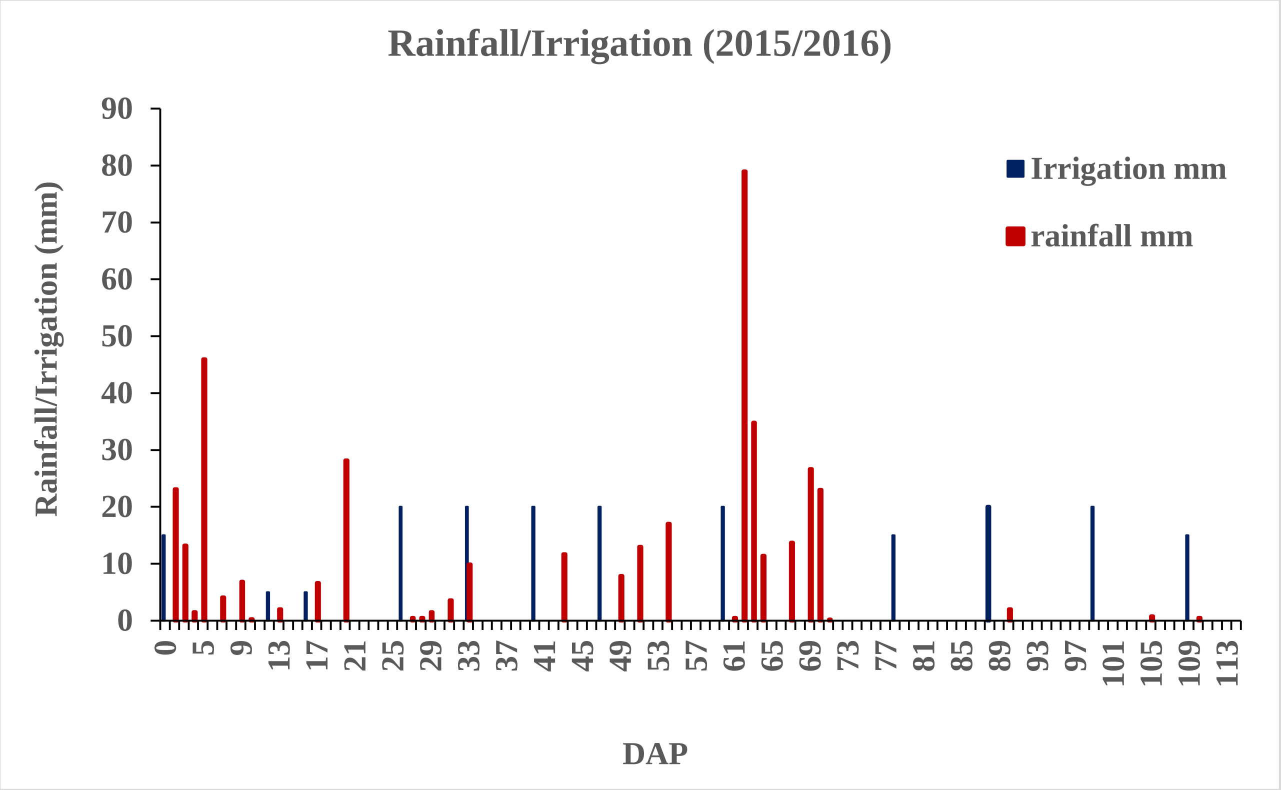


Figure 3.3: Rainfall amount and irrigation applied for growing season two (2015/2016)

(DAP = days after planting)

3.3.2 Leaf area index and fractional interception

The LAI (Figure 3.4) and FI (Figure 3.5) recorded during both growing seasons followed similar trends. The values increased from the early stage to middle stage, but decreased in the late growth stage and dropped quickly after reaching maturity. The sharp decrease of LAI in late growth stage was due to the fact that the crop reached maturity and decreases in temperatures (Table 3.2) and senescence of leaves. Sweet potato requires plenty of sunshine for optimum growth (van den Berg and Laurie, 2004; Nedunchezhiyan et al. 2012). The LAI of season one was higher than the LAI of season two, throughout the season, also FI during season one was higher than during season two, throughout the season therefore high PAR was intercepted during growing season one. This measurement was done to assess if the ET measured using EC system increased with canopy development.

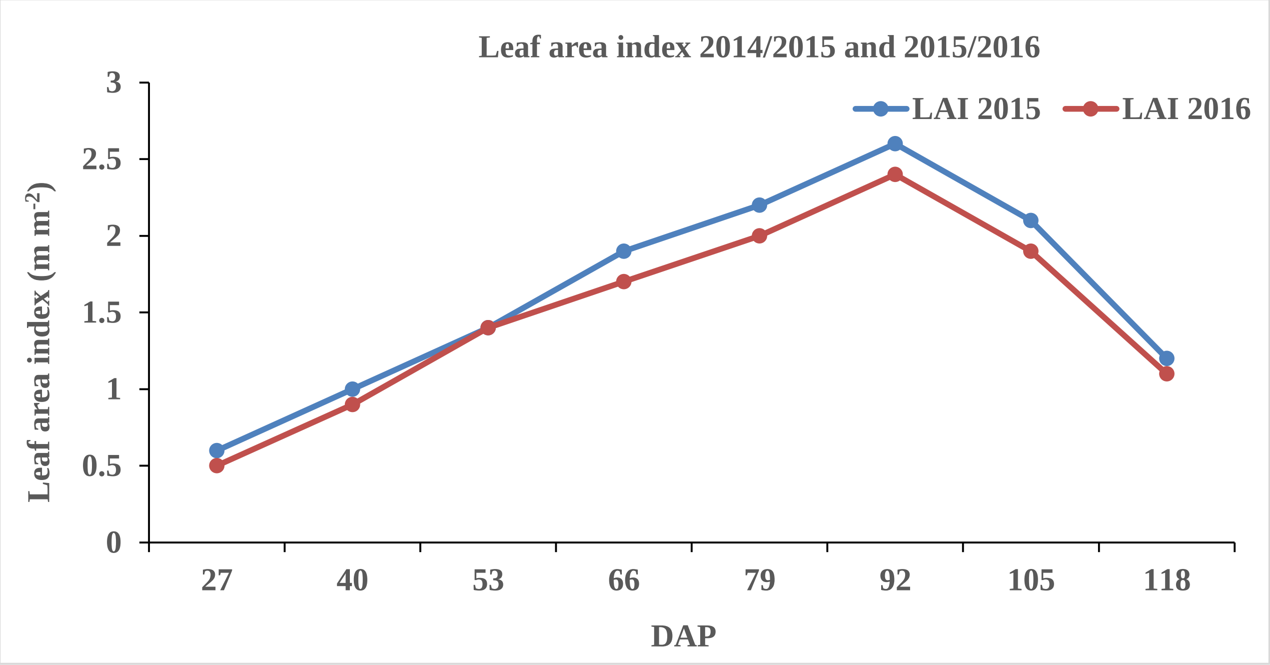


Figure 3.4: Leaf area index of sweet potato during growing season one (2014/2015) and growing season two (2015/2016) (DAP = days after planting)

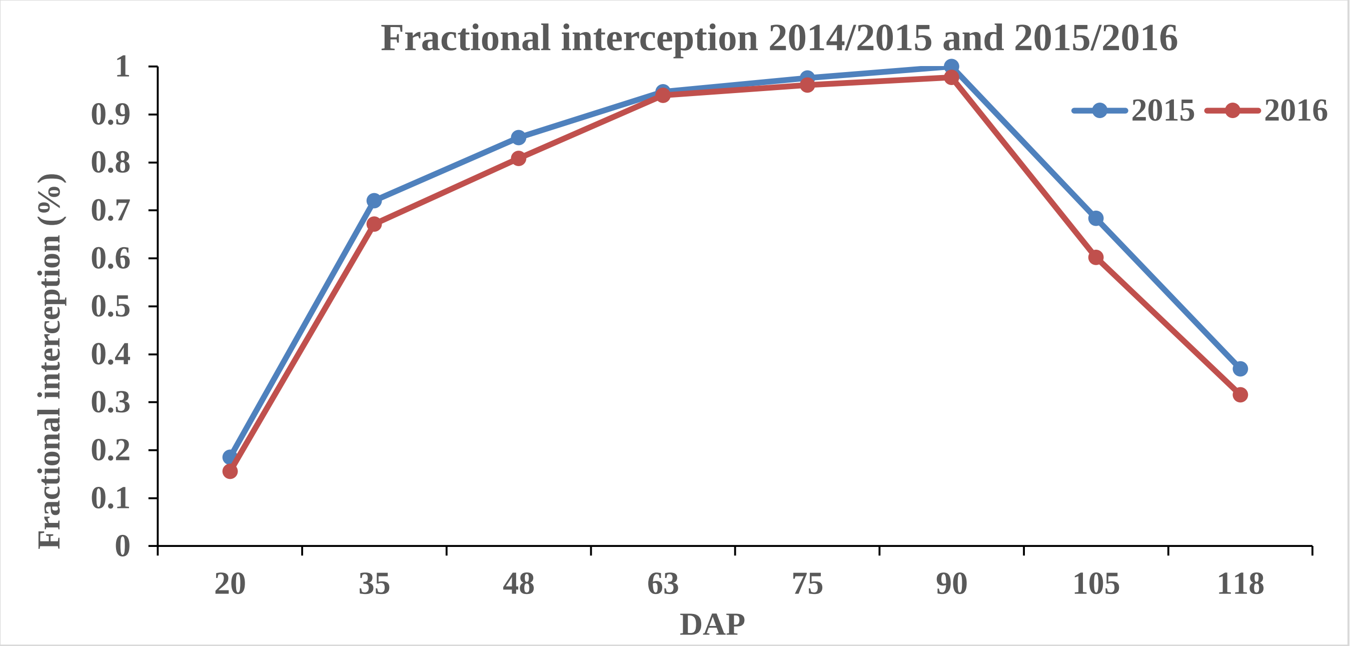
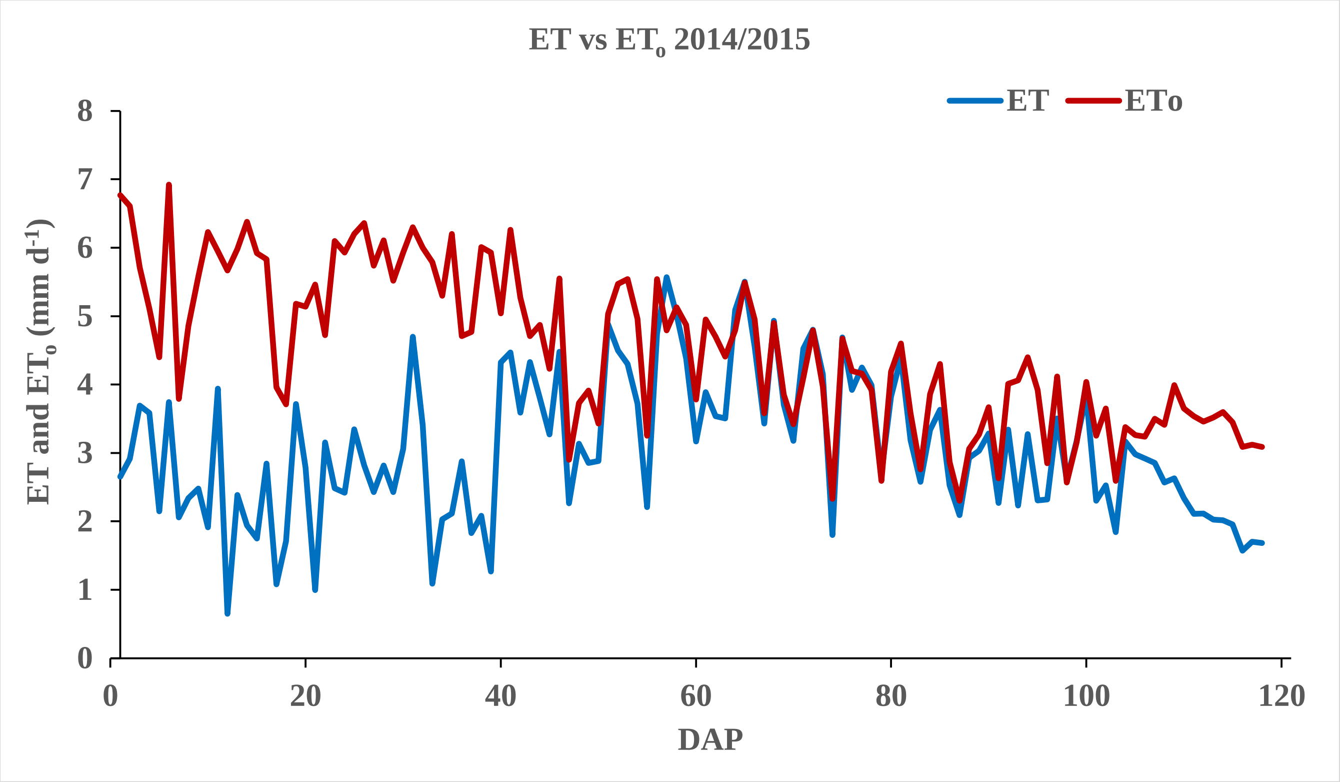


Figure 3.5: Fractional interception of sweet potato during growing season one (2014/2015) and growing season two (2015/2016) (DAP = days after planting)

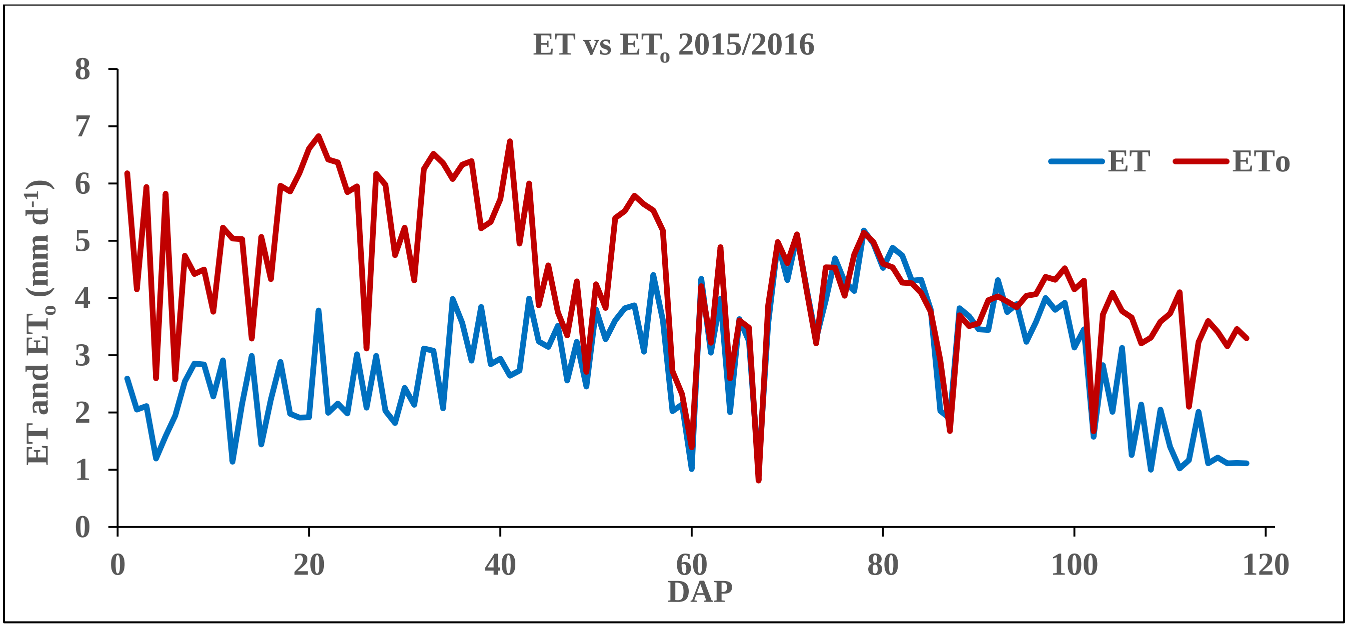
The LAI reported in this study was within the LAI ranges reported in the scientific literature (Shibayama and Akita, 2002; Masango, 2014). The maximum LAIs observed in this study were 2.4 and 2.6 m^2 m^{-2}. This was in agreement with Shibayama and Akita (2002) and Masango (2014) who reported maximum LAIs of 2.7 and 3.0 m^2 m^{-2}, respectively. Bourke (1984) reported that storage root dry matter accumulation is determined by the period that the crop leaves are green where high PAR will be intercepted. In this study, the crop was actively growing between 27 and 92 DAP where LAI values were between 0.6–2.6 m^2 m^{-2} during season one, and 0.5–2.4 m^2 m^{-2} during season two. Fractional interception during both growing seasons rapidly increased from 20 to 90 DAP, then from 95 DAP FI started to decrease, due to crop reaching maturity and decreases in temperatures. Maximum fractional interception recorded values during 2014/2015 and 2015/2016 seasons were 0.99 and 0.97, respectively. In this study it was observed that FI was mainly dependent on LAI. These simple means that the fractional interception increases with increased LAI, which lead to high rate of photosynthesis thereby maximizing biomass production.

3.3.3 Evapotranspiration

Daily ET of sweet potato varied from 0.5 mm (during rainy days) to 5.54 mm (during clear and sunny days) during growing season one, and 0.9 to 5.14 mm during growing season two (Figure 3.6a, b). The ET_o varied between 2.33 mm (cloudy days) and 7 mm (sunny days) during growing seasons one, and between 0.8 mm (cloudy days) and 6.9 mm (sunny days) during growing season two. At the beginning and towards the end of both growing seasons, the daily ET was lower than ET_o because of lower LAI which resulted in less PAR to be intercepted by the crop. The main reasons for the low ET estimates at the beginning and at the end of the season were due to partial canopy cover, crop maturity and leaf senescence, respectively, resulting in low PAR interception. The ET estimates increased from 1–90 DAP as the canopy developed, and there was a close match between ET and ET_o values at 55–90 DAP when the LAI reached maximum (Figure 3.6a, b). These results shows that sweet potato ET depend on number of factors, such as canopy cover and growth stages, therefore, for optimum ET is important to cultivate this crop when environmental conditions are favorable.



(a)



(b)

Figure 3.6: Comparison of daily evapotranspiration (ET) measured using the eddy covariance system and daily reference evapotranspiration (ET$_o$) calculated following the FAO-Penman-Monteith (Allen et al. 1998) equation during: (a) 2014/2015; and (b) 2015/2016 growing seasons (DAP = days after planting)

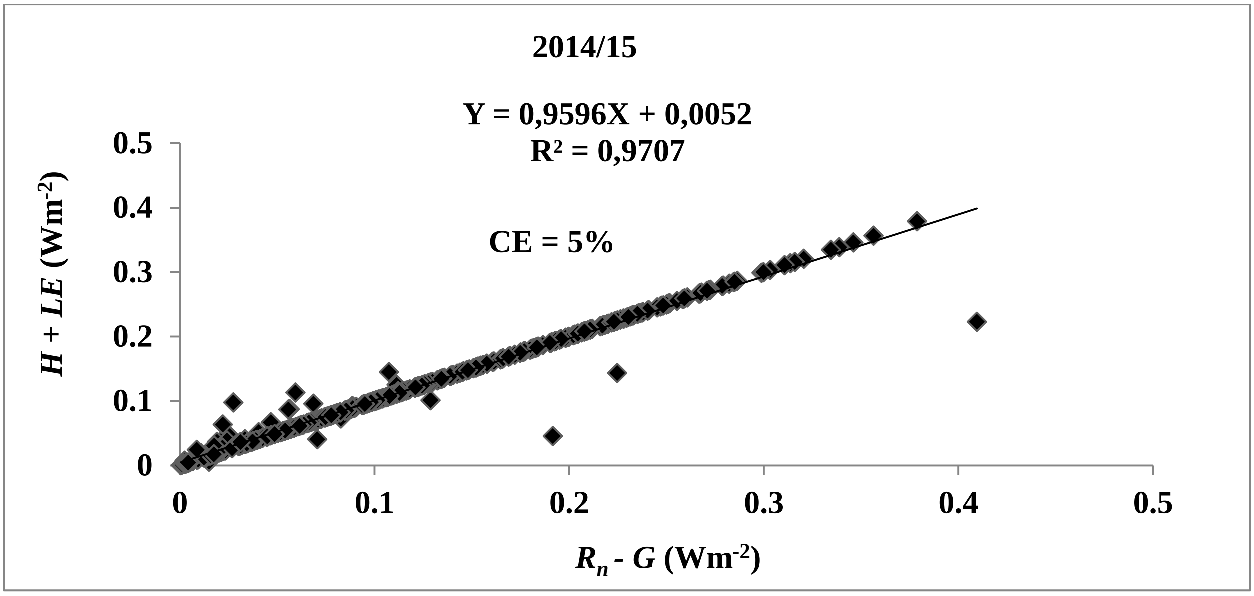
For both seasons, seasonal ET_o (535 and 521 mm) was higher than measured ET (361 and 344 mm), and this simple means that sweet potato is a drought tolerant crop. Under South African conditions Laurie et al. (2009) reported sweet potato water use ranging from 182–1400 mm per season, and Masango (2014) reported sweet potato water use estimates ranging between 298–478 mm. Gome and Carr (2003) reported sweet potato water use ranges between 350–850 mm for Mozambique, and Karanja (2006) reported an average sweet potato use of 366 mm per season in Kenya estimated using CROPWAT model. The difference in water use is due to the different methods that were used to estimate ET, crop management practices as well as environmental conditions (Kuslu et al. 2010; Abyane et al. 2011). ET varies seasonally within the same area and regionally due to different weather conditions.

3.3.4 Energy balance closure

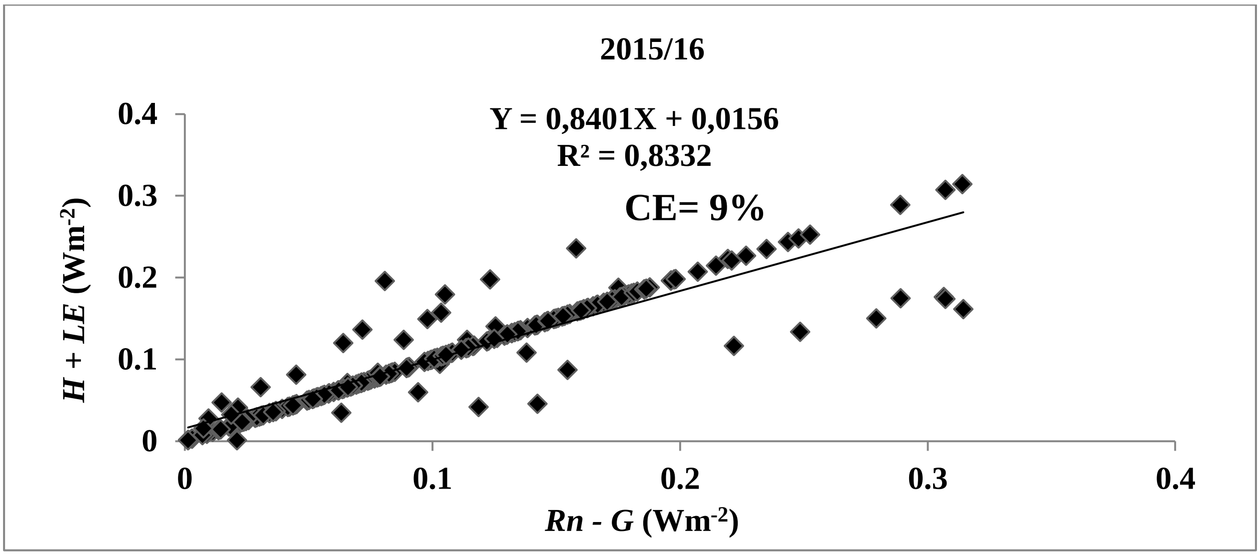
An energy imbalance between $H + LE$ and R_n - G was observed during both growing seasons. During growing season one, the energy balance closure error was 45%, and during growing season two the energy balance closure error was 48%. Therefore, this showed that $H + LE$ was underestimated by EC system, while $R_n - G$ was overestimated by surface energy balance method. For this study Twine et al. (2000) method was followed, who suggested forcing closure was justified when available energy was known and errors in its measurement modest. As a result, the LE and H heat fluxes were scaled to force closure while conserving the measured Bowen ratio. Therefore, Bowen ratio closure (BRC) method was used to improve $H + LE$, by adding to $H + LE$ fluxes, this method assumes that $R_n - G$ was correctly measured by the EC system, so that both values of $H + LE$ could be increased according to the ratio of H and LE in order to balance equation (3.1) as described in (Fitzjarrald and Moore, 1994; Blanken et al. 1997; Twine et al. 2000). The adjustment was done by calculating the difference between direct and indirect values measured at the same time and dividing the difference between direct and indirect measurements by two, then the product was used to compensate values of $LE + H$ (Blanken et al. 1997; Twine et al. 2000; Cleverly et al. 2002; Hipps et al. 2002; Scott et al. 2004; Nagler et al. 2005). Twine et al. (2002) stated that for their study $LE + H$ measured using the EC system were most often less than R_n - G.

The reasons that caused energy imbalance between $H + LE$ and R_n - G in our study, could be due to errors in EC measurement see section 2.7 (chapter two) which may be caused by dirt on the sonic transducers, noise in the measurement system, lack of steady state conditions, consumption of net radiation by photosynthesis, neglected energy sinks, heat storage in the top soil, mismatch in footprint, and malfunctions of sensors during rainfall conditions (Paw et al. 2000; Baldocchi et al. 2001; Scott et al. 2003; Papale et al. 2006; Casttivelli et al. 2008; Wolf et al. 2008; Ezzahar et al. 2009; Teixeira and Bastiaanssen, 2010).

The energy balance closure in this study was again determined after adjustment of $H + LE$ using the BRC method, and the closure error during growing season one was 5% which has improved by 40% from the closure error before adjustment with BRC method. For growing season two the closure error was 9% which has improved by 39% from the closure error before adjustment. Therefore, the obtained energy balance closure values after adjustment using BRC method, for season one and two were 95% and 91%, respectively. In this study, the linear regression between $H + LE$ and $R_n - G$ yielded a slope of 0.95, an intercept of 0.0052 Wm^{-2} and correlation coefficient $R^2 = 0.97$ for growing season one (Figure 3.7a), and during growing season two a slope of 0.84, an intercept of 0.0156 Wm^{-2} and $R^2 = 0.83$ were obtained (Figure 3.7b). This shows that there was a good relationship between the available energy with surface energy balance method and the adjusted turbulent fluxes. Therefore, it is crucial to estimate ET using LE values after closure is forced using the BRC method.



(a)



(b)

Figure 3.7: Surface energy balance closure: relation between half hourly data, *LE* + *H* (sum of turbulent flux) and $R_n - G$ (available energy): (a) for selected 20 days in season one; and (b) 11 days during growing season two.

The findings of this study were comparable to observations reported in the scientific literature. Ma et al. (2009) reported energy balance closure of 70% in summer and 92% in winter over a flat Prairie on the northern Tibetan plateau, while Ezzahar et al. (2009) reported the closure of 86% in olive orchards in Morocco. Sanchez et al. (2010) reported energy balance closure of

89% in a study of the analysis of the energy balance closure in a flux network (FLUXNET) boreal forest site in Finland. Teixeiva and Bastiaanssen (2010) have reported an energy balance closure of 92% for a mango *(mangifera indica)* orchard in Brazil. Baldocchi and Mayers (1991), reported closure of 84% for a deciduous forest, while Law et al. (1999) reported closure of between 70% to 88% for a Ponderosa pine forest, and Wright et al. (1992) reported excellent closure of 99% during the dry season in Brazil over ranchland of prairie grasses.

Over the years different researchers have reported average EC energy balance closure of between 75–87% for different surfaces (Falge et al. 2001; Wilson et al. 2001; Li et al. 2005; Barr et al. 2006), and a lack of closure on the surface energy budget by 5–30% has been reported by different researchers, while measuring turbulent fluxes using EC system under different areas (Twine et al. 2000; Wilson et al. 2002; Aubinet et al. 2002; Oncley et al. 2002; Barr et al. 2006; Liu et al. 2006; Gao et al. 2009; Ma et al. 2009; Su et al. 2009). Pirvulesca (2013) stated that in reality the perfect closure is not simple to obtain. Whereas, Wilson et al (2002) and Twine et al. (2000) reported an imbalance of surface energy budget by 20% at 22 FLUXNET site. There is no perfect closure for the energy balance and the lack of closure usually results in $H + LE < R_n - G$ (Wilson et al. 2002; Twine et al. 2000).

3.3.5 Crop coefficient

Daily values of crop coefficients (K_c) for sweet potato grown under optimum management practices were determined using the FAO single crop coefficient methodology (Allen et al. 1998) for two consecutive growing seasons (2014/2015 and 2015/2016). From Figure 3.8 it was observed that values of K_c increased from 1 DAP (0.2–0.3) to 90 DAP (1.1–1.2), and subsequently decreased from 0.5–0.2 at 95 DAP, respectively, during both growing seasons. Average weekly K_c values for both growing seasons show the same pattern, K_c values increased from the initial stage to middle stage then decreased at the final stage as shown in Figure 3.9. Crop coefficient values increased from initial stage to middle stage, and started to decrease at the final stage. Figure 3.10, shows average K_c values for the different growing stages, with value of 0.46 during the initial stage, 0.92 during the middle stage, and 0.57 during final stage. The sweet potato K_c values reported in this study were similar to the seasonal pattern of sweet potato K_c values reported in the scientific literature. Allemann (2004) reported sweet potato K_c values of 0.5 during the initial stage and 1–1.2 during the middle to maturity stages. While Dukes et al. (2012) reported sweet potato K_c value of 1.1 during middle stage. All reported K_c values in the literature were from international studies. The differences in sweet potato K_c values reported were related to the differences in the sites and cultivars used.

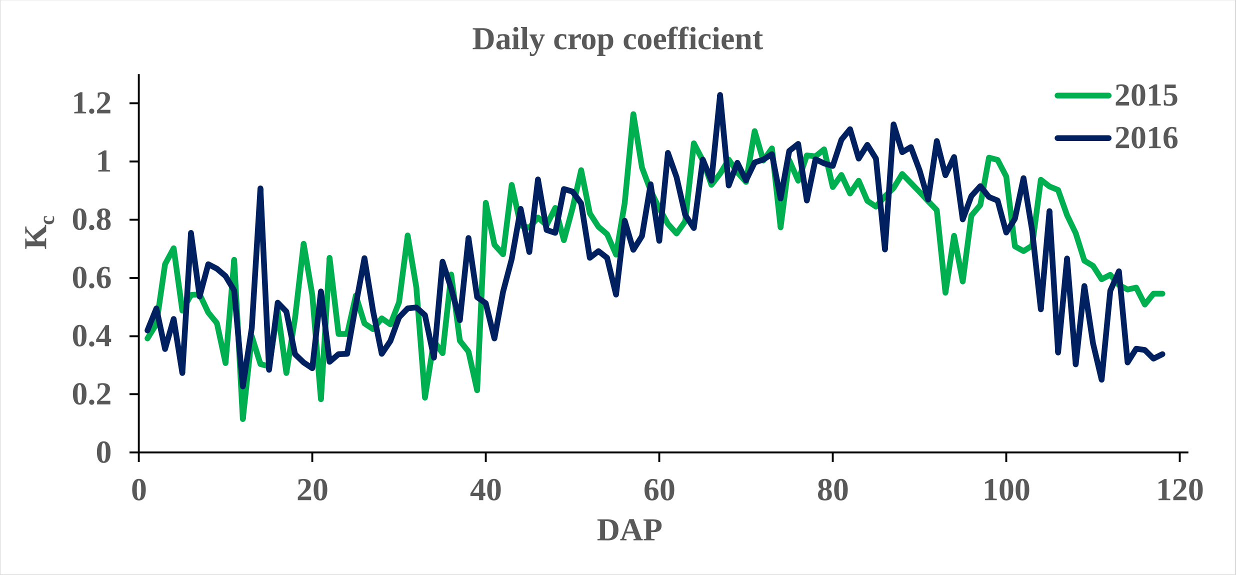


Figure 3.8: Comparison of daily sweet potato crop coefficient (K_c) values during growing season one (2014/2015) and two (2015/2016)

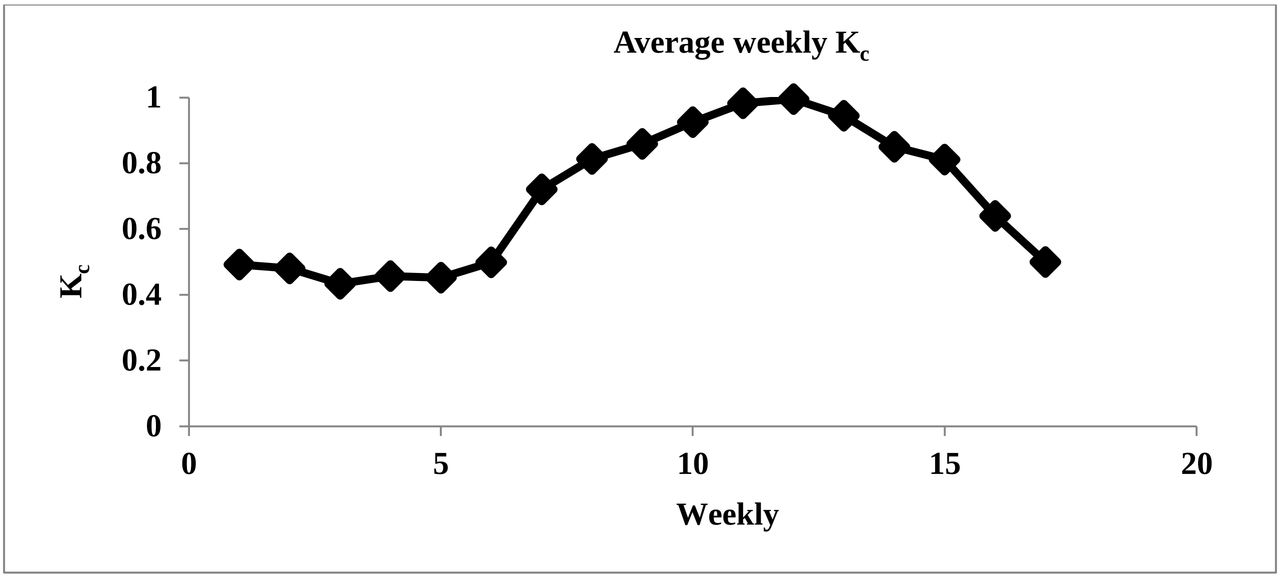


Figure 3.9: Average weekly sweet potato crop coefficient (K_c) values for growing season one (2014/2015) and two (2015/2016)

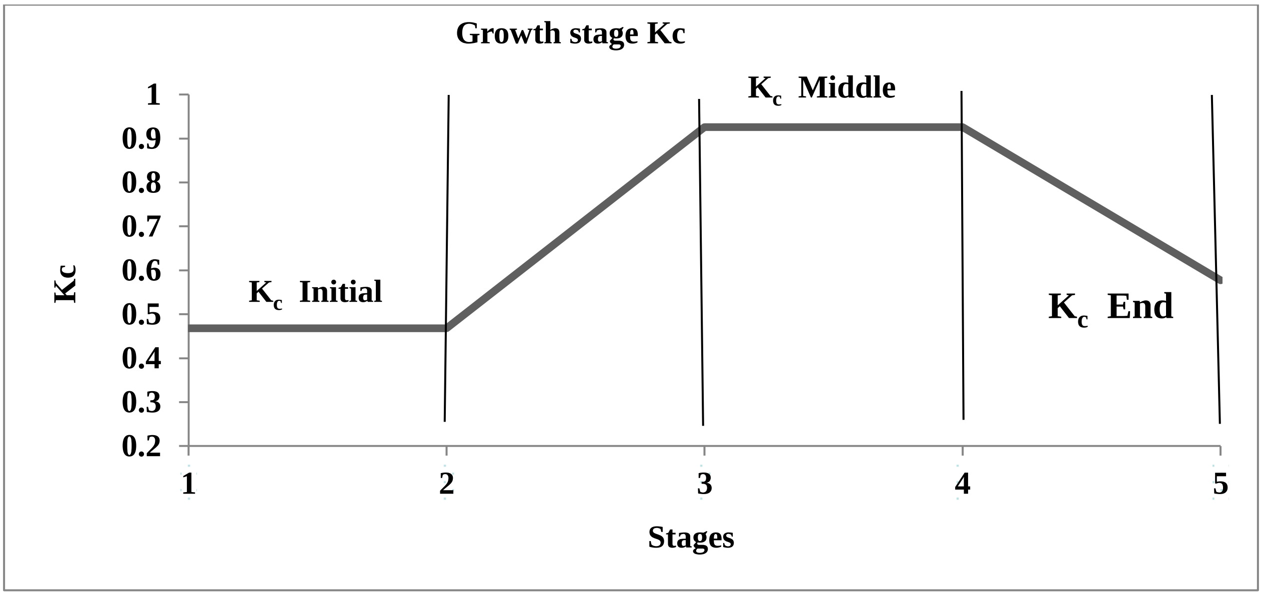


Figure 3.10: Average sweet potato crop coefficient (K_c) values for the different growing stages of season one (2014/2015) and two (2015/2016)

The reversed calculation of the determined K_c in this study showed that, the estimated ET_c using derived K_c were 381 and 375 mm for season one and two, respectively. The estimated ET_c using derived K_c are similar, but bit higher than measured ET (361 and 344 mm) using EC system during growing season one and two, respectively. The estimated ET_c using derived K_c was higher due to the fact that, at early and late growth stage, ET_o was higher than ET of OFSP as the canopy cover at early growth stage was small, due to the fact that the crop was still developing and at late growth stage the crop was reaching maturity.

3.3.6 Storage root yield (fresh and dry mass basis)

Weather and climatic conditions are considered to be the main factors that cause fluctuations in sweet potato storage root yield if other growth variables are not limiting (Oweis and Hachum, 2004). In this study, the fresh mass (32.2 t ha^{-1}) and dry matter (8.7 t ha^{-1}) sweet potato storage root yield of growing season one was slightly higher than that of season two, fresh mass (29.7 t ha^{-1}) and dry matter (7.5 t ha^{-1}). Even though sweet potato is consumed fresh, the dry matter is important for industrial process of dried products. Evapotranspiration measured during season one (361 mm) was slightly higher than ET measured during season two (344 mm). Evapotranspiration of crops is influenced by different factors such as weather variables (air temperature, solar radiation, wind speed, relative humidity), soil water availability, pest infestations and nutrients deficiencies (USDA-NRCS, 1997). The results of this study showed that yield of sweet potato increases with evapotranspiration. Steduto et al. (2012) reported that there is direct relationship between crop ET and yield, they also reported that reduced ET will cause the reduction in yield, and increased ET normally increases yield. However, irrigation applied plus rainfall received during season one was lower than irrigation applied plus rainfall received during season two, this means that applying water more than what crop require is a waste, as more water is lost through drainage and runoff, than through evapotranspiration. (Table 3.4).

Table 3.4: Growing season 2014/2015 (season one) and 2015/2016 (season two) storage root yield, water use (evapotranspiration) and water productivity of sweet potato

Seasons	Storage root yield (kg ha^{-1})	Rainfall plus irrigation (mm)	Evapotranspiration (mm)	Water use efficiency (kg ha^{-1} mm^{-1})
2014/2015	32 000	481	361	89
2015/2016	29 000	585	344	84

Nedunchezhiyan (2012) reported that sweet potato storage root yield varied between 20–25 t ha^{-1}. In Mozambique, Gomez and Carr (2001) reported storage root yield of 34.2 t ha^{-1}. Under South African conditions, Masango (2014) reported storage root yield of between 25 and 31 t ha^{-1}, while Laurie et al. (2009) reported sweet potato storage root yield ranging from 7.65–46.95 t ha^{-1}, in an experiment conducted under different soil water levels. Laurie et al. (2012) also reported storage root yield ranging between 10.3–49.1 t ha^{-1}. Masango (2014) reported storage root yield in dry matter basis that varied between 6.5–7.6 t ha^{-1} under different irrigation levels. The sweet potato storage root yield obtained from this study were comparable to other studies reported in the literature.

3.3.7 Water use efficiency under optimal conditions

The WUE values obtained were 89 kg ha^{-1} mm^{-1} in growing season one and 84 kg ha^{-1} mm^{-1}during season two (Table 3.4). The results from this study showed that sweet potato used water efficiently in both growing seasons, and that the crop can be grown with relatively little water and still produce high yields. Crop WUE depends on different factors such as genotype, crop species and the available energy from the sun (Wallace and Batchelor, 1997). Therefore, the difference in crop WUE values between the two seasons in this study could be attributed to the aforementioned factors.

The reported values of sweet potato WUE in this study were comparable to WUE values reported in the literature. For studies conducted in South Africa, Masango (2014) reported WUE of sweet potato to be between 65 and 98 kg ha^{-1} mm^{-1}, while Bok (1998) reported WUE of sweet potato to be between 69.83 and 131.78 kg ha^{-1} mm^{-1}. Laurie et al (2012) reported the WUE of sweet potato variety 'Resisto' to be between 54.0 and 70.5 kg ha^{-1} mm^{-1}. Laurie et al (2009) observed that WUE of 'Resisto' variety was between 8.12 and 97.50 kg ha^{-1} mm^{-1} for the experiment that was conducted under three different irrigation levels, whereas they obtained WUE values ranging between 34.96 and 71.08 kg ha^{-1} mm^{-1} for a different variety 'Isondlo' under the same experiment. Therefore the WUE values reported in this study were higher than the WUE values reported in other studies in South Africa. The high WUE values obtained in this study could be due to high canopy cover development that led to more PAR interception, which in turn increased the rate of photosynthesis, thereby increasing dry matter production.

3.4 Conclusion

The EC system was used to estimate seasonal water use (ET, in mm) during two growing seasons, and the average seasonal water use obtained in this study was 356 mm. From the findings of these study it was observed that sweet potato used water productively as high yield was obtained with less amount of water used, and averaged yield and WP were 30500 kg ha^{-1} and 87 kg ha^{-1} mm^{-1}, respectively. The surface energy balance closure was also determined in order to validate the EC flux estimates, and 95 and 91% closure was obtained for both seasons, respectively after correcting turbulent fluxes using BRC method. The K_c for OFSP grown under optimum management practices was developed for summer season and in both growing seasons the average K_c values were 0.46 during the initial stage, 0.92 during middle stage, and 0.57 during late growing stages. These is reasonable results which can in future be used to aid in the extrapolation of measured experimental results to different climatic conditions in South Africa using the FAO-56 methodology for estimation of OFSP water use.

CHAPTER FOUR

Influence of different irrigation strategies on yield and water productivity of sweet potato (*Ipomoea batatas*)

4.1 Introduction

In semi-arid countries like South Africa (SA), low rainfall is one of the main yield limiting factors for sweet potato (*Ipomoea batatas*) production (Anselmo et al. 1998; van Heerden and Laurie, 2008). Since potential evapotranspiration (ET) exceeds rainfall in many parts, water in SA is a scarce resource. This coupled with an ever increasing population and high food demand, as well as the competition among different sectors for water (agriculture, domestic and industrial), means it is important to use our water resources in an efficient and sustainable way (DWAF, 1994; Jovanovic and Annandale, 2000; Jarmain et al. 2009; Beletse et al, 2013).

Ali and Takukder (1999) reported that careful use of water and optimizing crop water productivity (WP) which can be defined as yield per unit water used (kg m^{-3}) (Molden, 2003), are extremely important in areas with scarce water resources. This can be done by selecting drought tolerant crops such as sweet potato, and implementing agricultural practices that can improve yield, water use and WP (Bennie and Hensley, 2001; Molden, 2003; Igbadum et al. 2006; Laurie et al. 2009). Sweet potato can survive in tough conditions, which makes it a key crop grown in SA for food security by small holder farmers under rain-fed conditions (van den Berg and Laurie, 2004; Laurie et al. 2012; Motsa et al. 2015).

In literature, it has been reported that deficit irrigation influences sweet potato yield, water use and WP (Lana and Peterson, 1956; Smittle et al. 1990; Gomes and Carr 2001; Lewthwaite and Triggs, 2012; Laurie et al. 2012; Felix et al. 2012; Beletse et al. 2013; Masango, 2014). But more knowledge is needed on how to manage water optimally, especially when farmers only have limited irrigation water available.

In this study, the influence of different irrigation strategies on yield and WP of two major SA-grown sweet potato types, namely orange-flesh (OFSP) cultivar 'Bophelo' and one white-flesh (WFSP) cultivar 'Blesbok' was investigated.

4.2 Materials and methods

4.2.1 Site description and agronomic practices

The study was conducted at the Roodeplaat Experimental Farm of the Agricultural Research Council, Vegetable and Ornamental Plants (ARC–VOP) (25°35'N, 28°21'E, 1164 m above sea level) in Gauteng Province, SA during the 2015/2016 summer (November to March) season. The region experiences summer rainfall with an average of about 650 mm per annum (Jovanovic and Annandale, 1999). The study area has a humid subtropical climate, and average daily temperature ranges between 8–34°C in summer and 4–23°C in winter (Beletse, 2013).

Soil samples were collected from the top 0.30 m soil depth at the beginning of the season to determine the physical and chemical properties (Table 4.1). The soil of the site was classified as a Hutton soil form (Soil Classification Working Group, 1991) with a loamy texture (69.6% sand, 6.7% silt, and 20.1% clay) and bulk density of 1.6 g cm^3. Based on the soil analysis test results, 100 kg ha^{-1} N [limestone ammonium nitrate (LAN) 28%] and 21 kg ha^{-1} P superphosphate, (10.5%), was applied at planting potassium (K) was sufficient, and a top dressing of 50 kg ha^{-1} N (LAN) was applied 21 days after planting. Fertilizer was applied in rows and incorporated into the soil manually using hand hoes and rakes.

Table 4.1: Soil chemical analysis results for the growing season (2015/2016)

Chemical elements	Units	2015/2016
Ammonium nitrogen (NH_4–N)	mg kg	5.63
Nitrate nitrogen (NO_3–N)	mg kg^{-1}	7.73
pH (H_2O)	–	6.87
Phosphorus (P) (Bray–1)	mg kg^{-1}	5.99
Calcium (Ca)	mg kg^{-1}	696.28
Magnesium (Mg)	mg kg^{-1}	273.95
Potassium (K)	mg kg^{-1}	250.78
Sodium (Na)	mg kg^{-1}	17.85

For comparative purposes, the cultivar 'Bophelo' (Figure 4.1a) was chosen due to its high nutritional value, while 'Blesbok' (Figure 4.1b) was chosen due its high yield potential (Bester et al. 1991). Sweet potato cuttings used were 0.3 m long and without roots and were manually planted on the 2nd November 2015, at a planting density of 33 333 plants per ha. The ridges were 1 m apart and on each ridge one row of sweet potato was planted at a spacing 0.30 m between plants. Each plot was composed of five rows 4 m long. The spacing between drippers was 0.3 m and one dripper line was installed on each row with one dripper per plant (Figure 4.1c).

Figure 4.1: Orange and white-flesh sweet potato type ‘Bophelo’ (a) and ‘Blesbok’ (b) leaves and one dripper line installed per ridge (c)

Irrigation was applied using a high density, pressure-compensated drip irrigation system. The system had a delivery rate of 2.5 ℓ hr^{1} at a pressure range of 100–150 kPa. Neutron probe access tubes were installed in each plot. Chameleon moisture sensors (www.via.farm) (CSIRO, Canberra, Australia) (Stirzaker et al. 2017) were also installed in each plot at depths of 0.15, 0.30, 0.45 and 0.6 m. Each plot was equipped with a water valve used to control the irrigation amount. Immediately after planting, the plots were irrigated with the same amount of water, in order to keep the soil profile at field capacity (FC), for 29 days until the plants were fully established.

4.2.2 Treatments and design

The trial was composed of 18 plots of 5 m × 4 m (20 m^2) with a 2 m border between plots, in order to restrict lateral flow of water in the root zone between plots. The six treatment combinations of two sweet potato cultivars and three water levels, termed, full irrigation (FI), supplementary irrigation (SI) and rainfed (RF), were arranged in a randomized complete block design (RCBD) with three replications (Table 4.2). The field was slightly sloped, therefore the RCBD design was laid perpendicular to the source of variation.

Block I		**Block II**		**Block III**	
R O	**S W**	**R W**	**R O**	**F O**	**F W**
F O	**F W**	**F O**	**F W**	**S O**	**R O**
S O	**R W**	**S O**	**S W**	**S W**	**R W**

Table 4.2: Layout of experimental design based on a randomized complete block design under three different irrigation treatments (RO = rainfed ‘orange’, FO = full ‘orange’, SO = supplementary ‘orange’, RW = rainfed ‘white’, FW = full ‘white’, SW = supplementary ‘white’)

The original plan was to use a neutron probe water meter (model 503DR CPN Hydroprobe) (Campbell Pacific nuclear Inc., California, USA) that measures volumetric water content (θ) for irrigation scheduling. But the neutron probe broke during the trial so the Chameleon soil moisture sensors that measure soil water potential (ψ) (Stirzaker et al. 2017) were used for irrigation scheduling. Irrigation treatments commenced 30 days after planting and irrigation was scheduled based on the observed relationship between soil water potential (ψ) and volumetric water content (θ). The relationship between the neutron probe was (calibrated on the site) and Chameleon soil moisture sensors was developed from the data collected simultaneously in the first two months (02 November – 28 December 2015), which was used to convert Chameleon ψ to θ. It was also decided that the orange and white-fleshed cultivars must be irrigated same amount of water for comparative purposes.

For the FI treatment, soil moisture depletion was not allowed to reach above 20% (30 mm) of the deficit to FC [scenario B (FI)] (refer to Appendix 5). Measured three times per week 15 mm applied to FC when colors of the Chameleon sensors at 0.15–0.30 m depths turned from blue to green. The SI treatment was irrigated when soil moisture depletion reached 70% (105 mm) to revive the plants deficit to FC [scenario F (SI)] (refer to Appendix 5). So when colors of the Chameleon sensors at 0.15–0.30 m depths turned red 23 mm applied. For the RF treatment, irrigation was withheld completely. The strategy used for irrigation was deficit irrigation, where a specific percentage was allowed to deplete from the effective rooting zone depth of sweet potato before refilling the soil profile back to FC. Therefore this practice was done in order to assess the effects of different irrigation strategies on nutritional content, nutritional yield, NWP and Yield of sweet potato.

4.2.3 Data collection

4.2.3.1 Crop growth analysis

Leaf area index (LAI) and fractional interception of photosynthetically active radiation (PAR) were measured using a Decagon Sunfleck ceptometer (Decagon, Pullman, Washington, USA) in order to check canopy development. One reading was taken above the canopy and four readings were taken below the canopy. While LAI 3100 belt driven leaf area meter (LI-COR, Inc., Lincoln, Nebraska, USA) was also use to measure Leaf area index destructively and was determined using Equation 4.1:

$$\text{LAI } (\text{m}^2\text{m}^{-2}) = \frac{Measured\ total\ leaf\ area}{Sampled\ ground\ area} \tag{4.1}$$

Crop leaves were measured at three weeks interval throughout the growing season, and was done by sampling the aboveground and harvestable storage root plant material of two plants from each plot. Samples were separated into stems, leaves and storage roots, and fresh mass was immediately determined. Separated sample (stems, leaves and storage roots) were oven dried at 50°C to a constant mass in order to determine dry matter of the different plant organs.

4.2.3.2 Final yield

Fresh marketable yield was determined at final harvest by weighing the storage roots of three selected plants from each plot. Sweet potato storage roots were oven dried at 50°C to determine the dry matter yield. Harvest index (HI) (%) was calculated as the ratio of the dry storage root yield over the total plant dry matter (dry leaves, storage roots and vines) from the same area multiplied by 100.

4.2.3.3 Weather data

A fully automatic weather station located about 500 m from the trial site in Roodeplaat, Pretoria, was used to measure weather data. The station measured daily relative humidity and temperatures (maximum and minimum) using a CS-500 Vaisala temperature and relative humidity probe (Campbell, Scientific. Inc., Logan. Utah. USA); Total daily solar radiation using LI-200 Pyranometer (LI-COR Inc., Lincoln, Nebraska, USA); Rainfall amount and intensity using TE 525 tipping bucket rain gauge (Texas Instruments Inc.); Wind speed and direction were measured using 03002 Wind Sentry (RM Young, Michigan, USA). The weather data was recorded and averaged hourly and stored in a data logger CR10X (Campbell Scientific, Inc., UT, USA).

4.2.3.4 Water use and water use efficiency

Crop ET and WP of the sweet potato storage root (fresh mass basis) were calculated at final harvest according Equation 4.2 as defined by (Howell et al. 1992) and 4.3 (Rana and Katerji, 2000):

$$\text{ET (mm)} = I + R - D - R \pm \Delta S \qquad (4.2)$$

where ET is evapotranspiration (mm),

I is irrigation (mm),

P is precipitation (mm),

D is drainage (mm) (assumed to be zero),

R is runoff (mm) (assumed to be zero),

ΔS is change in soil water storage (mm).

Drainage is the most difficult parameter to measure and is the most unknown of equation (4.2) (Rana and Katerji, 2000; Zeleke and Wade, 2012). Therefore in general practice at daily scale it can be neglected especially if the water supply (P and I) does not exceed the soil water capacity (Holmes, 1984; Lhomme and Katerji, 1991). In different agricultural fields, the amount of runoff is generally small so is often considered negligible (Zeleke and Wade, 2012).

$$\text{WUE (kg ha}^{-1}\text{ mm}^{-1}) = \frac{SRY}{ET} \qquad (4.3)$$

where SRY is storage root yield (fresh mass) in kg ha^{-1}.

4.2.4 Data analysis

GenStat 15th Edition statistical package was used to test the effects of different irrigation levels on yield, total dry matter (aboveground plus storage root) (TDM) yield, HI and WP. Data was subjected to Analysis of Variance (ANOVA) at a threshold *P* value of 0.05. When the effects were significantly different, the least significant difference (LSD) test ($\alpha = 0.05$) separated the means.

4.3 Results and discussion

4.3.1 Weather variability during the study period

Table 4.3 shows the maximum, minimum and average weather variables during the growing season. Rainfall was not well distributed over the growing season with the highest rainfall in January (135.1 mm) after planting and the lowest rainfall in March was (17 mm). The total monthly ET_o was always above 150 mm, except in March. Throughout the growing season, the rainfall was lower than reference (ET_o) which shows the need for irrigation to improve yields. Average maximum and minimum temperatures of between 15 to 30°C throughout the growing season were optimal for sweet potato growth (Du Plooy, 1989; van den Berg and Laurie, 2004; Masango, 2014).

Table 4.3: Monthly minimum, maximum and averaged weather data for the 2015/2016 growing season (Tx = maximum temperature, Tn= minimum temperature, ET_o = reference evapotranspiration)

Year	**Month**	**Mean Tx (°C)**	**Mean Tn (°C)**	**Rainfall (mm)**	**ET_o (mm)**
2015/2016	**November**	31.77	13.95	29.7	176.0
	December	33.88	18.09	60.2	176.9
	January	31.67	17.63	135.1	165.9
	February	32.46	17.82	49.5	152.8
	March	29.35	15.61	17.0	61.9 (until harvest)

4.3.2 Growth analysis

4.3.2.1 Leaf area index

The LAI of both sweet potato cultivars followed similar trends, with the highest values being observed for the FI treatment followed by SI and RF (Figure 4.2). The maximum LAI values recorded in this experiment was 2.7 m^2 m^{-2} for OFSP and 2.5 m^2 m^{-2} for WFSP (Figure 4.2). Masango (2014) reported a maximum LAI of 3 m^2 m^{-2}, while Shibayama and Akita (2002) reported a maximum LAI value of 2.7 m^2 m^{-2}. During the growing season, the LAI of both cultivars increased from the early stage to middle stage, and decreased at the late growth stage with a sharp drop after the crop reached maturity.

The maximum LAI values observed in this study are within the range of 1.03 to 8.23 m^2 m^{-2} reported for sweet potato in literature (Shibayama and Akita, 2002; Masango, 2014). The highest LAIs under FI, were due to rank growth caused by increased water application. The lowest LAI was reported under RF due to less overall growth and the partitioning of more energy to roots than aboveground (leaves and stems) under these water-stress conditions (Laurie et al. 2009; Beletse et al. 2013; Yooyongwech et al. 2014; Gajanayake, 2014).

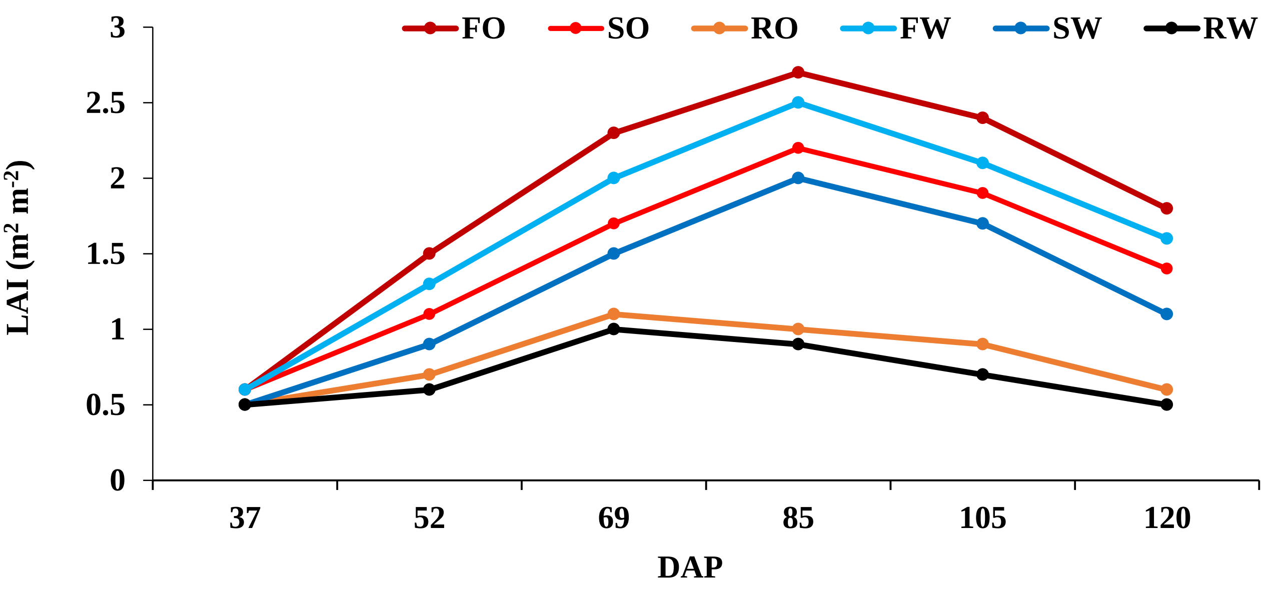


Figure 4.2: Leaf area index (LAI) of orange (OFSP) and white-fleshed (WFSP) sweet potato as influenced by different irrigation treatments during the growing season (2015/2016) (FO = full ‘orange’, SO = supplementary ‘orange’, RO = rainfed ‘orange’, FW = full ‘white’, SW = supplementary ‘white’, RW = rainfed ‘white’ and DAP = days after planting)

4.3.2.2 Fractional interception

Fractional interception of photosynthetically active radiation followed the same trend for both cultivars and across treatments. The highest values were observed for the FI treatment followed by the SI treatment and were lowest under the RF treatment (Figure 4.3). The highest fractional interception recorded under FI treatments for both cultivars was due to a large canopy development as a result of high soil moisture levels, while the lowest recorded under RF condition was due to low canopy development caused by water stress. Under RF conditions, it was observed that length of the vines as well as leaves of both cultivars were smaller compared to irrigated treatments.

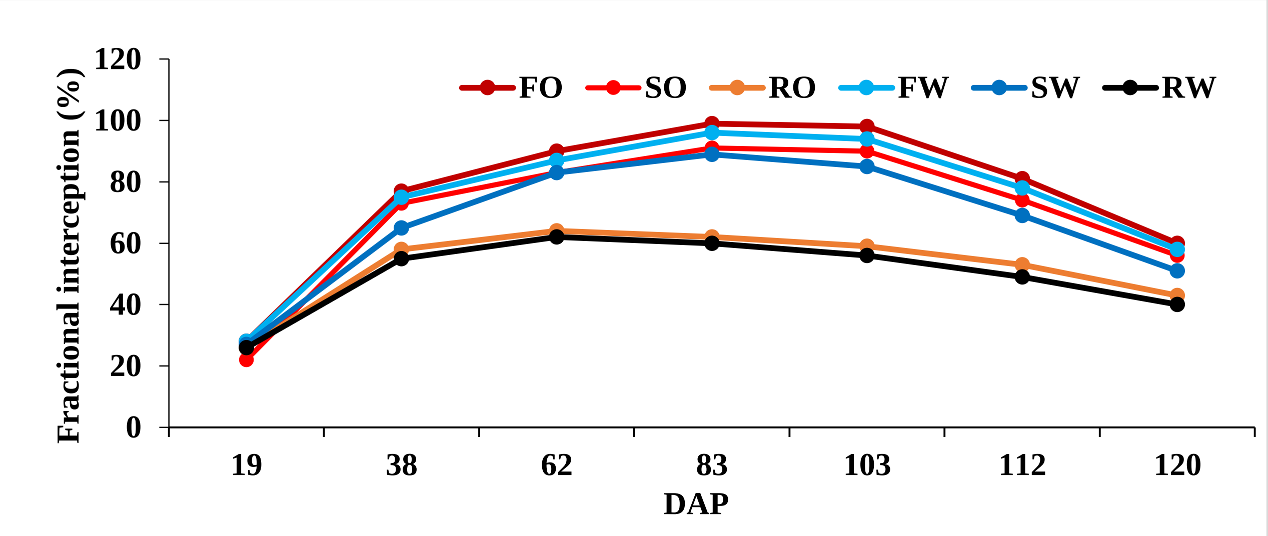


Figure 4.3: Fractional interception for orange (OFSP) and white-fleshed sweet potato (WFSP) as influenced by different irrigation treatments during the growing season (2015/2016) (FO = full ‘orange’, SO = supplementary ‘orange’, RO = rainfed ’orange’, FW = full ‘white’, SW = supplementary ‘white’, RW = rainfed ‘white’ and DAP = days after planting)

4.3.3 Yield and harvest index

The statistical analysis results show that the interaction between cultivars and different irrigation levels was highly significant. It was also observed that differences between different irrigation treatments was significant. Therefore, different irrigation treatments significantly affected both cultivars in terms fresh storage root yield, TDM and HI.

Table .4.4: Statistical differences between cultivars and irrigation treatments

Cultivar	**Treatments**	**Fresh root yield (t ha^{-1})****	**Total dry matter yield (t ha^{-1})****	**Harvest index (%)****	**Irrigation + rainfall (mm)****
OFSP	**FI**	35.5^{b}	11.1^{b}	63.4^{b}	451^{a}
	SI	22.0^{d}	7.2^{d}	57.2^{c}	331^{b}
	RF	6.2^{e}	3.0^{f}	52.9^{c}	261^{c}
WFSP	**FI**	39.9^{a}	13.3^{a}	72.7^{a}	451^{a}
	SI	27.0^{c}	8.3^{c}	67.4^{b}	331^{b}
	RF	9.0^{e}	4.8^{e}	64.7^{b}	261^{c}

**** significant at 0.01**

4.3.3.1 Fresh storage root yield

For the final storage root yield, the interactions between cultivar and irrigation was highly significant (P = <0.001) (Table 4.4). For equivalent irrigation treatments, WFSP out-yielded OFSP as hypothesized (Figure 4.4). This is because OFSP cultivars are generally less drought tolerant than the WFSP cultivars, as for the OFSP more energy is used for the production of β-carotene and other nutrients which are lower in WFSP (Tumwegamire et al. 2004), therefore, OFSP can be cultivated in rural area where agricultural is mostly rainfed, for its nutritious content. Both cultivars of sweet potato were significantly affected by the different irrigation treatments, although the reduction was more pronounced in OFSP than WFSP. Under SI and

RF conditions, yield reductions were by 30 and 76% for WFSP, and 37 and 82% for OFSP, when compared to the FI treatment.

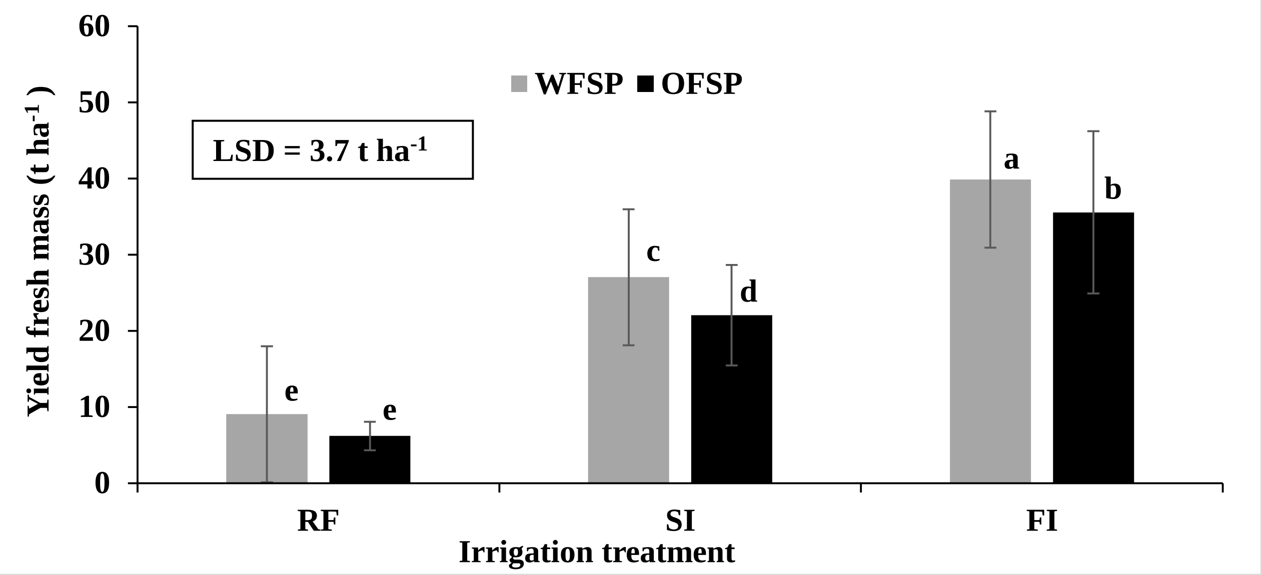


Figure 4.4: Fresh storage root yield of orange (OFSP) and white-fleshed sweet potato (WFSP) as influenced by different irrigation treatments (RF = rainfed, SI = supplementary irrigation, FI = full irrigation)

Finding of this study match what has been reported by Van Heerden and Laurie (2008) and Laurie et al. (2009) who observed that yield decreases significantly with water stress. Laurie et al. (2009) reported significant differences in total storage root yields when they imposed 30% and 100% depletion with values ranging from 7.62–46.95 t ha^{-1}. Nat et al. (2006) reported 26 t ha^{-1} roots yield under irrigated conditions, while Van Heerden and Laurie (2008) reported storage root yields of OFSP cultivar ‘Resisto’ and variety A15 values that were in the range of 5–27 t ha^{-1} under 30% and 80% depletion.

4.3.3.2 Total dry matter yield

Interactions between cultivar and irrigation were highly significant (P = <0.001) for TDM (Table 4.5). For all irrigation treatments, WFSP out-yielded the OFSP (Figure 4.5). Masango (2014) reported significant different in TDM yield ranging from 10.31–13.95 t ha^{-1} for OFSP cultivar 'Resisto' grown under different water levels. Whereas Oboh et al. (1989) reported sweet potato TDM yield 11. 20 t ha^{-1}. However Ekanayake (1989) reported that under water stress conditions, TDM yield was reduced to similar yields as what was observed in this study.

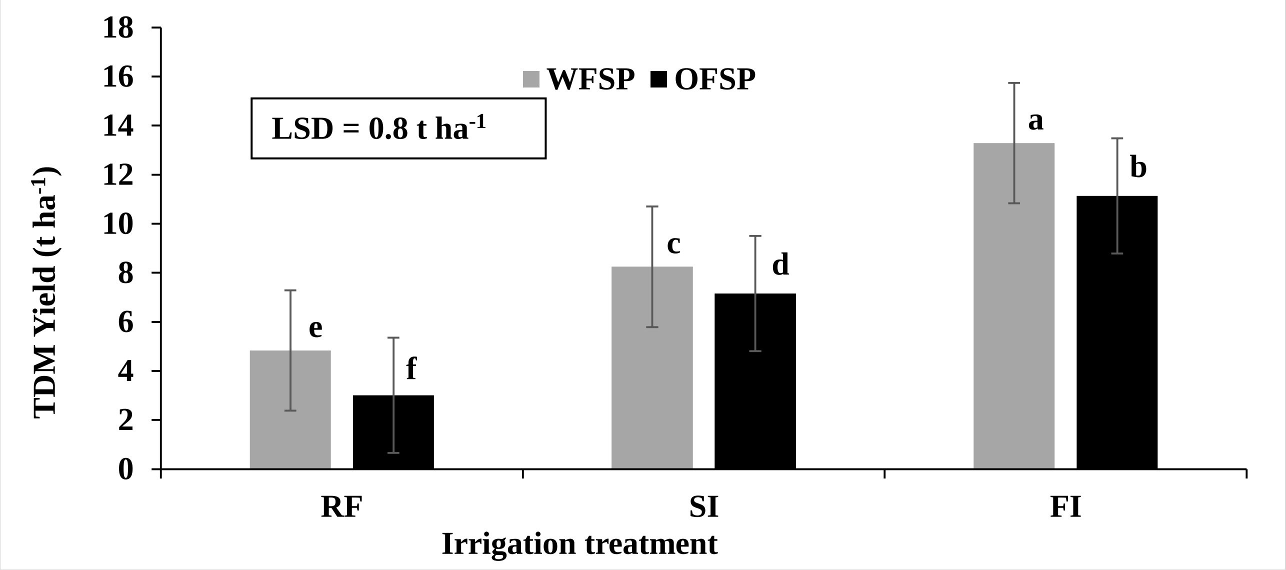


Figure 4.5: Effects of different irrigation treatments on total dry matter yield (TDM) of orange (OFSP) and white fleshed-sweet potato (WFSP) (RF = rainfed, SI = supplementary irrigation, FI = full irrigation, WFSP= white-fleshed sweet potato, OFSP = orange-fleshed sweet potato)

4.3.3.3 Harvest index

It was observed that HI interactions between cultivar and irrigation treatment were highly significant (P = <0.001) (Table 4.5). Similar to the fresh mass storage root yield and total dry matter yield, WFSP outperformed the OFSP for all treatments (Figure 4.6). This was due to higher above ground biomass produced by OFSP than WFSP, and this can be further supported by higher LAI (Figure 4.2) and Fractional interception (Figure 4.3) observed for OFSP than WFSP across all irrigation treatments. According to Zhi (1991) and Hartemink et al. (2000), high vegetative growth causes the reduction in economical root yield, which in turn decreases the HI. Therefore, in this study, the vegetative growth of OFSP under all irrigation treatments was higher, and the economic yield was lower, which resulted in a lower HI than that of WFSP. It was observed that for both cultivars there were no statistical differences between SI and RF treatments, the FI, however, showed significant increase in HI when both cultivars of sweet potato were optimally irrigated.

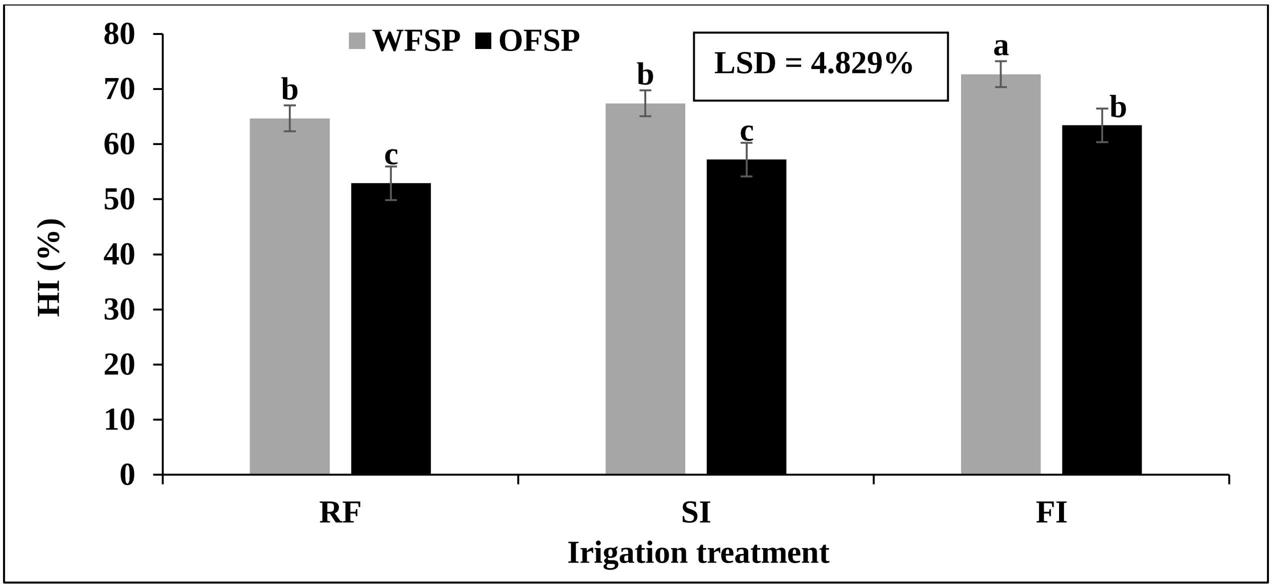


Figure 4.6: Harvest index (HI) of orange and white-fleshed sweet potato as influenced by different irrigation treatments (RF = rainfed, SI = supplementary irrigation, FI = full irrigation, WFSP = white-fleshed sweet potato, OFSP = orange-fleshed sweet potato)

Masango (2014) reported HI values under different water levels that ranged from 52–59%. Yeng et al. (2012) reported HI values that ranged from 41–61%. Bouwkamp and Hassam (1988) reported HI values that ranged from 37–81%. Contrary to the current study, Bhagsari (1990) reported higher HI values under RF conditions with, HI values ranging from 22–77%.

Harvest index is essential in crop production and can be used to assess yield under different irrigation levels, as it represents the efficiency of the conversion of photosynthetic products into economic valuable form (Kawano, 1990; Masango, 2014). All irrigation treatments in this study showed similar HIs (Figure 4.6) which showing the adaptability of sweet potato (especially white) to efficiently convert photosynthetic products into economical yield even under water stressed conditions (Kawano, 1990), therefore this crop is highly suitable to be cultivated in areas with shortage of water, especially in rural areas where farmers depends on rainwater for irrigation.

4.3.4 Water use and water use efficiency

4.3.4.1 Profile soil water extraction

The seasonal change in soil water content in response to rainfall and irrigation is shown by the patterns measured using Chameleon soil moisture sensors (Table 4.5, Table 4.6 and Table 4.7) for the FI, SI and RF treatment, respectively. Figure 4.7 shows irrigation applied and rainfall received during growing season (2015/2016), the irrigation amount applied was 190 mm for FI and 69 mm for SI (Figure 4.7).

Table 4.5: Chameleon patterns measured during growing season (2015/2016) under the full irrigation treatment for orange (OFSP) and white-flesh sweet potato (WFSP).

Depth	2-Nov	4-Nov	6-Nov	9-Nov	11-Nov	13-Nov	16-Nov	18-Nov	20-Nov	23-Nov	25-Nov	27-Nov	30-Nov	2-Dec	4-Dec	9-Dec	16-Dec	18-Dec	21-Dec	23-Dec	28-Dec	4-Jan	6-Jan	18-Jan	20-Jan	22-Jan	25-Jan	29-Jan	1-Feb	3-Feb	5-Feb	10-Feb	12-Feb	15-Feb	17-Feb	19-Feb	22-Feb	29-Feb	2-Mar	4-Mar	7-Mar (OFSP)	7-Mar (WFSP)
0.15	B	B	B	G	B	B	B	B	B	G	B	B	G	G	G	B	G	G	G	G	G	G	B	G	B	G	G	B	G	B	G	B	G	G	B	B	G	B	B	B	G	G
0.30	B	B	B	B	B	B	B	B	B	B	B	B	B	B	G	B	B	G	B	B	G	G	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	G	B	B	G
0.45	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	G	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	
0.60	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	G	B	B	G	G	G	B	B	B	B	B	G	B	B	B	G	B	B	B	B	G	B	B	G	G

Table 4.6: Chameleon patterns measured during growing season (2014/2015) under the supplementary irrigation treatment for orange (OFSP) and white-flesh sweet potato (WFSP).

Depth	2-Nov	4-Nov	6-Nov	9-Nov	11-Nov	13-Nov	16-Nov	18-Nov	20-Nov	23-Nov	25-Nov	27-Nov	30-Nov	2-Dec	4-Dec	9-Dec	16-Dec	18-Dec	21-Dec	23-Dec	28-Dec	4-Jan	6-Jan	18-Jan	20-Jan	22-Jan	25-Jan	27-Jan	29-Jan	1-Feb	3-Feb	5-Feb	10-Feb	12-Feb	15-Feb	17-Feb	19-Feb	22-Feb	29-Feb	2-Mar	4-Mar	7-Mar (OFSP)	7-Mar (WFSP)
0.15	B	B	B	G	B	B	B	B	B	G	B	B	G	G	R	G	G	G	G	R	R	R	G	G	G	R	R B	B	G	G	R	R	B	B	R	R	B	G	B	B	B	B	G
0.30	B	B	B	B	B	B	B	B	B	B	B	B	G	B	G	B	B	G	R	R	R	R	B	B	B	G	G	B	B	G	R	B	B	B	B	R	B	B	B	B	G	R	R
0.45	B	B	B	B	B	B	B	B	B	B	B	B	B	G	G	B	B	G	G	R	R	G	G	B	G	G	B	B	B	B	G	G	B	G	G	G	B	B	B	B	G	G	G
0.60	B	B	B	B	B	B	B	B	B	B	B	B	B	B	G	B	B	G	R	G	R	R	R	B	G	B	R	G	G	G	R	G	G	B	G	R	B	G	G	G	G	B	B

Table 4.7: Chameleon patterns measured during growing season (2015/2016) under the rainfed treatment for orange (OFSP) and white-flesh sweet potato (WFSP).

Depth	**2-Nov**	**4-Nov**	**6-Nov**	**9-Nov**	**11-Nov**	**13-Nov**	**16-Nov**	**18-Nov**	**20-Nov**	**23-Nov**	**25-Nov**	**27-Nov**	**30-Nov**	**2-Dec**	**4-Dec**	**9-Dec**	**16-Dec**	**18-Dec**	**21-Dec**	**23-Dec**	**28-Dec**	**4-Jan**	**6-Jan**	**18-Jan**	**20-Jan**	**22-Jan**	**25-Jan**	**27-Jan**	**29-Jan**	**1-Feb**	**3-Feb**	**5-Feb**	**10-Feb**	**12-Feb**	**15-Feb**	**17-Feb**	**19-Feb**	**22-Feb**	**Feb29**	**2-Mar**	**4-Mar**	**7-Mar (OFSP)**	**7-Mar (WFSP)**
0.15	**B**	B	**B**	G	**B**	B	**B**	B	**B**	G	**B**	B	**G**	G	**R**	**G**	G	**G**	R	R	**R**	**R**	R	**B**	G	**R**	R	**B**		**R**	R	**R**	G	G	R	R	B	R	B	B	R	R	R
0.30	**B**	B	**B**	B	**B**	B	**B**	B	**B**	B	**B**	B	**B**	B	**B**	**B**	B	**G**	G	R	**G**	**R**	R	**B**	B	**R**	B	**B**		**G**	R	**R**	B	G	R	R	B	G	B	B	B	G	R
0.45	**B**	B	**B**	B	**B**	B	**B**	B	**B**	B	**B**	B	**B**	B	**G**	**B**	B	**B**	G	R	**R**	**G**	R	**B**	G	**R**	G	**B**		**B**	G	**R**	B	B	B	R	B	G	B	B	B	G	
0.60	**B**	B	**B**	B	**B**	B	**B**	B	**B**	B	**B**	B	**B**	B	**G**	**B**	B	**G**	R	G	**R**	**R**	R	**B**	B	**G**	G	**B**	R	G	**B**	**R**	B	B	G	R	G	B	R	B	B	G	

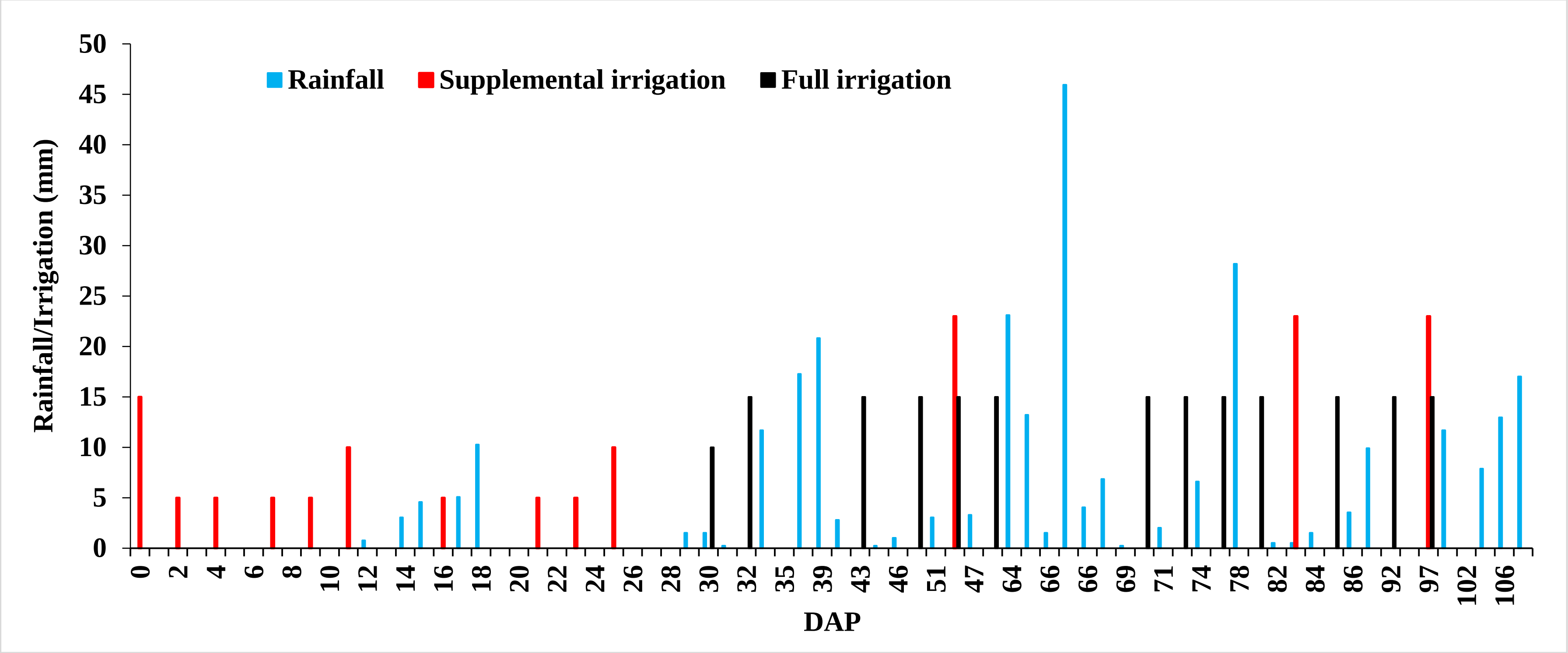


Figure 4.7: Irrigation (full and supplementary treatments) applied and rainfall received during growing season (2015/2016), (Trt = treatment, I = irrigation, R = rainfall and DAP = days after planting), from 0 to 25 DAP the same amount of irrigation applied to all treatments (also in red colour)

4.3.4.2 Crop evapotranspiration

Under well-watered conditions, OFSP ET estimated using the soil water balance equation in this chapter was (437 mm), comparable to the water use of 361 and 344 mm during 2014/2015 and 2015/2016 seasons, respectively, measured using eddy covariance (EC) system in Chapter 3. The ET values estimated using the EC system were therefore lower than the water use values estimated in this chapter using soil water balance method. The ET measured with EC system was low due to the fact that EC system usually underestimates turbulent flux (sensible heat + latent heat flux) due to exclusion of data during processing as well as for periods when there were no steady state conditions. Therefore ET estimated with soil water balance equation was high due to the fact that soil water balance equation can overestimate ET especially when the soil water balance is not calculated fully for instance, when assumptions are made for runoff and drainage. The differences of water use values were also due to methodology used to measure rate of ET as (direct and indirect) methods were used and were also due to weather variables during growing seasons. Based on Table 4.5 and how the Chameleon read blue even at 0.60 m depth for much of the season, another reason for the much higher estimate for crop ET in this chapter could be/is due to the under-estimation of deep drainage in FI treatment. This is why using EC method is valuable.

Table 4.8 shows components of the water balance that were estimated using data collected throughout the growing season for the FI, SI and RF treatments for both the sweet potato cultivars. For all irrigation treatments, both cultivars were estimated to use similar amounts of water, with the OFSP cultivar using slightly higher amounts than WFSP cultivar, although difference was significant (Table 4.8). Evapotranspiration under the same treatment of both WFSP and OFSP was averaged, the FI treatment (432 mm) used significantly more water than the SI and RF treatments by about 34% (285 mm) and 53% (202 mm), respectively. In this study it was estimated that OFSP used more water than WFSP under both treatments.

Table 4.8: Water balance components for full (FI), supplementary (SI) irrigation and rainfed treatments for both white (WFSP) and orange-flesh sweet potato (OFSP) over growing season (2015/2016) (mm)

Treatments		**Irrigation + rainfall***	**ET**	**ΔSWC****
OFSP	**FI**	451	437^a	14
	SI	331	293^c	38
	RF	261	208^e	53
WFSP	**FI**	451	427^b	24
	SI	331	278^d	53
	RF	261	196^f	65

*Seasonal rainfall of 261 mm, ** change in the soil water content between initial and final. ET LSD = 1.993.

4.3.4.3 Water use efficiency

Water use efficiency for both cultivars under FI and SI treatment was not significantly different (P = 0.003 for OFSP) and (P = 0.002 for WFSP), however, results showed that the RF treatment WUE for both cultivars was significantly lower to FI and SI treatments. The SI treatment for the WFSP cultivar recorded the highest WUE 97 kg ha^{-1} mm^{-1}, which shows that under the SI treatment water was most productively used. The FI treatment of the OFSP cultivar recorded the highest WUE 81 kg ha^{-1} mm^{-1}, which shows that under SI for OFSP, yield was highly affected. The lowest WUE was recorded under RF treatment for both cultivars with WFSP recorded 46 kg ha^{-1} mm^{-1}, while OFSP recorded 30 kg ha^{-1} mm^{-1}. For all irrigation treatments the WFSP cultivar had a higher WUE than OFSP cultivar, as higher energy was used for greater total dry matter production, unlike in OFSP where higher energy was used for the more energy-intensive.

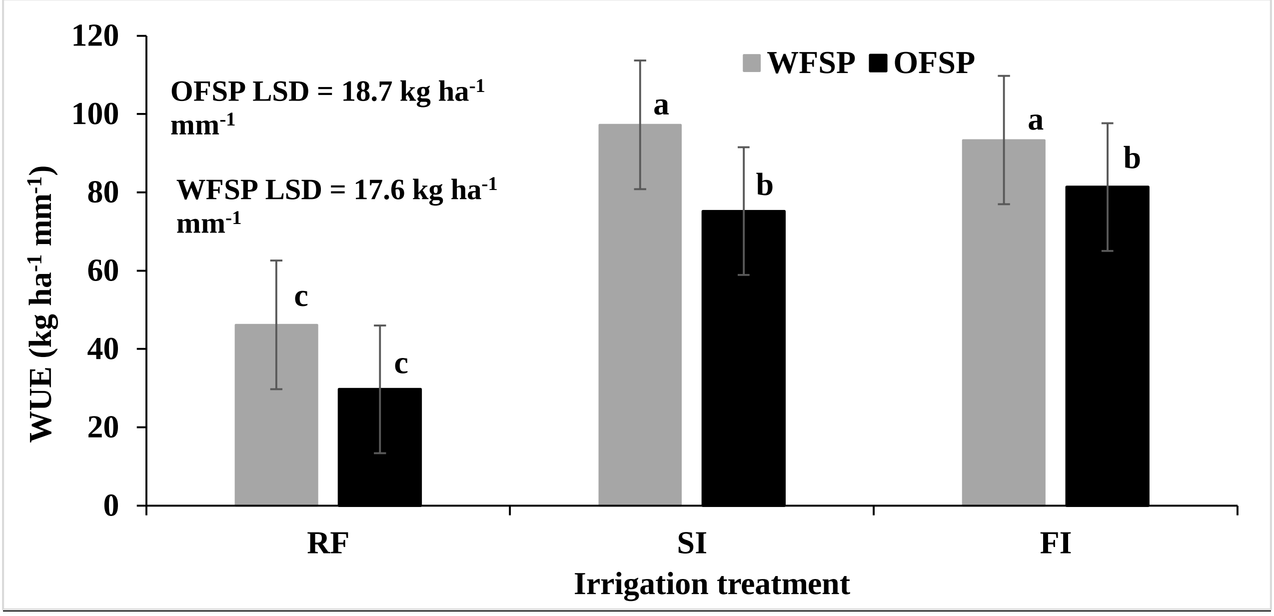


Figure 4.8: Water use efficiency (WUE) of orange (OFSP) and white-fleshed sweet potato (WFSP) grown under full, supplementary irrigation and rainfed treatments (RF = rainfed, SI = supplementary irrigation, FI = full irrigation)

The reported values of sweet potato WUE in this study were in range with what has been reported in literature under SA conditions, under different irrigation levels from 8.12–131.8 kg ha^{-1} mm^{-1} (Bok 1998; Laurie et al. 2009; Laurie et al. 2012; Masango, 2014). Therefore the findings of this study were comparable to what other researchers have reported in literature.

Table 4.9: Yield reduction and ET reduction under supplemental irrigation and rainfed treatment (%)

Treatment	% Yield reduction		% ET reduction	
	OFSP	**WFSP**	**WFSP**	**OFSP**
SP	37	30	32	35
RF	82	76	52	54

4.4 Conclusions

The findings of this study show that the interaction between both cultivars and different irrigation treatments was highly significant. Leaf area index and fractional interception of PAR for both cultivars increased with water application, therefore, it was observed that LAI and fractional interception of PAR was highest under FI treatment and lowest under RF treatment. The results also showed that yield of sweet potato increases with water application as it was higher under FI treatment and lowest under RF treatment. The HI was also higher under FI than both SI and RF treatments. For all treatments WFSP cultivar recorded higher storage root yield than OFSP cultivar.

Different results were obtained when looking at the WP of WFSP it was observed that WP was higher under SI and FI treatments compared to RF. Similar results was obtained for OFSP and the maximum WP was recorded under SI and FI treatments compared to the RF treatment which shows that yield under RF treatment was highly affected due to no irrigation applications. Water productivity of WFSP under FI, SI and RF treatments were higher than WP of OFSP under the same treatments, which shows that WFSP cultivar used water in a productive way, as higher yield produced per mm of water. Therefore sweet potato WP can be improved under supplemental irrigation treatment, however yield will be reduced but not highly affected. Drainage could've been estimated for FI treatment due to using the Chameleon to schedule irrigation.

CHAPTER FIVE

Influence of irrigation strategies on the nutritional water productivity of sweet potato (*Ipomoea batatas*)

5.1 Introduction

Globally, iron (Fe), zinc (Zn) and vitamin A are among the most important micronutrients and vitamin, respectively (Gester, 1993; Szpylka and DevRies, 2005; Faber, 2006; Burri, 2011). Shortage of these nutrients in daily consumption pose a health risk to children and pregnant women, mostly in rural and peri-urban areas (Tumwegamire et al. 2004; Bowell, 2007; Laurie et al. 2012). As food quality has become as important as quantity, addressing deficiencies will help in reducing "hidden hunger", which is defined as a chronic lack of vitamins and micronutrients, where effects may not immediately felt but may be felt in future (Bumgarner, 2012; Luoh, 2014; Brouwer, 2014). Therefore, it is important to produce crops such as orange-flesh sweet potato (OFSP) (*Ipomoea batatas*) that are rich in β-carotene, Fe and Zn in order to improve human diets and reduce risk malnutrition (Bowell, 2007; Wenold, 2012).

Currently, the most commonly produced sweet potato cultivars in South Africa (SA) are white-fleshed (WFSP) that contain very little amounts of β-carotene (converted to vitamin A by the body), but high amounts of Fe and Zn (Tumwegamire et al. 2004). There has recently been an initiative by SA's Agricultural Research Council (ARC) in releasing locally adapted sweet potato cultivars with high β-carotene/vitamin A content.

Water scarcity is becoming more and more of a threat to food and nutritional security (Luoh et al. 2014), therefore it is important to produce higher nutrients per unit of water used in order to alleviate malnutrition and to conserve natural water resources. In Chapter 4, yield produced per mm of water used was reported. In this chapter, nutritional yield (NY) and nutritional water productivity (NWP) (Renault and Wallender, 2000), a relatively new method of quantifying the nutrient produced per mm of water used, are discussed. The influence of different irrigation strategies on nutritional content (NC), NY and NWP for the major South African grown sweet potato cultivars, orange-fleshed (OFSP) 'Bophelo' and WFSP 'Blesbok' was investigated.

5.2 Materials and methods

5.2.1 Site description, treatments and agronomic practices

The site description, experimental treatments and other cultural practices followed during the study are described in detailed in Chapter 4.

5.2.2 Data collection

5.2.2.1 Nutritional content

For nutritional content determination, sweet potato storage roots from each plot were oven dried at 50°C. Zinc and Fe (mg 100 g^{-1}) were analyzed at the Agricultural Research Council Soil Climate and Water (ARC–SCW) laboratory and β- carotene (mg 100 g^{-1}) was analysed at the, Agricultural Research Council Vegetables and Ornamental Plants (ARC–VOP) laboratory.

Methods followed for β-carotene, Fe and Zn analysis

Extraction of β-carotene was done using tetrahydrofuran methanol (1:1 vol/vol) according to the method explained by Biehler et al. (2010). Extracts were analyzed using an HPLC-DAD (Shimadzu, Kyoto, Japan) at 450 nm wavelength. A five-point standard curve that bracketed the concentration of the samples was constructed for quantitative analysis of β-carotene. Iron and Zn contents were determined following a method recommended by the Association of Official Analytical Chemists (AOAC, 1990).

5.2.2.2 Nutritional yield

For the current study, the NY which is the function of raw edible yield and nutrients content of crops was calculated using the Equation 5.1 (Bumgarner et al. 2012):

$$\text{NY (mg ha}^{-1}\text{)} = \text{NC} \times \text{Ya} \qquad (5.1)$$

where NC is nutritional content (dry matter) (mg 100 g^{-1})

Ya is actual harvested yield (dry matter) (g ha^{-1}).

5.2.2.3 Nutritional water productivity

Nutritional water productivity was calculated using Equation 5.2 (Renault and Wallender, 2000):

$$\text{NWP (mg m}^{3}\text{)} = \text{WP} \times \text{NC} \qquad (5.2)$$

where WP yield produced per mm of water used (dry matter) (kg m^{-3})

NC is the nutritional content (mg) kg^{-1} of storage roots

5.2.2.4 Data analysis

Nutritional content, NY and NWP of the OFSP and WFSP cultivars as affected by different irrigation levels were analysed statistically using GenStat 15th Edition statistical package. Data was subjected to Analysis of Variance (ANOVA) at a threshold *P* value of 0.05. When the effects were significantly different, the least significant difference (LSD) test ($\alpha = 0.05$) separated the means.

5.3 Results and discussion

5.3.1 Nutritional content

5.3.1.1 Beta-carotene content

For the β-carotene content, the interactions between cultivar and irrigation treatment were highly significant ($P = <0.001$) (Figure 5.1). For OFSP, β-carotene values were significantly higher in the rainfed (RF) treatment than the supplementary irrigation (SI) and full irrigation (FI) treatments (Figure 5.1). For WFSP, however, β-carotene content was not significantly different among different irrigation treatments. The results of this study showed that water stress increased β-carotene content values for both sweet potato cultivars (Figure 5.1). However, for all irrigation treatments, OFSP recorded higher β-carotene content (6–14 mg 100 g^{-1}) than WFSP (< 2 mg 100 g^{-1}). Similarly, Laurie et al. (2012) reported higher β-carotene values for OFSP (4.26–20.53 mg 100 g^{-1}) than WFSP (0.01–0.21 mg 100 g^{-1}). Higher energy was therefore used in OFSP for the production of β-carotene, while in WFSP this energy most likely went towards producing greater amount of simple sugars/carbohydrate as overall yield was higher for WFSP.

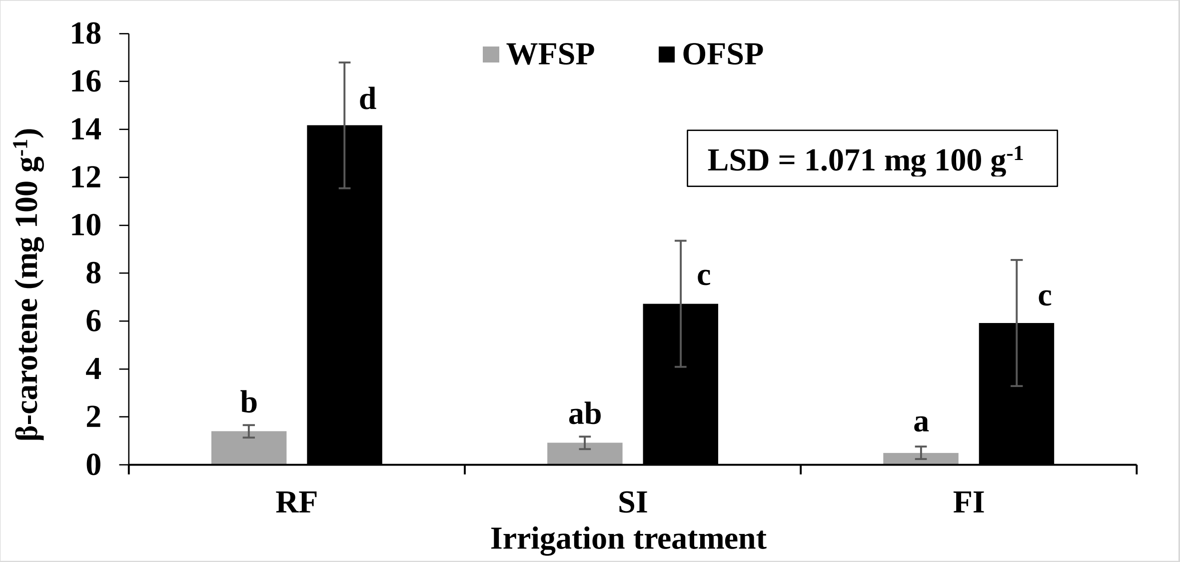


Figure 5.1: Effects of different irrigation treatments on β-carotene content of orange (OFSP) and white-fleshed sweet potato (WFSP) (RF = rainfed, SI = supplementary irrigation, FI = full irrigation)

Therefore, this shows that β-carotene content in OFSP can meaningfully contribute to human nutrition, especially in rural areas where sweet potato is mainly cultivated under rainfed conditions. The amounts of β-carotene content in OFSP recorded in this study are appreciable enough relative to recommended daily allowance (Tumwegamire et al. 2004; Tumwegamire et al. 2011, Laurie et al. 2012). Masango (2014) reported the values of β-carotene content in OFSP under four irrigation treatment ranged from 10–12 mg 100 g^{-1}, the highest being observed for the dry-land treatment. In agreement with the current study, the maximum values recorded by Laurie et al. (2012) were 0.177 and 0.212 mg 100 g^{-1} for WFSP and 14.9 and 20.5 mg 100 g^{-1} of OFSP for the well-watered and water stressed treatments, respectively.

5.3.1.2 Iron content

Similar to β-carotene, Fe content of OFSP was significantly ($P = <0.001$) higher than for WFSP (Figure 5.2). For both cultivars Fe content under the RF treatment was significantly higher than under the SI and FI treatments, but there were no statistically significant differences in terms of Fe content recorded under FI and SI treatments (Figure 5.2). The results of this study showed that water stress improved Fe content in both sweet potato cultivars. Therefore, Fe content in both WFSP and OFSP can greatly contribute to human nutrition, especially in areas with limited water resources. Iron content in both cultivars was not that high; therefore, breeding efforts, have to double Fe contents in storage roots so that they can greatly contribute to recommended daily allowance (Tumwegamire et al. 2011; Laurie et al. 2012). The Fe content ranged from 0.8–1.5 mg 100 g^{-1} for OFSP and 0.7–1.2 mg 100 g^{-1} for WFSP. High variation in Fe content in sweet potato cultivars have been reported, ranging from 0.16–0.94 mg 100 g^{-1} (Leighton, 2007; STA 2005; USDA 2009; Wolmarans et al. 2010; Woolfe, 1992; Laurie et al. 2012). Laurie et al. (2012) reported increased Fe content in WFSP and OFSP storage roots ranging from 0.36–0.84 mg 100 g^{-1} and 0.37–0.92 mg 100 g^{-1}, respectively, under well-watered conditions. Under water stress conditions, the Fe content in WFSP and OFSP ranged from 0.60 –1.1 mg 100 g^{-1}, and 0.62–1.18 mg 100 g^{-1}, respectively.

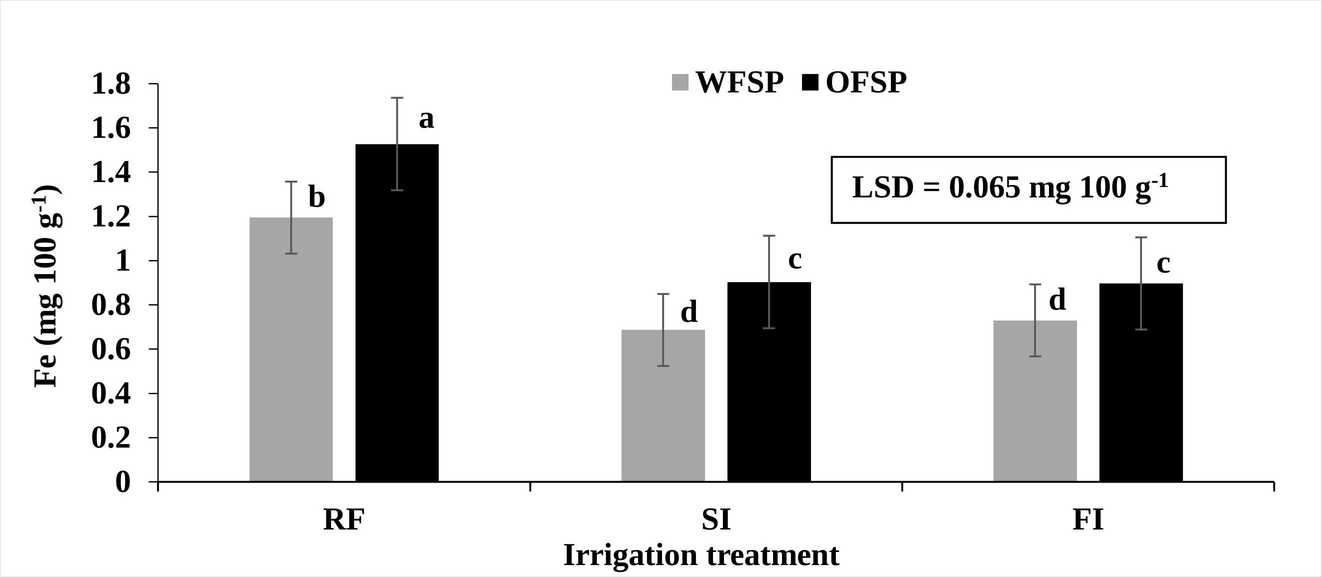


Figure 5.2: Effects of different irrigation treatments on iron (Fe) content of orange (OFSP) and white-fleshed sweet potato (WFSP) (RF = rainfed, SI = supplementary irrigation, FI = full irrigation)

5.3.1.3 Zinc content

For Zn content, the interactions between cultivar and irrigation was highly significance (P = <0.001) (Figure 5.3). Similar to β-carotene and Fe, Zn content for the RF treatment was significantly higher than for the SI and FI treatments. But the results also indicated that there was no statistically significant differences in terms of Zn content mean values under the FI and SI treatments for both cultivars (Figure 5.3). Under SI and RF, conditions the increase in Zn content were by 11 and 124% for WFSP, and 9 and 90% for OFSP when compared to the FI treatment. The results of this study showed that water stress improved Zn content in both cultivars, the Zn content in both WFSP and OFSP can improve human nutrition. Laurie et al. (2012) reported Zn content values in WFSP and OFSP varieties ranging from 0.37–0.51 mg 100 g^{-1} and 0.32–0.59 mg 100 g^{-1}, respectively, under standard irrigation practices. While under water-stress conditions, values of Zn content in WFSP and OFSP varieties ranged from 0.50–0.73 mg 100 g^{-1}, and 0.47–0.77 mg 100 g^{-1}, respectively. Values of Zn content in sweet potato storage roots grown under different soil water levels reported in the literature range from 0.27–1.89 mg 100 g^{-1} (Woolfe, 1992; STA 2005; Leighton, 2007; USDA 2009; Wolmarans et al. 2010).

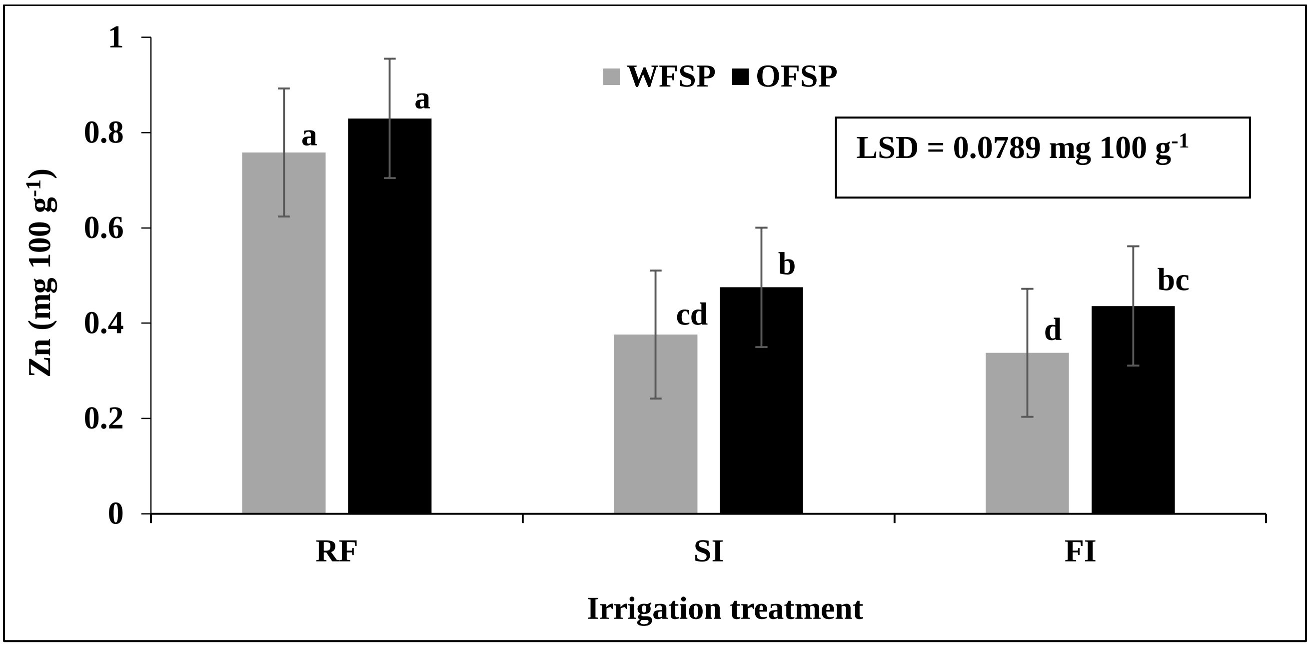


Figure 5.3: Effects of different irrigation treatments on zinc (Zn) content of orange (OFSP) and white-fleshed sweet potato (WFSP) (RF = rainfed, SI = supplementary irrigation, FI = full irrigation)

The NC (β-carotene, Fe, Zn) reported in this study could have been more than what was obtained, if it was not for the oven drying method that was used to dry the sweet potato samples. The oven drying method damages the colour quality and leads to loss of nutrients due to high temperatures (Stawczyk et al. 2004; Ali et al. 2016). Comparing to other drying method such as freeze drying, which is considered one of the best drying method because, it preserves natural colour, original flavor and maximum nutrients (Marques et al, 2007; Kumar and Sagar, 2014).

5.3.2 Nutritional yield

5.3.2.1 Beta-carotene yield

For β-carotene yield, the interactions between cultivar and irrigation was significant (P = <0.001). For all irrigation treatments, OFSP recorded a higher β-carotene yield than WFSP. The results indicate that, even if the total yield obtained from WFSP is higher than OFSP (Chapter 4), the total nutritional β-carotene yield, is still higher in OFSP. There were statistically significant differences in β-carotene yield among irrigation treatments in OFSP, this however, was not true for WFSP (Table 5.1). The maximum β-carotene yield was observed under FI for OFSP and under SI for WFSP, and the lowest values were observed under RF treatment. Different irrigation treatments affected β-carotene yield of OFSP and β-carotene yield decreased with water stress and increased with water application. Similar results were reported by Nyathi et al. (2016), where β-carotene yield of OFSP decreased as the water application amount decreases.

Table 5.1: Nutritional yield of [β-carotene, iron (Fe) and zinc (Zn)] for orange (OFSP) and white-flesh sweet potato (WFSP) storage root (dry matter) (mg ha^{-1})

		Nutritional yield (mg ha^{-1})		
Treatments		**β-carotene**	**Fe**	**Zn**
OFSP	**FI**	419 463.0^{a}	63 473.0^{a}	30 755.0^{a}
	SI	275 130.0^{b}	36 982.0^{b}	19 570.0^{b}
	RF	225 576.0^{b}	24 289.0^{c}	13 208.0^{c}
WFSP	**FI**	48 710.0^{c}	70 480.0^{a}	32 610.0^{a}
	SI	51 750.0^{c}	38 695.0^{b}	21 207.0^{b}
	RF	43 595.0^{c}	37 350.0^{b}	23 694.0^{b}
LSD		**70438.7**	**7462.6**	**5035.1**

Treatments FIO = full irrigation OFSP, SIO = supplemental irrigation OFSP, RFO = rainfed OFSP, FIW = full irrigation WFSP, SIW = supplemental irrigation WFSP, and RFW = rainfed WFSP

5.3.2.2 Iron and zinc yield

Both Fe and Zn yields showed similar trends, and for both, the interactions between cultivar and irrigation was highly significant (P = <0.001) (Table 5.1). For both cultivars, water stress reduced Fe and Zn yields significantly, with the highest values being recorded under FI and the lowest under RF condition (Table 5.1). For OFSP, Nyathi et al. (2016) also reported significant Fe and Zn NY reductions as a result of water stress. In terms of Zn yield, OFSP was more affected by water stress than WFSP. For OFSP, the reduction in Zn yields was by 132%, when full irrigation was compared to RF, which is higher that the reduction observed for WFSP which was 37%.

5.3.3 Nutritional water productivity

5.3.3.1 Beta-carotene water productivity

The interaction of β-carotene WP between irrigation and cultivar was not significant. For all irrigation treatments, significantly higher β-carotene WP was observed for OFSP than WFSP. Water availability did not significantly affect the amount of β-carotene produced per m^3 of water, for both sweet potato cultivars, although best crop performance was obtained under RF treatment. The RF treatment yielded 13 and 15% for OFSP, and 94 and 19% for WFSP, higher than the FI and SI treatments, respectively. This results indicated that under RF treatment, water was used productively as high β-carotene content in OFSP was produced with little amount of water used.

Table 5.2: Nutritional water productivity (mg m^{-3}) values of white (WFSP) and orange-fleshed sweet potato (OFSP)

Treatments		**β-carotene**	**Fe**	**Zn**
OFSP	**FI**[*]	95.9^a	14.5^{bc}	7.0^b
	SI	93.9^a	12.6^{cd}	6.7^b
	RI	108.5^a	11.7^d	6.4^b
WFSP	**FI**[**]	11.4^b	16.5^b	7.6^b
	SI	18.6^b	13.9^{cd}	7.6^b
	RI	22.2^b	19.0^a	12^a
LSD		**19.60**	**2.359**	**1.716**

[*] FIO = full irrigation OFSP, SIO = supplemental irrigation OFSP, RFO = rainfed OFSP,

[**] FIW = full irrigation WFSP, SIW = supplemental irrigation WFSP, RFW = rainfed WFSP

The highest β-carotene WP for OFSP recorded was under RF treatments. Nyathi et al. (2016), reported β-carotene WP under FI treatment ranging from 4906–5417 mg m^{-3} and from 6129–6710 mg m^{-3} under SI treatment. Masango (2014) reported values of β-carotene WP for OFSP ranged from 656–1177 mg m^{-3}, where the highest value was recorded under RF treatment, and the lowest in fully irrigated treatment. Similar to what observed in this study. The differences in recorded values could be due to the fact that the experiments were conducted during different season and a different cultivars was used.

5.3.3.2 Iron water productivity

The Fe WP interaction between irrigation and cultivar was significant (P = <0.001) (Table 5.2.). There was statistically significant difference for Fe WP between cultivars. Water stress had effected both WFSP and OFSP Fe levels when grown under RF treatment. For OFSP the highest Fe WP observed under FI treatment, and for WFSP highest Fe WP observed under RF treatment. In literature, Nyathi et al. (2016) reported OFSP Fe WP ranged between 84–1366 mg m^{-3} under FI treatment and 100–1964 mg m^{3}under SI. In another study, Wenold et al. (2012) reported 26 mg m^{-3} Fe WP of OFSP under well-watered conditions, this could be due to the differences in the soil Fe content as most soils are not analysed for Fe.

5.3.3.3 Zinc water productivity

For Zn WP interaction between irrigation and cultivar was significant (P = <0.001) for WFSP, however for OFSP was not significant (Table 5.2). The highest Zn WP recorded was under RF treatment for WFSP, this shows that under RF treatment water was used productively, as high Zn content produced with little water used. Wenold et al. (2012) reported Zn WP at 15.08 mg m^{-3}. Nyathi et al. (2016) reported OFSP Zn WP values under FI and SI treatments that ranged from 35.6–79.52 mg g^{-3} and 45.9–70.71 mg m^{-3}, respectively. The differences in recorded values could be due to the fact that the experiments were conducted during different season and a different cultivars was used.

5.4 Conclusions

The results showed that deficit irrigation significantly affected NY and NC of both sweet potato cultivars, but NWP was not significantly affected by deficit irrigation. In this study OFSP recorded higher NC (β-carotene, Fe and Zn) than WFSP under both treatment. This is due to the fact that higher energy was therefore used in OFSP for the production of β-carotene and other nutrients while in WFSP this energy most likely went towards producing greater amount of simple sugars/carbohydrate as overall yield was higher for WFSP. It was also observed that the NC and NWP of sweet potato increases with water stress and decreases with water application (dry matter basis), as high NC recorded under RF treatment for both cultivars. However, different results obtained wen looking at NY for β-carotene, Fe and Zn as it increases with water application, and decreases with water stress in both cultivars. The results of this study showed that the NC (β-carotene, Fe and Zn) in OFSP can greatly contribute to human nutrition and alleviating malnutrition, especially in dry regions, where water is the main factor that is reducing crop production. The amounts of NC (β-carotene, Fe and Zn) recorded for OFSP in this study, are appreciable enough to can contribute to recommended daily allowance.

CHAPTER SIX

6.1 General conclusions, summary and recommendations

Water scarcity, food and nutrition security are key issues that South Africa (SA) is currently facing. There is thus, a need to quantify water use and investigate the influence of different irrigation strategies to improve water productivity in order to produce nutritious food in a sustainable way. Ultimately, this can improve food and nutrition security. In this study the evapotranspiration (ET) of sweet potato (*Ipomoea batatas*) was successfully quantified using an eddy covariance (EC) system. Results show that sweet potato ET increases from the initial to middle growth stage as the result of canopy development, and then start to decrease during the late growth stage when the crop reaches maturity. Crop coefficients (K_c) for an orange-flesh sweet potato (OFSP) cultivar have been derived for the first time in SA, and the developed K_c values for summer season are 0.46 during the initial stage, 0.92 during middle stage, and 0.57 during late growing stage. Similar to ET, the K_c increases from the initial to middle stage and decreases during the late growth stage. The developed K_c values can be used to aid in the extrapolation of measured results to different climatic conditions and crop management practices in SA using crop modelling. This will hopefully contribute to improved sweet potato irrigation management under different climatic conditions.

The performance of white-flesh sweet potato (WFSP) and OFSP cultivars in terms of yield, nutrient content (NC) [β-carotene, iron (Fe) and zinc (Zn)], nutritional yield (NY), water productivity (WP) and nutritional water productivity (NWP) under different irrigation treatments [full irrigation (FI), supplemental irrigation (SI) and rainfed (RF)] was studied in order to better understand how different irrigation treatments can affect these variables. Findings show that the interaction between both cultivars and different irrigation treatments was highly significant. For instance, the yield of sweet potato increased with water application as it was higher under FI treatment and lowest under RF treatment. With regards to equivalent irrigation treatments, the WFSP recorded higher yields than the OFSP cultivar. The results also showed that the WP of WFSP cultivar was higher under the SI and FI treatments compared to RF. Similar results were obtained for the OFSP cultivar, where maximum WP was recorded under the SI and FI treatments compared to the RF treatment. This shows that the yield under RF treatment was highly reduced as results of no irrigation applications.

For equivalent irrigation treatments, WP of WFSP was higher than OFSP. However, different results were obtained for the NC of both sweet potato cultivars, which generally increase with water stress and decrease with irrigation application. The NC under RF treatments for both cultivars was generally higher than under FI and SI treatments. Orange fleshed sweet potato outperformed WFSP in terms of β-carotene, Fe and Zn content under all irrigation treatments. Beta-carotene content in OFSP was higher than both Zn and Fe content, whereas in WFSP β-carotene content was only slightly higher than both Zn and Fe.

The nutritional (β-carotene, Zn and Fe) yield increases with water application, and decreases with water stress in both cultivars. For equivalent irrigation treatments, OFSP had higher β-carotene yield than WFSP, but WFSP yielded slightly higher Fe and Zn than OFSP, albeit non-significant. These results indicate that both sweet potato cultivars used water in a productive way, as higher yield was produced per mm of water for WFSP and higher NC was produced per mm of water for OFSP.

The β-carotene WP for the OFSP cultivar was highest under the RF treatment and was lowest under the SI treatment. However, different results were obtained for Fe and Zn WP, where the highest Fe and Zn WP was recorded under FI treatment and lowest under the RF treatment. For

WFSP, the highest β-carotene, Fe and Zn WP was observed under RF treatment. Generally, therefore, the nutritional WP of sweet potato increases with water stress.

In both sweet potato cultivars, the highest ET was estimated under the FI treatment, and the lowest ET estimated under the RF treatment. For equivalent irrigation treatments, OFSP had higher ET values than WFSP. It was observed that deficit irrigation significantly affects yield, NC, NY and WP of both sweet potato cultivars, but NWP was not significantly affected. In this study it was observed that deficit irrigation improved NC and NWP for sweet potato.

The WFSP cultivar is the most promising to address food security under optimum irrigation conditions. On the other hand OFSP, may be the best to address nutrition security, especially when cultivated under RF conditions.

The more-accurate quantification of ET, WP and NWP of sweet potato can potentially contribute to:

- Improved crop yield and quality to address food and nutrition security, which will ultimately contribute to poverty alleviation;
- Water and money savings under agricultural production;
- Improved irrigation water management in order to minimize the effects of climate change;
- Environmental protection through improved water management strategies.

Since preliminary FAO-type values have now been established, it is recommended they be used to estimate sweet potato ET in other regions of SA where sweet potato is produced. Moreover, OFSP is recommended to be cultivated under RF conditions for high NC, while WFSP can be cultivated under optimum irrigation conditions for higher yield. However, it is important to note that these cultivars can also be cultivated under SI conditions when irrigation water is limited, although, WFSP cultivar yields might be reduced, whereas for OFSP, yield will also be reduced, with lower NC but not highly affected. It is recommended that future work of this nature be done on other sweet potato cultivars and other crops, including for an expanded range of nutrients. Trials should also be planted in different agro-climate regions of SA to validate and improve the K_c values obtained in this study.

REFERENCES

ABYANEH HZ, VERKESHI MB, GHASEWI A, MAROFI S, CHAYJAN RA. 2011. Determination of water requirement, single and dual crop coefficient of garlic (Allium Sativum) in the cold semi-arid climate. *Australia Journal of Crop Science*, 5 (8): 1050-1054.

ALI MA, YUSOF YA, CHIN NL, IBRAHIM MN. 2016. Effects of different drying treatments on colour quality and ascorbic acid concentration of guava fruit, *International Food research Journa,l* 23, 155 - 161

ALLEN RG, SMITH M, PERRIER A, PEREIRA LS. 1994. An update for the definition of reference evapotranspiration, *Journal of irrigation and drainage*. 43 (2), 1-34.

ALLEN RG, PEREIRA LS, RAES D, SMITH M. 1998. Crop evapotranspiration guidelines for computing crop water requirements FAO irrigation and drainage paper 56. FAO Food and Agriculture Organization of the United Nations, *Rome, Italy*.

ALLEN RG. 2000. Using the FAO-56 dual crop coefficient method over an irrigated region as part of an evapotranspiration inter comparison study, *Journal Hydrology*. 229: 27-41.

ALLEN RG, WRIGHT JL, PRUITT WO, PEREIRA LS, JENSEN ME. 2007. Water requirement in design and operation of farm irrigation system, 208 - 288. Hoffman Gl, Evans RG, Jensen ME, Martin DL, Elliot RL (eds), MI: ASABE.

ALLEN RG, PEREIRA LS, HOWELL TA, JENSEN ME .2011. Evapotranspiration information reporting: In. Factors governing measurement accuracy, *Agricultural Water Management* 98 (6): 899-920.

ALLEMANN J. 2004. Fertilisation, irrigation and weed control: In a guide to sweet potato production in South Africa, CDP printers, (G.J. NIEDERWIESER, ed), ARC-VOP Roodeplaat vegetable and ornamental plant institute, Pretoria, South Africa.

ALLEMANN J, LAURIE SM, THIART S, VOSTER HJ. 2004. Sustainable production of root and tuber crops in Southern Africa. *South Africa Journal of Botany*, 70 (1): 60-67.

AGHADIS F. 2010. Crop water requirement assessment and annual planning of water allocation. International institute for Geo-information science and earth observation ensched, *The Netherlands* (Thesis).

AL-GHOBARI HM, MOHAMMAD FS, EL MARAZKY MSA. 2013. Effects of intelligent irrigation on water use efficiency of wheat crop in arid region, *The Journal of Animal and Plant Science*, 23 (69): 1691-1699.

ALI MH, TALUKDER MSU. 2008. Increasing water productivity in crop production – A synthesis, *Agricultural Water Management*. 95: 1201-1213.

ANNANDALE JG, BENADEʹ N, JOVANOVIC NZ, STEYN JM, DUSAUTOY N. 1999. Facilitating irrigation scheduling by means of the soil water balance model, *Water Research Commission Report No* 753/1/99.

ANNANDALE JG, JOVANOVIC NZ, CLAASSENS AS, BENADÉ N, LORENTZ SA, JOHNSTON MA, TANNER PD, AKEN ME, HODGSON FDI. 2002. Modelling and monitoring crop production, soil properties and drainage water under centre pivot irrigation with gypsiferous mine water. *Water Research Commission Report No*. K5/858.

ANNANDALE JG, BELETSE YG, DE JAGER PC, JOVANOVIC NZ, STEYN JM. 2007. Predicting the environmental impact and sustainability of irrigation with coal mine water. WRC Report No 1149/01/07

ANSELMO BA, GANGA ZN, BADOL EO, HEINER YM, NEIIDAT A. 1998. Screaning sweet potato for drought tolerance in the Philippine highlands and genetic diversity among selected genotypes, *Tropical Agriculture* 75: 189-196.

ASCE-EWR. 2005. The ASCE standardized reference evapotranspiration equation, Report 0-7844-0805-X, ASCE Task committee on standardization of reference evapotranspiration, Reston VA, *American Society Civil engineers*.

ASSOCIATION OF OFFICIAL ANALYTICAL CHEMISTS, AOAC. 1990. Official Methods of Analysis of the Association of Official. Analytical Chemists (15th edition), Washington DC, 992-995.

AUBINET M, HEINESCH B, LONGDOZ B. 2002. Estimation of carbon sequestration by a heterogeneity of site and inter-annual variability. *Global Change Biology*, 8: 1053-1071.

BIEHLER E, MAYER F, HOFFMANN L, KRAUSE E and BOHN T. 2010. Comparison of 3 spectrophometric methods for carotenoid determination in frequently consumed fruits and vegetables, *Journal of Food Chemistry*, 5: 55-61.

BALDOCCHI DD, HICKS BB, MEYERS TP. 1988. Measuring biosphere-atmosphere exchange of biologically related gases with micrometeorological methods, *Ecology*, 69 (5): 1331-1340

BALDOCCHI DD, MAYERS T. 1991. Trace gas exchange above the floor of a deciduous forest. Evaporation and CO_2 efflux. *Journal of Geophysical Research*, 96: 727-7285.

BALDOCHHI DD, FALGE E, WILSON KW. 2001. A spectral analysis of biosphere-atmosphere trace gas flux densities and meteorological variables across hour to multi-year time scales, *Agricultural and Forest Meteorology* 107 (1): 1-27.

BARR AG, MORGENSTERN K, BLACK TA, MCCAUGHEY JH. 2006. Surface energy balance closure by the eddy covariance method above three boreal forest stands and implications for the measurements of the CO_2 flux. *Agriculture and Forest Meteorology Journal*, 140: 322-337.

BEKELE S, TILAHUN K. 2007. Regulated deficit irrigation scheduling of onion in a semiarid region of Ethiopia, *Agriculture Water Management*, 89: 148-152.

BELETSE YG. 2004. Modelling the soil water and salt balance of planted pastures irrigated with sodium sulphate rich mine effluent. PhD dissertation, University of Pretoria, Pretoria

BELETSE YG, ANNADALE JG, STEYN JM, HALL I, AKEN ME. 2008. Can crops be irrigated with sodium bicarbonate rich CBM deep aquifer water? Theoretical and field evaluation, *Ecology Engineering Journal*. 33: 26-36.

BELETSE YG, LAURIE R, DU PLOOY CP, VAN DENBERG A, LAURIE SM. 2011. Calibration and validation of AquaCrop model for orange fleshed sweet potato. In: Capacity development for farm management strategies to improve crop water productivity using AquaCrop. Learson learned. Editors. Reza Ardakanian and Teresa Walter. UNW-DPC publication series. Knowledge, 7. Bonn, Germany.

BELETSE YG, LAURIE R, DU PLOOY CP, LAURIE SM, VAN DEN BERG A. 2013. Simulating the yield response of Orange Fleshed Sweet Potato 'Isondlo' to water stress using the FAO AquaCrop Model. Hannweg K, Penter M (eds). Proc. Second all Africa Horticulture Congress. ARC-Roodeplaat, Vegatable and Ornamental Plant Institute, Pretoria. South Africa.

BENNIE ATP, HANSLEY. 2001. Maximizing precipitation utilization in dryland agriculture in South Africa, *Journal of Hydrology*. 241: 124-139.

BESTER C, VAN DEN BERG A, DU PLOOY CP. 1991. 'Blesbok' sweet potato. *Hortscience*, 26 (9): 1229-1230

BHAGSARI AS, DOYLEAA. 1990. Relationship of photosynthesis and harvest index to sweet potato yield. *Journal American Society of Horticultural Science*, 115, 288-293.

BIEHLER E, MAYER F, HOFFMANN L, KRAUSE E and BOHN T (2010) Comparison of 3 spectrophometric methods for carotenoid detrmination in frequently consumed fruits and vegetables, *Journal of Food Chemistry,* 5: 55-61.

BLANKEN PD, BLACK TA, YANG PC, DEN HARTOG G, NEUMANN HH, NESIC Z, NOVAK MD, STAEBLER R, LEE X. 1997. Energy balance and surface conductance of a boreal aspen forest: Partitioning over story and understory components. *Journal of Geophysical Research*, 102: 28915-28927.

BLANKEN PD, BLACK TA, NEUMANN HH, DENHARTOG G, YANG PC, NESIC Z, STAEBLER R, CHEN W, NOVAC MD. 1998. Turbulent flux measurements above and below the over story of a boreal aspen forest. *Boundary layer Meteorology,* 89: 109-140.

BURBA GG, ANDERSON DJ. 2010. A brief practical guide to eddy covariance flux measurements principles and workflow examples for scientific and industrial applications. LI-COR Niosciences, Lincoln, USA.

BOK I. 1998. Response of sweet potato to different soilmoisture regimes. MSc (Agric). University of Pretoria. South Africa.

BOS MG, KSELIK RAL, ALLEN GR, MOLDEN D. 2008. Water requirement for irrigation and the environment. Springer Science and Business Media.

BOURKE RM. 1982. Sweet potato in Papua New Guinea. P. 45-57. In: R.L. Villarreal & Griggs, T.D. (eds), Sweet potato. Proceedings of the first Int. *Symposium Taiwan, China.*

BOURKE RM. 1985. Sweet potato production and research in Papau New Guinea. Papau New Guinea Journal of Agriculture, *Forestry and Fisheries*, 33: 89-108.

BOUWKAMP JC, HASSAM MHM. 1988. Source-sink relationship in sweet potato. *Journal American Society of Horticultural Science*, 11: 627-629.

BOVELL – BENJAMIN AC. 2007. Sweet potato: A review of its past, present and future role in human nutrition, *Advances in Food Nutritional Research*, 52: 1-59

BOWERS JL, BENEDICT RH, MCFERRAN J. 1956. Irrigation of sweet potato, snap beans and cucumbers in Arkansas. Ark. *Agriculture Experiment Station Bul*. 578.

BRADBURY JH, HOLLOWAY WD. 1998. Chemistry of tropical root crops. Significance for nutrition and agriculture in the pacific, ACIAR monograph 6, *Australia Center for International Agricultural Research.*

BUMGARNER NR, SCHEERENS JC, KLEINHENZ MD. 2012. Nutritional yield: a proposed index for fresh food improvement illustrated with leafy vegetable data. *Journal of Plant Food Human Nutrition*, 67 (3): 215-222.

BURRI B J. 2011. Evaluating sweet potato as an intervention food to prevent vitamin A deficiency. *Comprehensive Reviews in Food Science and Food Safety,* 10: 118-130. http://dx.doi.org/10.1111/j.1541-4337.2010.00146.x

CANADELL J, MOONEY H, BALDOCCHI D. 2000. Commentary: Carbon metabolism of the terrestrial biosphere, a multitechnique approach for improved understanding. *Ecosystems*, 3 (2): 115-130.

CASTELLVI F. 2004. Combining surface renewal analysis and similarity theory: A new approach for estimating sensible heat flux. Water Resource. Research. 40 W05201 doi:10.1029/2003WR002677, 1-20.

CASTELLVI F, MARTINEZ-COB A, PEREZ-COVETA O. 2006. Estimating sensible and latent heat fluxes over rice using surface renewal. Agricultural and Forestry Meteorology. 139, 164-169.

CATTIVELLI L, RIZZA F, BADECK FW, MAZZUCOTELLI E, MASTRUNGELO AM. 2008. Drought tolerance improvement in crop plants: An integrated view from breeding to genomics, *Field Crop Research*, 105: 1-14.

CLARK GA, ALBERGTS EE, STANLEY CD, SMAJSTRALA AG, ZAZUETA FS. 1996. Water requirement and crop coefficient of drip irrigation Strawberry plants. Transaction of ASAE 39

CLEVERLY JR, DAHM CN, THIBAULT JR, GILROY DJ, COONROD JEA. 2002. Seasonal estimates of actual evapotranspiration from *Tamarix ramosissima* stands using 3-dimensional eddy covariance. *Journal of Arid Environments*, 52: 181-197

CONROY JW, WU J, ELLIOT W. 2003. Modification of the evapotranspiration routines the wepp model; part1 ASAE annual International meeting. Las Vegas Nevada,USA: 27-30 July.16p. In.httpa;//www.pubs.asce.org/www display.

CONSTANTIN RJ, HERNANDEZ TP, JONES LG. 1974. Effects of irrigation and nitrogen fertilization on quality of sweet potato. *Journal of the America Society for Horticultural Science,* (99).

CPPMU. 2010. Economic review of agriculture central planning and project monitoring unit, CPPMU. Ministry of agriculture, Nairobi

DEPARTMENT OF AGRICULTURE FORESTRY AND FISHERY SOUTH AFRICA. 2011. A profile of the South African sweet potato market value chain.www.nda.agric.za/docs/AMCP/SWEETPOTATOMVC12.

DEPARTMENT OF AGRICULTURE. 2004. Strategic plan for the department of agriculture 2004: consolidating the partnership for poverty eradicating, Accelerated growth and wealth creation. *Directorate agriculture information services*, Pretoria, 160.

DEPARTMENT OF WATER AFFAIRS AND FORESTRY. 1994. Water Supply and Sanitation Policy. White Paper, Cape Town.

DEBAEKE P, ABOUDRARE A. 2004. Adaptation of crop management to water limited environment, *European Journal of Agronomy*, 21(4): 433-446

DE VRIES CA, FERWERDA JD, FLACK M. 1967. Choice of food crops in relation to actual and potential production in the tropics. Netherlands *Journal of Agricultural Science*, 15: 241-248

DOMOLA MJ. 2003. Survey and characteristics of sweet potato viruses in South Africa M.Inst Agra (plant protection). University of Pretoria.

DOORENBOS J, PRUITT WO. 1977. Crop water requirements. FAO Irrigation and Drainage paper 24. Food and Agriculture Organization of United Nations. Rome, Italy.

DREXLER JZ, SNYDER RL, SPANO D, PAW UKT. 2004. A review of models and micrometeorological methods used to estimate wetland evapotranspiration. *Hydrological Processes*, 18: 2071-2101.

DUKES MD, ZOTARELLI L, LIU GD, SIMONNE EH. 2012. Principles and practices of irrigation management for vegetables. University of Florida: *IFAS Extension, Technology Report*.

DU PLOOY CP. 1989. Stoorwortelmorfogenese by die patal (Ipomoea batatas (L.) Lam). DSc. (Agric). University of Pretoria.

EDER F, ROO FD, KOHNERT K, DESJARDINS R, SCHMID HP, MAUDER M. 2014. Evaluation of two energy balance closure parametrizations. *Boundary-layer Meteorology*. 151 (2): 195-219.

EITZINGER J, MARINKORIC D, HOSCH J. 2002. Sensitivity of different evapotranspiration calculation methods in different crop weather models.

EKANAYAKE IJ, COLLINS W. 2004. Effects of irrigation on sweet potato root carbohydrate and nitrogenous compounds. *Journal of Food Agriculture and Environment*, 2: 243-293.

EKANAYAKE IJ. 1989. Methods of studying drought stress and irrigation requirements of potatoes. *CIP Research Guide* 30. Lima. Peru: CIP. 40.

ENGLISH M. 1990. Deficit irrigation. I. Analytical framework. *Journal of Irrigation and Drainage Engineering. ASCE*, 116 (3): 399-412.

EVERSON C, EVERSON TM, MODI AT, CSIWILA D, FANADZO M, NAIKEN V, AUERBACH RMB, MOODLEY M, MTSHALI SM, DLADLA R. 2011. Sustainable techniques and practices for water harvesting and conservation and effective application in resource poor agricultural production through participatory adaptive research. *Water Research Commission Report No* 146/1/11.

EVETT SR, HOWELL TA, SCHNEIDER AD, TOLK JA. 1995. Crop coefficient based evapotranspiration estimates compared with mechanistic model results. In: Espey WH, Combs PG, (Eds.). Proceedings of the first international conference on water resources engineering, Vol. 2, San Antonio, texas, USA, August 14-18.

EWELL PT, MUTUURA J. 1994. Sweet potato in the food systems of Eastern and Southern Africa. *In Symposium on Tropical Root Crops in a Developping Economy 380*, 405-412.

EZZAHAR J, CHEHBOUNI A, ER-RAKI S, KHABBA S, HANICH L. 2009. Estimating and monitoring seasonal water consumption of olive orchards in a semi-arid region (Morocco) using the eddy–covariance system In: El Moujabber M, Mandi L, Trisorio- Liuzzing, Martin I, Rabi A, Rodriguez R (Eds,) technological perspectives for rational use of water resources in the Mediterranean region. Bari.

FAO. 1996. FAO production yearbook. 1995, Vol. 49. FAO statistics series No.111. Rome. Food and agricultural organization of the united nation.

FAO. 2000. Forest resource assessment 2000. Rome, Food and Agriculture Organization (FAO), Forestry Department.

FAO. 2007. http://www.fao.org/newsroom/en/news/2007/1000654/index.html

FALGAE E, BALDOCCHI D, OLSON R, ANTHONI P, AUBINET M, BERNHOFER C, BURBA G, CEULEMANS G, CLEMENT R, DOMA H, GRANIER A, GROSS P, GRUNWAL T, HOLLINGER D, JENSEN NO, KATUL G, KEROMEN P, KOWALSKI A, LAI CT, LAW BE, MAYERS T, MONCRIEFF J, MOORS E, MUNYER JW, PILEGAARD K, RANNIK U, REBMANN C, SUYKER A, TENHUMEN J, TU K, VERMA S, VESALA T, WILSON K, WOFSY S. 2001. Gap filling strategies for long term energy flux data sets. *Journal of Agricultural and Forestry Meteorology*, 107 (1): 71-77.

FEIVRE F, LEENHARDT D, VOLTZ M, BENOIT M, PAPY F, DEDEU D, WALLACH D. 2004. Spatializing crop models. *Agronomie, EDP science*, 24 (4): 205-217.

FELIX J, SHOCK CC, ISHIDA J, FEIBERT EBG, SAUNDERS LD. 2012. Sweet potato cultivar performance and irrigation criteria for treasure valley. Malheur Experimental station, Oregon State University, Ontario, OR.

FERERES E, SARIANO MA. 2007. Deficit irrigation for reducing agricultural water use. *Journal of Experimental Botany*, 58 (2): 147-159.

FISHER DK, PRINGLE III HC. 2010. Effects of reference-ET method on irrigation scheduling model, 5th National decennial irrigation conference Proceedings, 5-8 December 2010, Phoenix Convention Center, Phoenix, Arizon USA IRRR10-9814.

FITZJARRALD DR, MOORE KE. 1994. Growing season boundary layer climate and surface exchanges in a subarctic lichen woodland. *Journal of Geophysical Research*, Vol 99: 1899-1917.

GAMO M. 1999. Classification of arid regions by climate and vegetation. *Journal of Arid Land Studies*, 1: 9-17.

GAO Z, LENSCHOW DH. HE Z, ZHOU M. 2009. Seasonal and diurnal variations in moisture, heat and CO_2 fluxes over a typical steppe prairie in Inner Mongolia, China, Journal of *Hydrology and Earth System Sciences*, 13: 987-998.

GEERTS S, RAES D. 2009. Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. *Agricultural Water Man*agement, 96 (9): 1275-1284.

GEERTS S, RAES D, GARCIA M, MIRANDA R, CUSICANQUI J, TABOADA C, MENDOZA J, HUANCA R, MAMANI A, OCTAVIO C, MAMANI J, MORALES B, OSCO V,STEDUTO P. 2009. Simulating yield response of quinoa (*Chenopodium quinoa willed*) to water availability with AquaCrop. Special issue on "Yield Response to Water: Examination of the role of Crop Models in Predicting Water Use efficiency" *Agronomy Journal*, 101: 499-508.

GEIDER RJ, DELUCIA EH, FALKOWSKI PG. 2001. Primary productivity of planet earth: biological determinants and physical constraits in terrestrial and aquatic habitats. *Journal of Global Change Biology*, 7: 848-882.

GEREME SB, STEYN JM, ANNANDALE JG. 2007. Evaluation of growth performance and dry matter partitioning of four processing potato (Solamm tuberosum) cultivars. New Zealand, *Journal of Crop and Horticultural Sciences*, 35: 385-393.

GESTER H. 1993. Anticarcinogenic effect of common carotenoid. *International Journal for Vitamin and Nutrition research*, 63: 93-121.

GILLIES R, CARLSON T, CUI J. 1997. A verification of the triangle method for obtaining surface soil water content and energy fluxes from remote measurements of the Normalized Different Vegetation Index (NDVI) and surface radiation temperature. *International Journal of Remote Sensing*, 18: 3145-3166.

GJANAYAKE B, REDDY KR, SHANKLE MW, ARANCIBIA RA, VILLORDON AO. 2014. Quantifying storage root initiation, growth and developmental responses of sweet potato to early season temperatures. *Agronomy Journal*, *Volume* 106: 1795-1804.

GOMES F, CARR MKV. 2001. Effects of water availability and vine harvesting frequency on the productivity of sweet potato in Southern Mozambique. I storage roots and vine yields. *Experimental Agriculture*, 37 (4): 523-537.

GOMES F, CARR MKV. 2003. Effects of water availability and vine harvesting frequency on the production of sweet potato in Southern Mozambique. Crop Water Use. *Experimental Agriculture,* 39 (4): 39-54.

GU, L, SHUGART H, FUENTES J, BLACK T, SHEWCHUK S. 1999. Micrometeorology, biophysical exchanges and NEE decomposition in a two storey boreal forest development and test of an integrated model. Journal of *Agricultural and Forest Meteorology,* 94: 123-148.

HAGENIMANA V, LOW J.2000. ‘Potential of orange-fleshed sweet potatoes for raising vitamin A intake in Africa’ *Food and Nutrition Bulletin,* 21 (4): 441-418.

HANSON BR, MAY DM. 2006. Crop coefficient for drip irrigated processing tomato. *Agricultural Water Management*, 81: 381-399

HANSON RL. 1991. Evapotranspiration and drought. In: Paulsson RW, Chase EB, Roberts RS, Moody DW, compilers, National Water Summary 1988–89. Hydrologic Events and Floods and Droughts: US. Geological survey water supply paper 2375, 99-104.

HAHN SK. 1977. Sweet potato. *Ecophysiology of tropical crops,* 237248.

HAM JM, HEILMAN JL. 2003. Experimental test of density and energy-balance corrections on carbon dioxide flux as measured using open-path eddy covariance. *Agronomy Journal*, 95: 1393-1403.

HAMAN DZ, PRITCHARD RT, SMAJSTRALA AG, ZAZUETA FS, LYRENE PM. 1997. Evapotranspiration and crop coefficient for young Blueberry in Florida. *Applied Engineering in Agriculture*, 13 (2): 209-216.

HAMMET HL, CONSTANTIN RJ, JONES LG, HERNANDEZ TP. 1982.The effects of phosphorus and soil moisture levels on yield and processing quality of ‘Contennial’ sweet potatoes. *Journal America Society of Horticultural Science*.

HANSEN JW, JONES JW. 200. Scaling-up crop models for climate variability applications. *Agricultural Systems*, 65 (1): 43-72.

HARTEMINK EA, JOHNSON M, O’SULLIVAN JN, POLOMA S. 2000. Nitrogen use efficiency of taro and sweet potato in the humid lowland of Papua New Guinea. *Journal of Agricultural Ecosystems and Environment*, 79: 271-280.

HENDRICKS FRANSSEN HS, STOCKLI R, LEHNER I, ROTENBERG E, SENEVIRATNE SI. 2010. Energy balance closure of eddy covariance data: A multisite analysis for European FLUXNET stations. *Journal of Agricultural and Forest Meteorology*, 150: 1553-1567.

HIPPS LE, IVANS S, JOHNSON DA, SALIENDRA NZ. 2002. Eddy covariance and Bowen ratio estimates of water vapor and CO_2 fluxes over crested wheatgrass. *In 25th Conference Agricultural and Forest Meteorology*, 19-23.

HOEDJES JCB, CHETIBOUNI A, JACOB F, EZZAHAR J, BOULET G. 2008. Deriving daily evapotranspiration from remotely sensed instantaneous evaporative fraction over olive orchard in semi-arid morocco. *Journal Hydrology*, 345.

HOJSTRUP J. 1993. A statistical data screening procedure. Measurement Science and Technology 4: 153-157

HOLMES JW. 1984. Measuring evapotranspiration by hydrological methods. Agricultural water management. 8, 29-40.

HORTON RJ. 1988. Introduction of halofantrine for malaria treatment. *Parasitology Today*, 4: 238-239.

HOWELL TA, CUENCA RH, SOLOMON KH. 1992. Crop yield response. In: Hoffman GJ, Howell TA, Solomon KH (Eds.), Management of farm irrigation system. ASAC Monograph No.9, 2950 Niles Road, St. Joseph. MI 49085-9659: 93-122.

HOWELL TA. 2001. Enhancing water use efficiency in irrigated agriculture. *Agronomy Journal*, 93: 281-289.

HUANG AS, TANUDJAJA L, LUM D. 1999. Content of alpha, Beta-carotene, and dietary fiber in 18 sweet potato grown in Hawaii. *Journal of food Composition and Analysis,* 12 (2): 147-151

IGBADUM HE, MAHOO HF, TARIMO AK, SALIM BA. 2006. Crop wtare productivity of an irrigated maize crop in Mkoji Sub – catchmentof the Great Ruaha River Basin, Tanzania. *Agricultural Water Management*, 85 (1): 141-150.

INOUE Y. 2003. Synergy of remote sensing and modelling for estimating ecophysiological processes in plant production. *Plant Production Science*, 6: 3-16.

JANA RK. 1982. Status of sweet potato cultivation in East Africa and in future. In: R.L Villarreal and Griggs T.D., (eds.), sweet potato. Proc. Int. Synmp., AVRDC, Taiwan, China, 63-76.

JARMAIN C, EVERSON CS, SAVAGE MJ, MENGISTU MG, CLULOW AD, WALKER S, GUSH MB. 2009. Refininh tools for evaporation monitoring in support of water resources management. WRC report No. 1567/1/08.

JENSEN ME. 1968. Water consumption by agricultural plants, water deficits and plants growth, KOZLPWSKI TT (ed.), Academic Press, N.Y. 11, 1-22.

JENSEN ME. 1969. Scheduling irrigations using computers. *Journal of Soil and Water Conservation*, 24 (8): 193-195.

JENSEN ME, ROB DC, FRANZOY CE. 1970. Scheduling irrigations using climate-crop-soil data. Proceeding of the America Society of Civil ENGINEERS, *Journal of the Irrigation and Drainage Division*, 96, 25-38.

JENSEN ME, WRIGHT JL, PRAT BJ. 1971. Estimating soil moisture depletion from climate, crop and soil data. Transactions of the ASAE, 14 (5): 945-959.

JARMAIN C, EVERSON CS, SAVAGE MJ, MENGISTU MG, CLULOW AD, WALKERS S, GUSH MB. 2009. Refining tools for evaporation monitoring in support of water resources management. WRC report No. 1567. *Water Research Commission*, Pretoria, South Africa. 137.

JOVANOVIC NZ, ANNANDALE JG. 1999. Crop growth model parameters of 19 summer vegetable cultivars for use in mechanistic irrigation scheduling models. ISSN 0378-4738: *Water South Africa*, 26.

JOVANOVIC NZ, ANNANDALE JG, MHLAULI NC. 1999. Field water balance and SWB parameter determination of six winter vegetable species. *Water South Africa,* 25 (2): 191-196.

JOVANOVIC NZ, ANNANDALE JG. 1999. An FAO type crop factor modification to SWB for inclusion of crops with limited data: examples for vegetable crops. ISSN 0378-4738, *Water South Africa* Volume 25 .http://www.wrc.org.za

JOVANOVIC NZ, ANNANDALE JG, NEL AA. 2000. Calibrationand validation of SWB model for Sunflower (*Helianthus annuus L.*) *South Africa Journal of plant and Soil*, 17 (3): 117-123.

JOVANOVIC NZ, STIKIC R, 2012. Strategies for improving water productivity and quality of agricultural crops in an area of climate change. In: Lee TS (Ed.) Irrigation system and practices in challenging environments. Intech, Croatia, ISBN: 978 -953-51-0420.

JOVANOVIC NZ, ISRAEL S. 2012. Critical Review of Methods for the estimation of actual evapotranspiration in Hydrological models. *Council for scientific and industrial Research, Stellenbosch South Africa.*

KANG S, GU B, DU T, ZHANG J. 2003. Crop coefficient and ratio of transpiration to evapotranspiration of winter wheat and maize in a semi humid region. *Agricultural Water Management, 59 (1): 239-254.*

KAPINGA R, ANDERSON A, CRISSMAN C, ZHANG D, LEMAGA B, OPIO F. 2005. Vitamin A Partnership for Africa: a food based approach to combat vitamin A deficiency in Sub-Saharan Africa through increased utilization of orange-fleshed sweet potato. *Chronica Horticulturae Journal*, *45*: 12-4.

KARANJA FK. 2006. CROPWAT model analysis of crop water use in six district in Kenya: Department of Meteorology, University of Nairobi.

KAWANO K. 1990. Harvest Index and evolution of major food crop cultivars in the tropics. *Euphytica*, 46 (3): 195-202.

KELM M, BRUCK H, HERMANN M, SATTELMACHER B. 2001. The effects of low nitrogen supply on yield and water use efficiency of sweet potato (Ipomoea batatas L.). *Plant and Soil science.*

KIDMORE U, CHRISTENSEN LP, AGILI SM, THILSTED SH. 2007. Effects of home preparation practices on the content of pro vitamin A carotenoids in coloured sweet potato varieties (Ipomoea batatas Lam.) from Kenya. *Innovative Food Science & Emerging Technologies*, 8 (3): 399-406.

KIKER GA. 2000. "Synthesis report for vulnerability and adaptation assessment section. South Africa country study on climate change" Pretoria, Department of Environmental Affairs and Tourism.

KITE GW, DROOGERS P. 2000. Comparing evapotranspiration estimates from satellites, Hydrological models and field data. *Journal of Hydrology*, 229.

K'OSAMBO LM, CAREY EE, MISRA AK, WILKES J, HAGENIMANN V. 1998. Influence of age, farming site, and boiling on pro vitamin A content in sweet potato *(Ipomoea batatas (L) Lam)* storage roots. *Journal of Food Technology in Africa*, 4 (3).

K'OSAMBO LM, CAREY EE, MISRA AK, WILKES J, HAGENLMANA V. 1999. Influence of age, farming site, and boiling on pro-vitamin A content in sweet potato (Ipomoea batatas (L.) Lam.) storage roots. *Journal of Food Technology in Africa*, 4 (3).

KUBOTA F. 2003. The effects of drought stress and leafageing on leaf photosynthesis and electron transport in photosystem 2 in sweet potato (*Impomoa batatas Lam.*) cultivars. *Photosynthetica*, 41 (2): 253-258.

KUMAR PS, SAGAR VR. 2014. Drying kinetics and physico-chemical characteristics of Osmo-dehydrated Mango, Guava and Aonla under different drying conditions, *Journal of Food Science and Technology*, 51 18): 1540 - 1546

KUSCU H, TURHAN A, OZMEN N, AYDINOL P, BUYUKANGAZ H, DEMIR AO. 2015. Deficit irrigation effects on watermelon (citrullus vulgaris) in Sub-humid environment. JAPS: *Journal of Animal & Plant Sciences*, 25 (6): 1652-1659.

KUSLU Y, SAHIN U, TUNC T, KIZILOGLU FM. 2010. Determining water yield relationship, water use efficiency, Seasonal Crop Pan Coefficient for alfalfa in a semi-arid region with high altitude. *Bulgarian Journal of Agricultural Sciences*, 16, 482-492.

LAMBETH VN. 1956. Studies in moisture relationships and irrigation of vegetables. *Missouri. Agricultural Experimental Station*, 55.

LANA EP, PETERSON LE. 1956. The effect of fertilizer-irrigation combinations on sweet potatoes in Buckner coarse sand. Proc. *American Society of Horticultural Sciences.*

LAURIE SM. 2004. Sweet potato in perspective: In a guide to sweet potato production in South Africa, CDP printers, (G.J. NIEDERWIESER, ed), ARC-Roodeplaat vegetable and ornamental plant institute, Pretoria, South Africa.

LAURIE SM, FABER M, VAN JAARSVELD J, LAURIE RN, DU PLOOY CP, MODISANE PC. 2012. β-Carotene yield and productivity of orange-fleshed sweet potato *(Ipomoea batatas L. Lam.)* as influenced by irrigation and fertilizer application treatments. *Scientia Horticultural*. 142: 180-184.

LAURIE RN, DU PLOOY CP, LAURIE SM. 2009. Effect of moisture stress on growth and performance of orange fleshed sweet potato varieties. In African Crop Science Conference proceedings. 9. 235-239.

LAURIE RN, LAURIE SM, DU PLOOY CP, FINNIE JF, VAN STADEN J. 2015. Yield of drought-stressed sweet potation relation to canopy cover, stem length and stomatal conductance. Journal of Agricultural Science, Vol. 7, No. 1; 2015.

LAW BE, RYAN MG, ANTHONI PM. 1999. Seasonal and annual respiration of a ponderosa pine ecosystem. *Global Change Biology*, 5: 169-182.

LENSCHOW DH. 1995. Micrometeorological technique for masuring biosphere-atmosphere trace gas exchange. In: *Biogenic trace gases: measuring emissions from soil and water*. Matson PA, Harriss RC (eds), 126-163. Black well, London.

LEWTHWAITE SL, TRIGGS CM. 2012. Sweet potato cultivar response to prolonged drought, *Agronomy New Zealand*. 42.

LHOMME JP, KATERJI N. 1991. A simple modelling of crop water balance for agrometeorological application. *Ecological Modelling*.57, 11-25.

LI Z, YU GR, WEN XF, ZHANG LM, REN CY, FU YL. 2005. Energy balance closure at ChinaFLUX sites. *Science China Earth Sciences*, 48: 51-62.

LIU H, RANDERSON JT, LINDFORS J, MASSMAN WJ, FOKEN T. 2006. Consequences of incomplete surface energy balance closure for CO_2 fluxes from open-path CO_2/ H_2O infrared gas analysers. *Boundary-Layer Meteorology*, 120: 65-85.

LOOMIS RS, RABBINGE R, Ng E. 1989. Explanatory models in crop physiology, *Annual Review of Plant physiology*, 30: 339-367.

LOW JW, ARIMOND M, OSMAN N, CUNUARCH B, ZANO F, TSCHIRLEY D. 2007. A food – based approach introducing orange fleshed sweet potatoes increased vitamin A intake and serum retinol concentration in young children in rural Mozambique. *Journal of Nutrition Community and International Nutrition*, 137: 1320-1327.

LUOH JW, BEGG CB, SYMONDS RC, LEDESMA D, YAMG RY. 2014. Nutritional yield of African indigenous vegetables in water deficient and water sufficient conditions. *Food and Nutrition Science*, 5: 812-822.

MA Y, WANG Y, WU R, HU Z, YANG K, LI M, MA W, ZHONG L, SUN F, CHEN X, ZHU Z, WANG S, ISHIKAWA H. 2009. Recent advances on the study of atmosphere land interaction observations on the Tibetan Plateau, *Hydrology and Earth System Sci*ence, 13: 1103-1111.

MACLOWN RL, HAMMER GL, HARGREAVES JNG, HOLZWORTH DP, FREEBAIRN DM. 1996. ASPIM: A novel software system for model development, model testing and simulation in agricultural system research. *Agriculture System*, 50: 255-271.

MAHRT L. 1998. Flux sampling errors for aircraft and towers. *Journal of Atmospheric Oceanic Technology*, 15: 416-429.

MARQUES LG, FERREIRA MC, FREIRA JT. 2007. Freeze-drying of acerola (*Malpighia glabra L*.) Chemical Engineering and Processing, 46: 451 - 457

MASANGO S. 2014. Water use efficiency of orange fleshed sweet potato *(Ipomoea batatas L. Lam.)*. MSc dissertation. University of Pretoria. South Africa.

MASSERONI D, CORBARI C, MANCINI M. 2014. Limitations and improvements of the energy balance closure with reference to experimental data measured over a maize field. *Journal of Atmósfera,* 27 (4): 335-352.

MASSMAN WJ. 2000. A simple method for estimating frequency response corrections for eddy covariance system. *Agricultural and Forest Meteorology,* 104: 185-198.

MAUDER M, FOKEN T. 2004. Documantation and instruction manual of the eddy covariance software package TK2. Arbeitsergebnisse, Universitat Bayreuth, Abt. Mikrometeorologie, 26, 44

MAYERS PT, BALDOCCHI DD. 2005. Current micrometeorology flux methodologies with application in agriculture. In: Micrometeorology in agriculture system, Agronomy monograph No, 47. American society of Agronomy, Crop science Society of America, *Soil Science Society of America, 677 Soe S, Madison RD. W153711, USA: 381-296* McGuire J.1993. “Addressing micronutrient malnutrition.” Scn News, 9, 1-10.

MBWAGA Z, MATAA M, MSABAHA M. 2007. Quality and yield stability of orange fleshed sweet potato (Ipomoea batatas) varieties grown in different agro-ecologies. *In 18th African Crop Science Society Conference*, El-minia, Egypt, 27-31 October 2007: 339-45.

MCCARTY JJ, LEARY OF, DOKKEN NA, DOKKEN KS, WHITE DJ. 2001, Climate change, impacts, adaptation, and vulnerability. Contribution of working group II to the third assessment report of the intergovernmental panel on climate change. No. 574. 5222 C639co 201. Cambridge University Press.

MENGISTU MG, SAVAGE MJ. 2007. Evapotranspiration measurement for a silvopastoral system consisting of *Jatropha* and Kikuyu grass. Paper presentation to the Combined Congress 2006, South African Society of Crop Production/Soil Science Society of South Africa, 29 Jan to 1Feb. 2007, Badplaas, South Africa.

MENGISTU MG. 2008. Heat and energy exchange above different surfaces using surface renewal. Unpublished PhD thesis, University of KwaZulu-Natal, Pietermaritzburg, South Africa. Pp.151.

MINDE IJ, EWELL PT, TERI JM. 1999. Contributions of cassava and sweet potato to food security and poverty alleviation in SADC countries: current status and future prospects in proceedings of the scientific workshop of SARRNET, Pamdozi hotel, Lusaka, Zambia, 17-19 August 1998.

MOLDEN D. 2003. A water- Productivity frame work for understanding and action. In: kijne JW, Barker R, Molden D. (eds) water productivity in agriculture: Limits and opportunities for improvement. *International Water Management Institution*, Colombo, Srilanka, 1-18.

MOLDEN D. 2007. Water for food water for life: A comprehensive assessment of water management in agriculture. International Water Management Institute, Battaramulla, Srilanka, 688.

MONTEITH JL. 1996. The quest for balance in crop modelling. *Agronomy Journal*, 88: 695-697.

MORAN MS, CLARKE TR, INOUE Y, VIDAL A. 1994. Estimating crop water deficit using the relation between surface-air temperature and spectral vegetation index. *Remote Sensing of Environment*, 49 (3): 246-263.

MOTSA NM, MODI AT, MABHAUDHI T. 2015. Sweet potato response to low-input agriculture and varying environments of KwaZulu-Natal, South Africa: implications for food security strategies. Acta Agriculturae Scandinavica, *Section B Soil and Plant Science*, 65 (4): 329-340.

MOTSA NM, MODI AT, MABHAUDHI T. 2015. Antioxidant activity, reducing sugar content and selected phytonutrients of orange -fleshed sweet potato cultivars as influenced by agroecological production area. *Food Science and Technology*, 35, 32–37.

MOTSA NM, MODI AT, AND MABHAUDHI T. 2015. Sweet potato (*Ipomoea batatas* L.) as a drought tolerant and food security crop. *South African Journal of Science.* 111, 1–8.

NAGLER PL, SCOTT RL, WESTENBURG C, CLEVERLY JR, GLENN EP, HUETE AR. 2005. Evapotranspiration on western US Rivers estimated using the enhanced vegetation index from MODIS and data from eddy covariance and Bowen ration flux towers. *Remote Sensing Environment*, 97: 337-351.

NATH R, KUNDU CK, MAJUNDER A, ISLAM SKJ, GUNRI S, CHATTOPADHYAG A. 2007. Production potential of sweet potation the red and laterite ecosystem of west Bengal. *Journal of Root Crops*, 33: 97-103.

NATIONAL DEPARTMENT OF AGRICULTURE. 2001. Abstract agricultural statistics Pretoria. South Africa.

NAYLER PL, SCATT RL, WESTERBURG C, CLEVERLY JR, GLENN EP, HUETE AR. 2005. Evapotranspiration on western US Rivers estimated using the enhanced vegetation index Modis and data from eddy covariance and bowen ratio flux towers. *Remote Sensing of Environment, 97.*

NEDUNCHEZHIYAN M, BYJU G, JATA SK. 2012. Sweet potato Agronomy In: Nedunchezhiyan M, Byju G (Eds.) sweet potato. *Fruit, Vegetable and Cereal Science and Biotechnology* 6 (Special Issue 1). 1-10.

NIEDERWIESER JG. 2004. Guide to sweet potato production in South Africa. ARC – Roodeplaat, Pretoria.

NYATHI MK, ANNANDALE JG, BELETSE YG, BEUKES DJ, DU PLOOY CP, PRETORIUS B, VAN HALSEN GR. 2016. Nutritional water productivity of traditional vegetable crops. *Water Research Commission Report No* 2171/1/16.

OBOH S, OLOGHOBO A, TEWE O. 1989. Some aspects of the biochemistry and nutritional value of the sweet potato (*Ipomoea batatas*). *Food Chem*istry, 31 (1): 9-18.

ONCLEY SP, FOKEN T, VOGT R, BERNHOFER C, KOHSIEK W, LIU HP, PITACCO A, GRANTE SP, RIBERIO L, WEIDINGER T. 2002. The energy balance experiment EBEX – 2000, In: 15th symposium on boundary layers and turbulence, Wegeningen, The Netherlands, July 15 – 19, 2002, *American Meteorological Society*, Boston MA, 1-4.

OPIO F. 1990. An assessment of root crop production and development in the south pacific islands. The case of look Islands, Kiribati, Solomons Islands, Tonga, Tavalu and western Simoa (Root crop project RAS/86/34).

O'SULLIVAN JN, ASHER CJ, BLAMEY FPC. 1997. Nutrients disorders of sweet potato. *ACIAR monograph No* 48, 136.

OWEIS T, HACHUM A. 2004. Water harvesting and Supplemental Irrigation for improved water production of dry farming system in west Asia and North Africa. "New directions for diverse planet". Proceedings of the 4th international crop science congress 26 Sep - 1 Oct 2004, Brisbane, Australia.

PAKOKTOM T, CHSICHANA N, PHATTARALERPHONY J, SATHORNKICH J. 2013. Water use efficiency of the first ratoon cane by eddy covariance technique. *International Journal of Environmental Science and Development,* 4.

PAPALE D, REICHSTEIN M, AUBINET M, CANFORA E, BERNHOFER C, KUTSCH W, LONGDOZ B, RAMBAL S, VALENTINI R, VESALA T, YAKIR D. 2006. Towards a standardized processing of wet ecosystem exchange measured with eddy covariance technique: algorithms and uncertainty estimation. *Biogeosciences*, 3: 571-583.

PAW U K.T., QIU J., SU H.B., WATANABE T., BRUNNET Y., 1995. Surface renewal analysis: a new method to obtain scalar fluxes without velocity data. Agricultural and Forestry Meteorology. 74, 119-137.

PAW U K T, BALDOCCHI DD, MEYERS TP. 2000. Correction of eddy covariance measurement incorporating both advective effects and density fluxes. *Boundary-Layer Meteorology*, 97: 487-511.

PAW U KT, SNYDER RL, SPANO D, SU HB. 2005. Surface renewal estimates of scalar exchange.

In: HATFIELD JL, BAKER JM. (Eds), Micrometeorology in Agricultural Systems Agronomy Monograph no. 47. Pp. 455-483.

PEREIRA SL, PERRIER A, ALLEN GI. 1996. Evapotranspiration Review of Concept and future trends. In: Evapotranspiration and irrigation scheduling. Proceedings of the international conference, November 3-6. San Antonio, Texas: 109-115.

PEREIRA SL, OWEIS ST, ZAIRI A. 2002. Irrigation management under water scarcity. *Agricultural Water Management*, 57: 175-206.

PIRVULESCA V. 2013. Application of the eddy covariance method under the canopy at a boreal forest sites in central Sweden. Master's thesis. Lund University. Sweden,

PERRY C, STEDUTO P, ALLEN GR, BURT CM. 2009. Increasing productivity in irrigaed agriculture, Agronomic constraint and hydrological realities. *Agricultural Water Management*, 96: 1517-1524.

PLASTER JE. 2003. Soil Science and Management. 4th edition. Delmar Learning. United State.

POSTEL S. 1998. Pillar of Sand: Can the Irrigation Miracle Last. Publ. WW Norton and Co, New York.

POSTEL S. 2000. Entering an era of water scarcity: The challenges ahead. *Ecological Applications*, 10 (4): 941-948.

PRABAWARDANI S, SUPARNO A. 2015. Water use efficiency and yield of sweet potato as affected by nitrogen and potassium application. *Journal of Agricultural Science*; Vol. 7, No. 7; 2015ISSN 1916-9752 E-ISSN 1916-9760 Published by Canadian Centre of Science and Education.

PRUITT WO, SNYDER RL. 1985. Crop water use. IN: Pettygrove GS, Ason T (Eds.), irrigation with Reclaimed Municipal Water: A Guidance Mannual. Lewi S publishers Inc.

RANA G, KATERJI N. 2000. Measurement and estimation of actual evapotranspiration in the field under Mediterranean climate: a review. *European Journal of Agronomy*, 13: 125-153.

RAUTENBACH F, FABER M, LAURIE S, LAURIE R. 2010. Antioxidant capacity and antioxidant content in roots of 4 sweet potato varieties. *Journal of Food Science,* 75: 400-412.

RENAULT TD, WALLENSER WW. 2000. Nutritional water productivity and diets. *Agricultural Water Management*, 45: 275-296.

RIVINGTON M, MATHEWS KB, BUHAN K. 2002. A comarison of methods for providing solar radiation data to crop models and decision support systems. *Proceedings of the international Environmental Modelling and Software Society*. Lugano, Switzerland, 3: 193-198.

RODIYATI A, ARISOESILANINGSIH E, ASAGI Y. 2005. Response of cyperus brevifolius (Rotts) Hassk and Cyperus kyllingia Endl.to varying soil water availability. *Environment Experimental Bot*any, 53: 259-269.

RONO CS, WANYAMA JM, MOSE LO, MUTOKO CM, LUSWETI E, WANJEKECHE E, WACHIYE B. 2006. Assessing the Impact of Sweet Potato Production and Utilisation 56 Technologies on Food Security in North Rift Region. A paper presented in 10th. KARI Biennial Scientific conference and the second Agricultural forum held between 13th – 17th November 2006 in Nairobi, Kenya.

RUNNING SW, BALDOCCHI DD, TURNER D. 1999. A global terrestrial monitoring network, scaling tower fluxes with ecosystem modelling and EOS satellite data. *Remote sensing environment,* 70.

SAVAGE MJ, EVERSO N CS, METELERKAMP BR. 1997. Evaporation measurement above vegetated surfaces using micro-meteorological techniques. *Water research commission report No. 349/1/97,* Pretoria, South Africa. ISBN No: 1 86845 363 4.

SAVAGE MJ, EVERSON CS, ODHIAMBO GO, MENGISTU MG, JARMAIN C. 2004. Theory and practice of evaporation measurement, with a special focus on SLS as an operational tool for the estimation of spatially-averaged evaporation, *water research commission report No. 1335/1/04.* Pretoria, South Africa. ISBN 1-77005-247-X.

SAVAGE MJ. 2008. Estimation of evaporation using a dual-beam surface layer scintillometer and component energy balance measurements. Journal of *Agricultural and Forest Meteorology.* In press.

SAVAGE MJ. 2009. Estimation of evaporation using dual-beam surface layer scintillometer and component energy measurements. *Journal of Agricultural and Forest Meteorology,* 149. 501-517.

SAVAGE MJ, ODHIAMBO GO, MENGISTU MG, EVERSON CS, JARMAIN C. 2010. Measurement of grassland evaporation using surface-layer scintilliometer. *Water South Africa Volume* 36.

SANCHEZ JM, CASELLES V, RUBIO EM. 2010. Analysis of the energy balance closure over a FLUXNET boreal forest in Finland, *Hydrology Earth System Sci*ence, 14: 1487-1497.

SNYDER RL, SPANO D, PAW U K.T. 1996. Surface renewal analysis for sensible heat and latent heat flux density. Boundary-Layer Meteorology. 77, 249-266.

SCOTT RL, EDWARDS EA, SHUTTLEWORTH WJ, HUXMAN TE, WATTS C, GOODRICH DC. 2004. Inter annual and seasonal variation in fluxes of water and carbon dioxide from a riparian woodland ecosystem. *Journal Agricultural and Forest Meteorology*, 122: 65-84.

SCOTT CA, BASTIAANSSEN WGM, AHMAD MD. 2003. Mapping root zone soil moisture using remotely sensed optical imagery. ASCE. *Journal of Irrigation and Drainage Engineering*, 129: 326-335.

SCOTT GJ, BEST R, ROSEGRANT M, BOKANGA M. 2000. Roots and tubers in the global food system. A vision statement to the year 2020. ACO – Publication by *CIP, CIAT, IFPRI, IITA and IPGRI, IIIPP*.

SCHOTANUS P, NIEUWSTADT FTM, DE BRUIN HAR. 1983. Temperature measurement with a sonic anemometer and its application to heat and moisture fluctuations. *Boundary-Layer Meteorology*, 26: 81-93.

SCHULZE R, MEIGH J, HORAN M. 2001. Present and potential future vulnerability of Eastern and Southern Africa's hydrology and water resources. *South Africa Journal of Science, 97: 150.*

SHIBAYAMA M, AKITA S. 2002. A portable spectropolarimeter for field crop canopies: Distinguishing species and cultivars of fully developed canopies by polarizes light, *Plant Production Science*, 5:4. 311-319.

SHUKLA S, JABER F, SRIVASTAVA S, KNOWLES J. 2007. Water use and crop coefficient for watermelon in Southwest Florida. Agriculture and biological Engineering Department.

SHUKLA PT. 1976. Stability performance of sweet potato (*Ipomoea batatas* L.) varieties in medium altitude areas of Tanzania. *Eastern Africa Forest Journal,* 42: 198-200.

SINGELS A, ANNANDALE JG, DE JAGER JM, SHULZE RE, INMAN-BAMBER NG, DURAD W, VAN RENSBERG LD, VAN HEERDEN PS, CROSSBY CT, GREEN GC, STEYN JM. 2008. Modelling crop growth and crop water relations in South Africa past achievements and lesson for the future. *South Africa Journal plant and soil,* (27) 1, 25 the Anniversary edition.

SIRVUWAN S, SIHACHAKR D, SILJAK-YAKOVLEV S. 2006. The origin and evolution of sweet potato (Impomoea batatas L.) and its wild relatives through the cytogenetic approaches. *Plant Science,* 171: 424-433.

SMITH M, ALLEN RG, MONTEITH JL, PERRIEA, PEEIRA L, SEGEREN A. 1991. Report of the expert consultation of procedures for revision of FAO guidelines for prediction of crop water requirement. UN-FAO, Rome, Italy, 54.

SMITH M, ALLEN RG, MONTEITH JL, PEREIRA LS, PERRIER A, PRUITT WO. 1992. Report on the expert consultation on procedures for revision of FAO guidelines for prediction of crop water requirement. Land and water development division, United Nations food and agriculture service, Rome, Italy.

SMITTLE DA, HALL MR, STANSELL JR. 1990. Effects of irrigation regimes on yield and water use by sweet potato. *Journal American society of Horticultural science,* 115 (5): 712-714.

SOIL CLASSIFICATION WORKING GROUP, MACVICAR CN. 1991. Soil classification: a taxonomic system for South Africa. Department of Agricultural Development.

SON HONG VU, WATANABE H, TAKAGI K. 2005. Application of FAO-56 for evaluating evapotranspiration in simulation of pollutant runoff from paddy rice field in Japan.

Agricultural Water Management, 76: 195-210.

SPANO D, SNYDER RL, DUCE P, PAW U KT, 2000. Estimating sensible and latent heat flux densities from grape vine canopies using surface renewal. *Journal of Agricultural and Forestry Meteorology*. 104, 171-183.

SRIVUWAN S, SIHACHAKR D, SILJAK-YAKOVLEV S. 2006. The origin and evolution of sweet potato (*Impomoea batatas L.*) and its wild relatives through the cytogenetic approaches. *Plant Science* 171: 424-433.

STANNARD DI, BLANFORD JH, KUSTAS WP, NICHOLS WD, AMER SA, SCHMNGGE TJ, WETTZ MA. 1994. Interpretation of surface flux measurements in heterogeneous terrain during the monsoon experiment. *Water Resources Research*, 83: 375-406.

STAWCZYK J.LI S ROMUALD Z. 2004. Freeze drying of food product in a closed system, Proceedings of the 14th International Drying Symposium (IDS 2004) – Sao Paulo, Brazil, vol.B. 949 - 953

STEDUTO P, HSIAO TC, RAES D, FERERES E. 2009. AquaCrop-The FAO model to simulate yield response to water: I. Concepts and underlining principles. *Agronomy Journal Volume 101, issue 3.*

STEDUTO P, HSIAO TC, FERERES E, RAES D. 2012. Crop yield response to water. *FAO Irrigation and Drainage Paper*. Rome Italy. ISBN 978-92-5-107274-5.

STEYN JM. 1997. Response of potato genotypes to different water regimes. Ph.D. thesis, University of Pretoria.

STIRZAKER R, MBAKWE I, MZIRAY NR .2017. A soil water and solute learning system for small-scale irrigators in Africa, *International Journal of Water Resources Development*, 33 (5): 788-803.

SU Z,TIMMERMANS WJ, VAN DER TOT C, DOT R, BIANCHI R, GOMEZ JA, HOUSE A, HAJNSEK I, MENENTI M, MAGLIULO V, ESPOSITO M, HAARBRINK R, BOSVELD F, ROTHE R, BALTINK HK, VEKERDY Z, SOBRIMO JA, TIMMERMANS J, VAN LAAKE P, SALAMA S, VAN DER KWAST H,CLASSEN E, STOLK A, JIA L, MOORS E,HARTOGEUSIS O. GILLESPIE H. 2009. EAGLE 2006 multi – purpose, multi – angle and multi – sensor in – site and airborne campaigns over grassland and forest, *Hydrology Earth System Sci*ence, 12: 833-845.

SUN H, LIU C, ZHANG X, SHEN Y, ZHANG Y. 2006. Effects of irrigation on water balance, yield and WUE of winter wheat in the north China plain. *Agricultural Water Manage*ment, 85: 211-218.

SWINBANK WC. 1951. Measurement of vertical transfere of heat and water vapour by eddies in lower atmosphere, *Journal of Meteorology*, 8: 135-145.

SZPYLKA & DE VREES. 2005. Determination of beta carotene in supplements and raw materials by reversed- phase higher preasure liquid chromotagraphy: collaborative study. *Journal of AOAC International*, 88: 5.

TAINTON NM. 2000. Pasture management in South Africa. University of Natal Press.

TAKAHATA Y, NODA T, NAGATA T. 1993. HPLC determination of β-carotene content of sweet potato cultivars and its relationship with color values. Japanese *Journal of Breeding*, 43 (3): 421-427.

TEIXEIRA AHC, BASTIAANSSEN WGM. 2010. Five methods to interpret field measurements of energy fluxes over a micro-sprinkler-irrigated mango orchard. *Journal of Irrigation Sciences.*

TEMESGEN B, ECHING S, DAVIDOFF B, FRAME K 2005. Comparison of some reference evapotranspiration equation for California. *Journal of irrigation and Drainage. Engineering*, 131(1): 73-84.

TEOW CC, TRUONG VD, MCFEETERS RF, THOMPSON RL, PECOTA KV, YENCHO GC. 2007. Antioxidant activities, phenolic and β – carotene contents of sweet potato genotypes with varying flesh colours. *Food Chemistry*, 103 (3): 829-838.

THE ECONOMIST. 2003. “Business: "Just do it" Chinese-style; China and brands”, 368 (8335), 67.

THIERMANN V, GRASSL H. 1992. The measurement of turbulent surface-layer fluxes by use of bichromatic scintillation. Boundary-Layer Meteorology 58, 367-389.

TIDEMANN - ANDERSEN I, ACHAM H, MAAGE A, MALDE MK. 2011. Iron and Zinc content of selected foods in the diet of school children in Kumi district, east of Uganda: A cross- sectional study. *Nutrition Journal*, 10 (1): 81.

THOMPSON PG, SMITTLE DA, HALL MR. 1992. Relationship of sweet potato yield and quality to amount of irrigation. *Horticultural Sciences*, 27: 23-26.

TREMBLAY M, WALLACH D. 2004. Comparison of parameter estimation for crop models. *Agronomie, EDP Science,* 2004, 24 (6-7). 351-365.

TUMWEGAMIRE S, KAPINGA R, ZHANG D, CRISNAM C, AGILLI S. 2004. Opportunities for promoting orange fleshed sweet potato among food based approach for combat Vitamin A deficiency in Sub – Saharan Africa. *African Crop Science Journal*, 12: 241-253.

TUMWEGAMIRE S, KAPINGA R, RUBAIHAYO PR, LABONTE DR, GRUNEBERG WJ, BURGOS G, ZUM FELDE T, CARPIO R, PAWELZIK E, MWANGA RO. 2011. Evaluation of dry matter, protein, starch, sucrose, Beta-carotene, iron, zinc, calciumand magnesium in East African sweet potato [*Ipomoea batatas (l)*] germplasm. *HortScience, 46(3). 348-357.*

TWINE TE, KUSTAS WP, NORMAN JM. 2000. Correcting eddy covariance flux underestimates over a grassland. *Agricultural and Forest Meteorology*, 103: 273-300.

UNITED STATES DEPARTMENT OF AGRICULTURE MARKETING SERVICE. 1981. United State standards for grades of sweet potato. U.S. Dept. Agr. Mktg. Serv, Wash, DC.

UNITED NATIONS, ADMINISTRATIVE COMMITTEE ON CO-ORDINATION SUBCOMMITTEE ON NUTRITION (ACC/SCN). 1997. Third report on the world nutrition situation. *World health organization, Gevera, Switzerland.*

UNITED STATES DEPARTMENT OF AGRICULTURE (USDA), AGRICULTURAL RESEARCH SERVICES. 2007. USDA table of nutrient retention factors, Release 6, http://www.ars.usda.gov/services/docs.hatm?.docid = 9448.

USDA – NRCS. 1997. Nutritionala range and pasture handbook. Washington, D: USDA NRCS.

VAN DAM JC, MALIK RS. 2003. Water productivity of irrigated crops in Sirsa district, India. Itergration of remote sensing, crop and soil models and geographical information system. WATPRO final report. 133

VAN DEN BERG AA, LAURIE SM, NIEDERWIESER JG. 2004. Harvest storage and marketing: In a guide to sweet potato production in South Africa, CDP printers, (G.J. NIEDERWIESER, ed), ARC-Roodeplaat vegetable and ornamental plant institute, Pretoria, South Africa.

VAN HEERDEN RD, LAURIE R. 2008. Effects of prolonged restriction in water supply on photosynthesis shoot development and storage root yield in sweet potato. *Physiologia Plantarum*, 134: 99-09.

VAN JAARSVELD P J, FABER W M, TANUMIHARDJO S A, NESTEL P, LOMBARD C JBENADE A J S. 2005. B-Carotene-rich orange-fleshed sweet potato improves the vitamin A status of primary school children assessed with the modified-relative-dose response test. *American Journal of Clinical Nutrition, 81*: 1080-1087.

VERMAN SB. 1990. Micrometeorological methods for measuring surface fluxes of mass and energy. *Remote sensing review*, 5: 99-115.

VICKERS D, MAHRT L. 1997. Quality control and flux sampling problems for tower and aircraft data. *Journal of atmospheric Oceanic Technology* 14: 512-170

VIMALA B, THUSHARA R, NAMBISAN B, SREEKUMAR J. 2006. Evaluation of orange flesh sweet potatoes for higher yield and carotene content. In: *14th Triennial Symposium of International Society of Tropical Roots Crops*, 20-26 November 2006. Central Tuber Crops Research Institute, Thiruvananthapuram, India, 55.

VILLALOBOS FJ, TESTI L, RIZZALLI R, ORGAZ F. 2004. Evapotranspiration and crop coefficients of irrigated garlic (Allium Sativum L.) in a semi-arid climate, *Agricultural Water Management*, 64: 233-249.

VU HS, WATANABE H, TAKAGI K. 2005. Application of FAO - 56 for evaluating evapotranspiration in simulation of pollutant runoff from paddy rice field in Japan. *Agricultural Water Management*, 76.

WALLACE JS, BATCHELOR CH.1997. Managing water resources for crop production. *Philosophical Transections of the Royal Society of London B: Biological Sciences* 352 (1356): 379-947.

WALLACE JS, GREGORY P. 2002. Water resource and their use in food production system. *Aquatic Science,* 64: 1-13.

WANG J, SAMMIS TW, MILLER DR. 2008. Eddy covariance measurements of crop water use: The energy closure problem and potential solutions. *Agricultural Water Management Research Trend.*

WATER RESEARCH COMMISSION. 2000. Improving agricultural water management. *Water Research Commission Report No TT 127/00.*

WENHOLD F, ANNANDALE J, FABER M, HERT T. 2012. Water use and nutrient content of crop and animal food products for improved household food security: A scoping study. South Africa: *Water Research Commission:* ‘You Can’t Eat Electricity.’

WHISLER FD, ACOCK B, BAKER DN, FYE RE, HODJES HF, LAMBERT JR, LEMMON HE, MACKININO JM, REELDY VR. 1986. Crop simulation models in agronomic system. *Advance Agronomy*, 40: 141-208.

WILSON KB, BALDOCCHI DD. 2001. Comparing independent estimates of carbon dioxide exchange over five years at a deciduous forest in the southern US. *Journal of Geophysical Research*, 106: 34167-34178.

WILSON KB, GOLDSTEIN A, FALGE E, AUBINET M, BALDOCCHI D, FIELD C, GRELLE A, IBROM A, LOW BE, KOWALSKI A, MEYERS T, MONCRIEFF J, MONSON R, OECHEL W, TENHUNEN J, VALENTINE R, VERMA S. 2002. Energy balance closure at FLUXNET sites. *Journal of Agricultural and Forest Meteorology*, 133: 223-243.

WOLMORANS P, DANSTER N, DALTON A, ROSSOUW K, SCHONTELDT H. (Eds). 2010. Condensed food composition tables for South Africa. *Medical Research Council*, Parow Valley, Cape Town, South Africa.

WOOLFE JA. 1992. Sweet potato: An untapped food resource. Cambridge University Press.

WRIGHT IR, GASH JHC, DAROCHA HR, SHUTTLEWORTH WS, NOBRE CA, MAITELLI GT, ZAMPARONI CAGP, CARVALHO PRA. 1992. Dry season micrometeorology of central Amazonian Rachland. *Quarterly Journal of the Royal Meteorological Society*, 118: 1083-1099.

YENG SB, AGYARKO HK, DAPAAH WS, ASARO E. 2012. Growth and yield of sweet potato (*Ipomoea batatas (l.)* lam) as influenced by integrated application of chicken manure and inorganic fertilizers. *African Journal of Agricultural Res*earch, 7: 5387-5395.

YE X, AL-BABIL S, KLOTII A, ZHANG J, LUCCA P, BEYER P, POTRYKUS I. 2000. Engineering the pro-vitamin A (β-carotene) biosynthetic pathway into (carotenoid-free) rice endosperm. *Science*, 287, 5451.

YOOYONGWECH S, THEERAMITAYA C, SAMPHUMPHUANG T, CHA-UM S. 2013. Water deficit tolerant identification in sweet potato genotypes *(Ipomoea batatas (L.) Lam.)* In vegetative developmental stage using multivariate physiological indices. *Scientia Horticulture*, 161: 242-251.

ZELEKE KT, WADE LJ. 2012. Evapotranspiration Estimation Using Soil WaterBalance, Weather and Crop Data, Evapotranspiration - Remote Sensing and Modeling, IRMAK A (Ed.),ISBN: 978-953-307-808-3, InTech, Available from: http://www.intechopen.com/books/evapotranspirationremote-sensing-and modeling/evapotranspiration-estimation-using-soil-water-balance-weather-and-crop-data.

ZHI L. 1991. Effects of potassium on the yield of three sweet potato varieties. Karsetsart University, Kamphaeng, Saen Campus, Nakhon Pathom. Thailand.

ZOTARELLI L, DUKES MD, ROMERO CC, MIGLIACCIO KW, MORGAN KT. 2013. Step by step of Penman-Monteith evapotranspiration (FAO-56 method). EDIS website at http://edis.ifas.ufl.edu.

LIST OF APPENDICES

APPENDIX 1: Analysis of variance tables

GenStat 64-bit Release 15.1 (PC/Unknown) 12 June 2015 08:16:02

Copyright 2012, VSN International Ltd.

Registered to: Plant Research International

GenStat Fifteenth Edition

GenStat Procedure Library Release PL23.1

Analysis of variance

Variate: Yield storage roots (fresh) (kg ha^{-1})

```
Source of variation        d.f.        s.s.        m.s.      v.r.   F pr.

rep stratum                   2   2.704E+06   1.352E+06      0.33

rep.*Units* stratum
Trt                           5   2.809E+09   5.617E+08    135.78   <.001
Residual                     10   4.137E+07   4.137E+06

Total                        17   2.853E+09
```

Tables of means

Variate: Yield (kg ha^{-1})

Grand mean 23287.

```
      Trt         fo        fw        ro        rw        so        sw
              35553.    39867.     6182.     9049.    22039.    27032.
```

Standard errors of differences of means

```
Table                    Trt
rep.                       3
d.f.                      10
s.e.d.                1660.7
```

Least significant differences of means (5% level)

```
Table                    Trt
rep.                       3
d.f.                      10
l.s.d.                3700.4
```

Duncan's multiple range test

```
 Trt
             Mean
ro           6182   e
rw           9049   e
so          22039   d
sw          27032   c
fo          35553   b
fw          39867   a
```

Analysis of variance

Variate: Total dry matter (TDM) yield (t ha^{-1})

```
 Source of variation   d.f.     s.s.     m.s.    v.r.    F pr.

rep stratum                  2      0.0426      0.0213     0.11

rep.*Units* stratum
Trt                          5    220.8025     44.1605   222.34   <.001
Residual                    10      1.9862      0.1986
```

Total	17	222.8313

Tables of means

Variate: TDM yield (t ha^{-1})

Grand mean 7.96

Trt	fo	fw	ro	rw	so	sw
	11.14	13.29	3.01	4.83	7.16	8.35

Standard errors of differences of means

Table	Trt
rep.	3
d.f.	10
s.e.d.	0.364

Least significant differences of means (5% level)

Table	Trt
rep.	3
d.f.	10
l.s.d.	0.811

Duncan's multiple range test

Trt

	Mean	
ro	3.007	f
rw	4.832	e
so	7.158	d
sw	8.347	c
fo	11.138	b
fw	13.289	a

```
Analysis of variance
 Variate: Harvest index (HI) %
 Source of variation    d.f.      s.s.      m.s.     v.r.      F pr.

rep stratum                            2          3.843          1.921        0.27

rep.*Units* stratum
Trt                                    5        754.665        150.933       21.42    <.001
Residual                              10         70.466          7.047

Total                                 17        828.973

Tables of means

Variate: HI (%)

Grand mean  63.05

            Trt          fo          fw          ro          rw          so          sw
                      63.42       72.70       52.92       64.68       57.20       67.39

 Standard errors of differences of means

Table                          Trt
rep.                             3
d.f.                            10
s.e.d.                       2.167

Least significant differences of means (5% level)

Table                          Trt
rep.                             3
d.f.                            10
l.s.d.                       4.829
```

```
Duncan's multiple range test

Trt

              Mean
ro           52.92   c
so           57.20   c
fo           63.42   b
rw           64.68   b
sw           67.39   b
fw           72.70   a

Analysis of variance

Variate: Irrigation + rainfall (mm)

Source of variation          d.f.          s.s.          m.s.       v.r.    F pr.

Rep stratum                     2         1.333         0.667       0.62

Rep.*Units* stratum
Trt                             5    110800.000     22160.000 20775.00    <.001
Residual                       10        10.667         1.067

Total                          17    110812.000

Tables of means

Variate: Irrigation + rainfall (mm)

Grand mean  347.67

        Trt          fo         fw         ro         rw         so         sw
                 451.00     451.00     261.00     261.00     331.00     331.00
```

Standard errors of differences of means

Table	Trt
rep.	3
d.f.	10
s.e.d.	0.843

Least significant differences of means (5% level)

Table	Trt
rep.	3
d.f.	10
l.s.d.	1.879

Duncan's multiple range test

Trt

	Mean	
ro	261.0	c
rw	261.0	c
so	331.0	b
sw	331.0	b
fo	451.0	a
fw	451.0	a

Analysis of variance

Variate: ET (mm)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	0.000	0.000	0.00	

Rep.*Units* stratum

```
Trt                          5   163372.500    32674.500 27228.75    <.001
Residual                    10       12.000        1.200

Total                       17   163384.500

Tables of means

Variate: ET_mm

Grand mean  306.50

        Trt        fo        fw        ro        rw        so        sw
               437.00    427.00    208.00    196.00    293.00    278.00

 Standard errors of differences of means

Table                      Trt
rep.                         3
d.f.                        10
s.e.d.                   0.894

Least significant differences of means (5% level)

Table                      Trt
rep.                         3
d.f.                        10
l.s.d.                   1.993

Duncan's multiple range test

 Trt
           Mean
rw         196.0   f
 ro        208.0   e
```

sw	278.0	d
so	293.0	c
fw	427.0	b
fo	437.0	a

Analysis of variance

Variate: Water use efficiency (WUE) (kg ha^{-1} mm^{-1})

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep1 stratum	2	11.87	5.94	0.09	
rep1.*Units* stratum					
Trt1	2	4773.94	2386.97	35.20	0.003
Residual	4	271.24	67.81		
Total	8	5057.05			

Tables of means

Variate: WP (kg ha^{-1} mm^{-1})

Grand mean 62.1

Trt1	fo	ro	so
	81.4	29.7	75.2

Standard errors of differences of means

Table	Trt1
rep.	3
d.f.	4

```
s.e.d.                        6.72
Least significant differences of means (5% level)

Table                         Trt1
rep.                             3
d.f.                             4
l.s.d.                       18.67

 Duncan's multiple range test
 Trt1
          Mean
ro        29.72   b
so        75.22   a
fo        81.36   a

Analysis of variance
Variate: WP (kg ha-1 mm-1)
Source of variation         d.f.        s.s.        m.s.      v.r.   F pr.

rep_1 stratum                  2      109.30       54.65      0.95

rep_1.*Units* stratum
Trt_1                          2     4850.20     2425.10     42.30   0.002
Residual                       4      229.31       57.33

Total                          8     5188.81
 Tables of means
Variate: WP (kg ha-1 mm-1)

Grand mean  78.9

     Trt_1         fw         rw         sw
                 93.4       46.2       97.2
```

Standard errors of differences of means

Table	Trt_1
rep.	3
d.f.	4
s.e.d.	6.18

Least significant differences of means (5% level)

Table	Trt_1
rep.	3
d.f.	4
l.s.d.	17.16

Duncan's multiple range test

Trt_1

	Mean	
rw	46.17	b
fw	93.37	a
sw	97.24	a

Analysis of variance

Variate: Beta carotene content (mg 100 g^{-1})

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	0.1543	0.0772	0.22	
rep.*Units* stratum					
Trt	5	413.3706	82.6741	238.55	<.001
Residual	10	3.4656	0.3466		
Total	17	416.9906			

Tables of means

Variate: Beta carotene content (mg 100 g^{-1})

Grand mean 4.94

Trt	fo	fw	ro	rw	so	sw
	5.92	0.50	14.17	1.40	6.72	0.92

Standard errors of differences of means

Table	Trt
rep.	3
d.f.	10
s.e.d.	0.481

Least significant differences of means (5% level)

Table	Trt
rep.	3
d.f.	10
l.s.d.	1.071

Duncan's multiple range test

Trt	Mean	
fw	0.50	c
sw	0.92	c
rw	1.40	c
fo	5.92	b
so	6.72	b
ro	14.17	a

```
Analysis of variance
Variate: Fe (mg 100 g-1)
Source of variation              d.f.        s.s.        m.s.     v.r.   F pr.

rep stratum                         2    0.005803    0.002901     2.23

rep.*Units* stratum
Trt                                 5    1.518358    0.303672   232.98   <.001
Residual                           10    0.013034    0.001303

Total                              17    1.537195

Tables of means

Variate: Fe (mg 100 g-1)

Grand mean  0.9897

        Trt        fo        fw        ro        rw        so        sw
               0.8972    0.7296    1.5270    1.1945    0.9034    0.6866

Standard errors of differences of means

Table                          Trt
rep.                             3
d.f.                            10
s.e.d.                     0.02948

Least significant differences of means (5% level)

Table                          Trt
rep.                             3
d.f.                            10
```

```
l.s.d.                    0.06568
```

Duncan's multiple range test

Trt

	Mean	
sw	0.6866	d
fw	0.7296	d
fo	0.8972	c
so	0.9034	c
rw	1.1945	b
ro	1.5270	a

Analysis of variance

Variate: Zn (mg 100 g^{-1})

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	0.001878	0.000939	0.50	
rep.*Units* stratum					
Trt	5	0.643989	0.128798	68.41	<.001
Residual	10	0.018826	0.001883		
Total	17	0.664693			

Information summary

All terms orthogonal, none aliased.

Tables of means

Variate: Zn (mg 100 g^{-1})

```
Grand mean  0.535

         Trt         fo        fw        ro        rw        so        sw
                  0.436     0.338     0.830     0.759     0.475     0.376

Standard errors of differences of means

Table                    Trt
rep.                       3
d.f.                      10
s.e.d.                0.0354

Least significant differences of means (5% level)

Table                    Trt
rep.                       3
d.f.                      10
l.s.d.                0.0789

Duncan's multiple range test

Trt
            Mean
fw        0.3375   d
sw        0.3758   dc
 fo       0.4359   bc
 so       0.4752   b
rw        0.7585   a
 ro       0.8299   a
```

Analysis of variance

Variate: Beta-carotene water productivity (mg m^{-3})

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	6.2	3.1	0.03	
rep.*Units* stratum					
Trt	5	30829.8	6166.0	53.11	<.001
Residual	10	1161.0	116.1		
Total	17	31996.9			

Information summary

Tables of means

Variate: Beta-carotene WP (mg m^{-3})

Grand mean 58.4

Trt	fo	fw	ro	rw	so	sw
	96.0	11.4	108.5	22.2	93.9	18.6

Standard errors of differences of means

Table	Trt
rep.	3
d.f.	10
s.e.d.	8.80

Least significant differences of means (5% level)

Table	Trt
rep.	3
d.f.	10
l.s.d.	19.60

Duncan's multiple range test

Trt

	Mean	
fw	11.41	b
sw	18.62	b
rw	22.24	b
so	93.90	a
fo	95.99	a
ro	108.45	a

Analysis of variance

Variate: Fe WP (mg_m^{-3})

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	1.659	0.830	0.49	
rep.*Units* stratum					
Trt	5	109.000	21.800	12.97	<.001
Residual	10	16.807	1.681		
Total	17	127.466			

Information summary

Tables of means

Variate: Fe WP (mg m^{-3})

Grand mean 14.72

Trt	fo	fw	ro	rw	so	sw
	14.52	16.51	11.68	19.06	12.62	13.92

Standard errors of differences of means

Table	Trt
rep.	3
d.f.	10
s.e.d.	1.059

Least significant differences of means (5% level)

Table	Trt
rep.	3
d.f.	10
l.s.d.	2.359

Duncan's multiple range test

Trt

	Mean	
ro	11.68	d
so	12.62	cd
sw	13.92	cd
fo	14.52	bc
fw	16.51	b
rw	19.06	a

Analysis of variance

Variate: Zn WP (mg m^{-3})

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	0.8643	0.4321	0.49	
rep.*Units* stratum					
Trt	5	66.9766	13.3953	15.06	<.001
Residual	10	8.8953	0.8895		
Total	17	76.7362			

Information summary

Tables of means

Variate: Zn WP (mg m^{-3})

Grand mean 7.90

Trt	fo	fw	ro	rw	so	sw
	7.04	7.64	6.35	12.09	6.68	7.63

Standard errors of differences of means

Table	Trt
rep.	3
d.f.	10
s.e.d.	0.770

Least significant differences of means (5% level)

Table	Trt
rep.	3

```
d.f.                          10
l.s.d.                     1.716

Duncan's multiple range test
Trt
            Mean
ro         6.350   b
so         6.679   b
fo         7.038   b
sw         7.629   b
fw         7.637   b
rw        12.089   a

Analysis of variance

Variate: Beta-carotene nutritional yield (NY) (mg ha-1)

Source of variation        d.f.        s.s.        m.s.    v.r.   F pr.

rep stratum                   2   4.836E+08   2.418E+08    0.16

rep.*Units* stratum
Trt                           5   3.622E+11   7.243E+10   48.32   <.001
Residual                     10   1.499E+10   1.499E+09

Total                        17   3.776E+11

Information summary

Tables of means

Variate: Beta-carotene nutritional yield (NY) (mg ha-1)

Grand mean  177371.
```

Trt	fo	fw	ro	rw	so	sw
	419463.	48711.	225576.	43595.	275131.	51750.

Standard errors of differences of means

Table	Trt
rep.	3
d.f.	10
s.e.d.	31613.3

Least significant differences of means (5% level)

Table	Trt
rep.	3
d.f.	10
l.s.d.	70438.7

Duncan's multiple range test

Trt

	Mean	
rw	43595	c
fw	48711	c
sw	51750	c
ro	225576	b
so	275131	b
fo	419463	a

Analysis of variance

Variate: Fe NY (mg ha^{-1})

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	1.167E+07	5.834E+06	0.35	

```
rep.*Units* stratum
Trt                          5   4.745E+09   9.490E+08     56.40    <.001
Residual                    10   1.683E+08   1.683E+07

Total                       17   4.925E+09

Information summary


Tables of means
Variate: Fe NY (mg ha-1)

Grand mean  45212.

         Trt          fo          fw          ro          rw          so          sw
                  63473.      70481.      24289.      37351.      36982.      38696.




Standard errors of differences of means

Table                      Trt
rep.                         3
d.f.                        10
s.e.d.                  3349.3

Least significant differences of means (5% level)

Table                      Trt
rep.                         3
d.f.                        10
l.s.d.                  7462.6

Duncan's multiple range test
```

Trt

	Mean	
ro	24289	c
so	36982	b
rw	37351	b
sw	38696	b
fo	63473	a
fw	70481	a

Analysis of variance

Variate: Zn NY (mg ha^{-1})

```
Source of variation             d.f.        s.s.        m.s.    v.r.  F pr.

rep stratum                        2   10773957.    5386978.    0.70

rep.*Units* stratum
Trt                                5  786884803.  157376961.   20.55  <.001
Residual                          10   76599810.    7659981.

Total                             17  874258570.
```

Information summary

Tables of means

Variate: Zn NY (mg ha^{-1})

Grand mean 23508.

```
     Trt        fo        fw        ro        rw        so        sw
            30756.    32610.    13208.    23694.    19570.    21208.
```

Standard errors of differences of means

Table	Trt
rep.	3
d.f.	10
s.e.d.	2259.8

Least significant differences of means (5% level)

Table	Trt
rep.	3
d.f.	10
l.s.d.	5035.1

Duncan's multiple range test

Trt

	Mean	
ro	13208	c
so	19570	b
sw	21208	b
rw	23694	b
fo	30756	a
fw	32610	a

APPENDIX 2: Beta carotene analysis (20156/2016)

Page **1** of **2**

Enquiries

Mr. Seepe H. Alfred
ARC-VOP
Roodeplaat
Tel: 012 808 8000 Internal: 068450
Email: SeepeH@arc.agric.za

ARC • LNR
Excellence in Research and Development

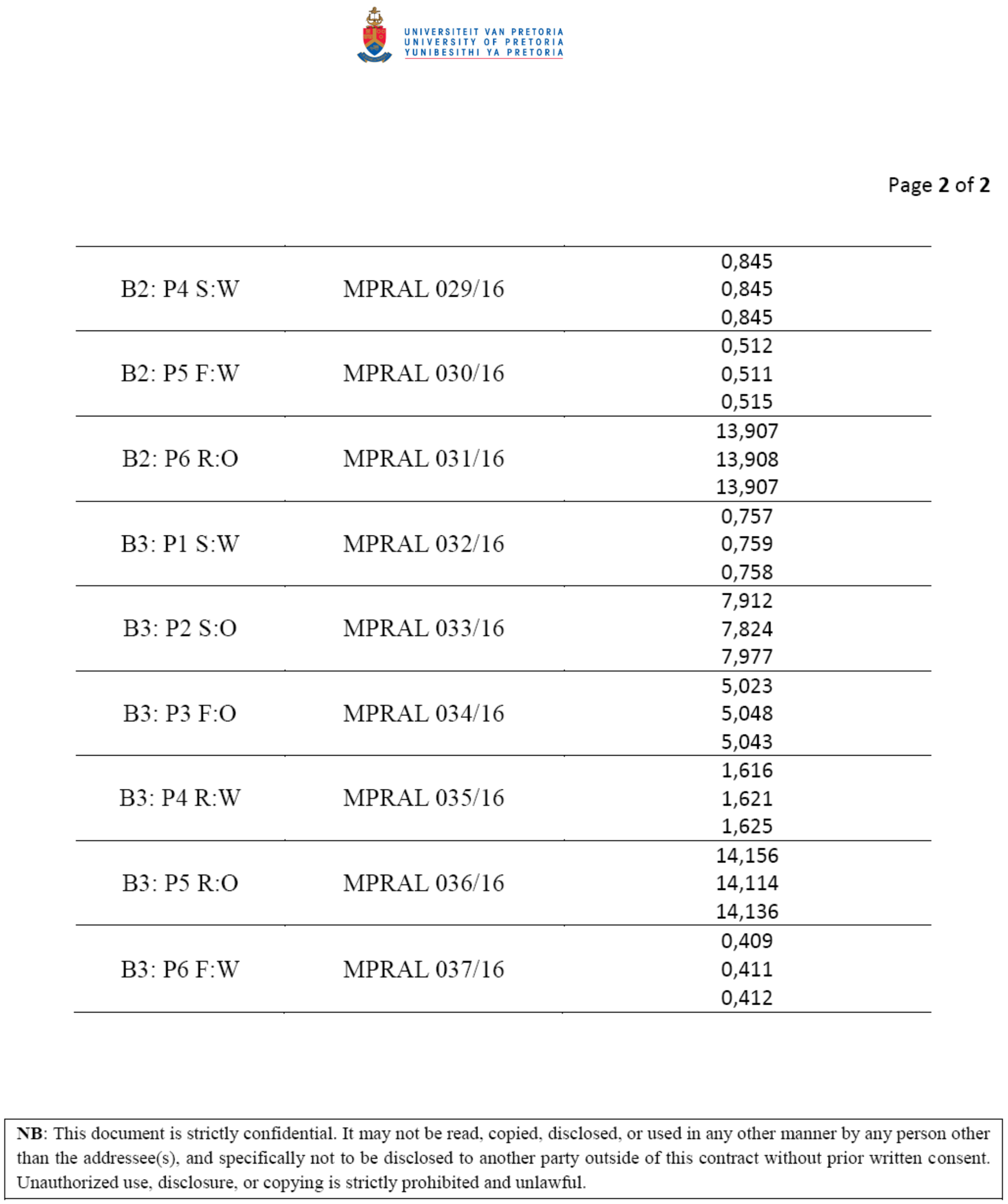
CROP SCIENCES ANALYTICAL LABORATORY

Beta-carotene analysis report for Sweet Potatoes tubers samples

Date of report: 10.01.2017

Description of samples: Dried tubers

Sample name	Laboratory sample code	Beta carotene (mg/100 g sample)
B1:P1 S: O	MPRAL 020/16	6,141 6,145 6,145
B1:P2 F: O	MPRAL 021/16	6,385 6,395 6,396
B1:P3 R: O	MPRAL 022/16	14,109 14,213 15,113
B1: P4 R:W	MPRAL 023/16	1,407 1,407 1,412
B1: P5 F:W	MPRAL 024/16	0,587 0,586 0,589
B1: P6 S:W	MPRAL 025/16	1,152 1,151 1,151
B2: P1 S:O	MPRAL 026/16	6,134 6,127 6,106
B2: P2 F:O	MPRAL 027/16	6,311 6,314 6,323
B2: P3 R:W	MPRAL 028/16	1,160 1,161 1,162



UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Page **2** of **2**

B2: P4 S:W	MPRAL 029/16	0,845 0,845 0,845
B2: P5 F:W	MPRAL 030/16	0,512 0,511 0,515
B2: P6 R:O	MPRAL 031/16	13,907 13,908 13,907
B3: P1 S:W	MPRAL 032/16	0,757 0,759 0,758
B3: P2 S:O	MPRAL 033/16	7,912 7,824 7,977
B3: P3 F:O	MPRAL 034/16	5,023 5,048 5,043
B3: P4 R:W	MPRAL 035/16	1,616 1,621 1,625
B3: P5 R:O	MPRAL 036/16	14,156 14,114 14,136
B3: P6 F:W	MPRAL 037/16	0,409 0,411 0,412

NB: This document is strictly confidential. It may not be read, copied, disclosed, or used in any other manner by any person other than the addressee(s), and specifically not to be disclosed to another party outside of this contract without prior written consent. Unauthorized use, disclosure, or copying is strictly prohibited and unlawful.

APPENDIX 3: Iron and zinc analysis (2015/2016)

ANALYSIS REPORT: ARC - INSTITUTE FOR SOIL, CLIMATE AND WATER (LNR - INSTITUUT VIR GROND KLIMAAT EN WATER)

ARC • LNR

600 Belvedere Street, Arcadia, Pretoria.
Telephone: (012) 310 2500

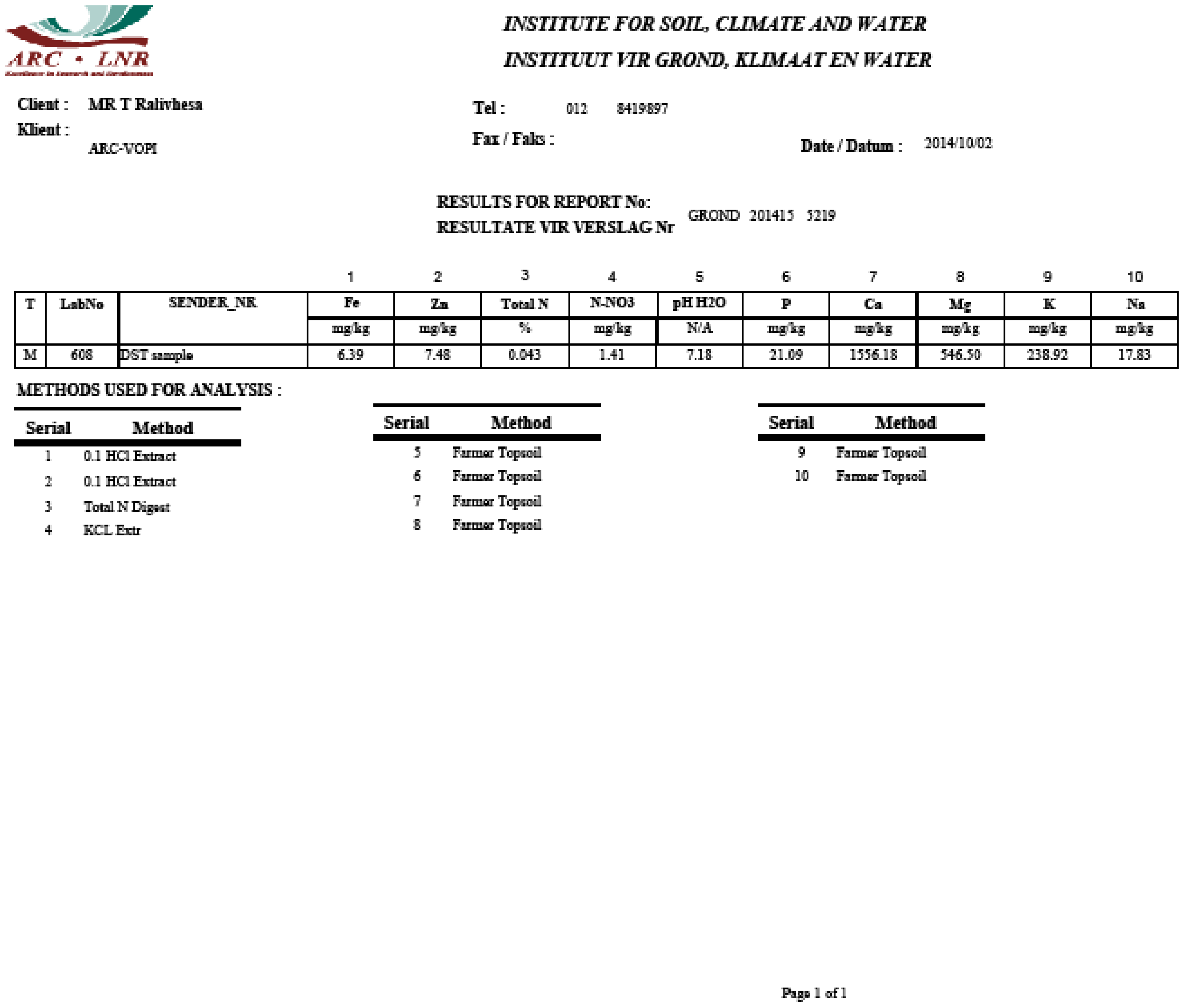
P.Bag X79, Pretoria, 00
Telefax (012) 323 1157

Report Number: PLANT 2016/17-0012

Report on: Analysis of Sweet Potato roots from VOP: Ntsieni Mulovhedzi

Lab No.	**B**	**P**	**Sender No.**	**Fe mg/kg**	**Zn mg/kg**
P137	B1	P1	S:0	8,8	4,2
P138	B1	P2	F:0	8,9	4,3
P139	B1	P3	R:0	14,7	8,4
P140	B1	P4	R:W	11,4	7,7
P141	B1	P5	F:W	7,5	3,1
P142	B1	P6	S:W	6,4	3,5
P143	B2	P1	S:0	9,1	5,7
P144	B2	P2	F:0	9,2	4,1
P145	B2	P3	R:W	12,3	7,3
P146	B2	P4	S:W	6,7	3,6
P147	B2	P5	F:W	7,1	3,6
P148	B2	P6	R:0	15,8	8,3
P149	B3	P1	S:W	7,3	4,1
P150	B3	P2	S:0	9,1	4,2
P151	B3	P3	F:0	8,6	4,4
P152	B3	P4	R:W	11,9	7,6
P153	B3	P5	R:0	15,1	8,5
P154	B3	P6	F:W	7,1	3,3

APPENDIX 4: Soil chemical analysis results (2014/2015 and 2015/2016)



ARC • LNR

INSTITUTE FOR SOIL, CLIMATE AND WATER

INSTITUUT VIR GROND, KLIMAAT EN WATER

Client : **MR T Ralivhesa**
Klient :
ARC-VOPI

Tel : 012 8419897
Fax / Faks :

Date / Datum : 2014/10/02

RESULTS FOR REPORT No:
RESULTATE VIR VERSLAG Nr GROND 201415 5219

			1	2	3	4	5	6	7	8	9	10
T	**LabNo**	**SENDER_NR**	**Fe**	**Zn**	**Total N**	**N-NO3**	**pH H2O**	**P**	**Ca**	**Mg**	**K**	**Na**
			mg/kg	mg/kg	%	mg/kg	N/A	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
M	608	DST sample	6.39	7.48	0.043	1.41	7.18	21.09	1556.18	546.50	238.92	17.83

METHODS USED FOR ANALYSIS :

Serial	**Method**
1	0.1 HCl Extract
2	0.1 HCl Extract
3	Total N Digest
4	KCL Extr

Serial	**Method**
5	Farmer Topsoil
6	Farmer Topsoil
7	Farmer Topsoil
8	Farmer Topsoil

Serial	**Method**
9	Farmer Topsoil
10	Farmer Topsoil

Page 1 of 1

ARC • LNR

INSTITUTE FOR SOIL, CLIMATE AND WATER

INSTITUUT VIR GROND, KLIMAAT EN WATER

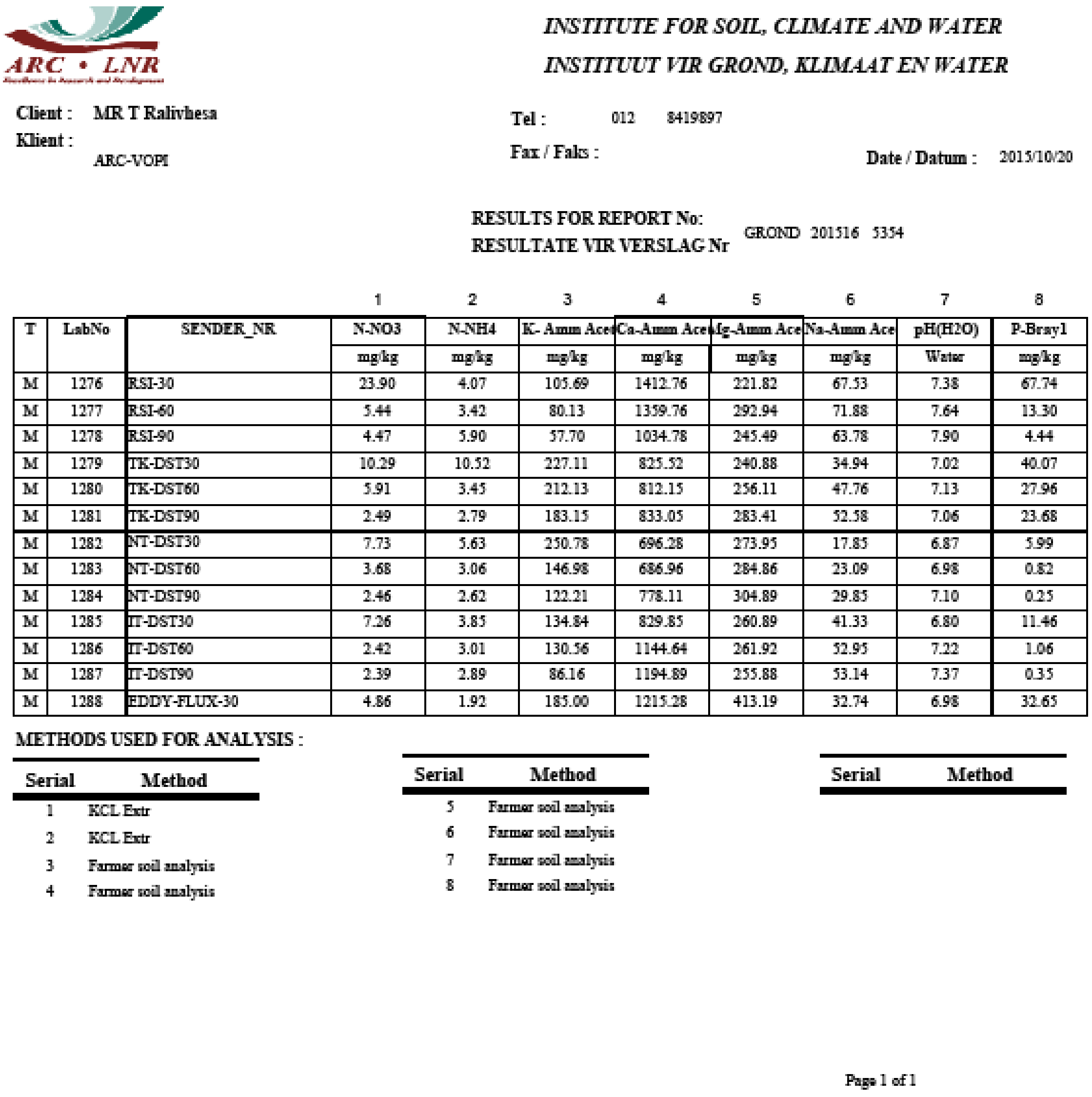
RESULTS FOR REPORT No:
RESULTATE VIR VERSLAG Nr: GROND 201415 5219

Client : **MR T Ralivhesa**
Klient :
ARC-VOPI

Tel : 012 8419897
Fax / Faks :
Date / Datum : 2014/10/02

PARTICLE SIZE DISTRIBUTION - 3 FRACTION / DEELTJIEGROOTTE VERSPREIDING

			SAND	SILT	CLAY
LabNo		**Sender ID**	%	%	%
M	608	DST sample	54.0	12.0	34.0



ARC • LNR

INSTITUTE FOR SOIL, CLIMATE AND WATER

INSTITUUT VIR GROND, KLIMAAT EN WATER

Client : MR T Ralivhesa
Klient :
ARC-VOPI

Tel : 012 8419897
Fax / Faks :

Date / Datum : 2015/10/20

RESULTS FOR REPORT No:
RESULTATE VIR VERSLAG Nr GROND 201516 5354

			1	2	3	4	5	6	7	8
T	LabNo	SENDER_NR	N-NO3	N-NH4	K- Amm Acet	Ca-Amm Acet	lg-Amm Ace	Na-Amm Ace	pH(H2O)	P-Bray1
			mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	Water	mg/kg
M	1276	RSI-30	23.90	4.07	105.69	1412.76	221.82	67.53	7.38	67.74
M	1277	RSI-60	5.44	3.42	80.13	1359.76	292.94	71.88	7.64	13.30
M	1278	RSI-90	4.47	5.90	57.70	1034.78	245.49	63.78	7.90	4.44
M	1279	TK-DST30	10.29	10.52	227.11	825.52	240.88	34.94	7.02	40.07
M	1280	TK-DST60	5.91	3.45	212.13	812.15	256.11	47.76	7.13	27.96
M	1281	TK-DST90	2.49	2.79	183.15	833.05	283.41	52.58	7.06	23.68
M	1282	NT-DST30	7.73	5.63	250.78	696.28	273.95	17.85	6.87	5.99
M	1283	NT-DST60	3.68	3.06	146.98	686.96	284.86	23.09	6.98	0.82
M	1284	NT-DST90	2.46	2.62	122.21	778.11	304.89	29.85	7.10	0.25
M	1285	IT-DST30	7.26	3.85	134.84	829.85	260.89	41.33	6.80	11.46
M	1286	IT-DST60	2.42	3.01	130.56	1144.64	261.92	52.95	7.22	1.06
M	1287	IT-DST90	2.39	2.89	86.16	1194.89	255.88	53.14	7.37	0.35
M	1288	EDDY-FLUX-30	4.86	1.92	185.00	1215.28	413.19	32.74	6.98	32.65

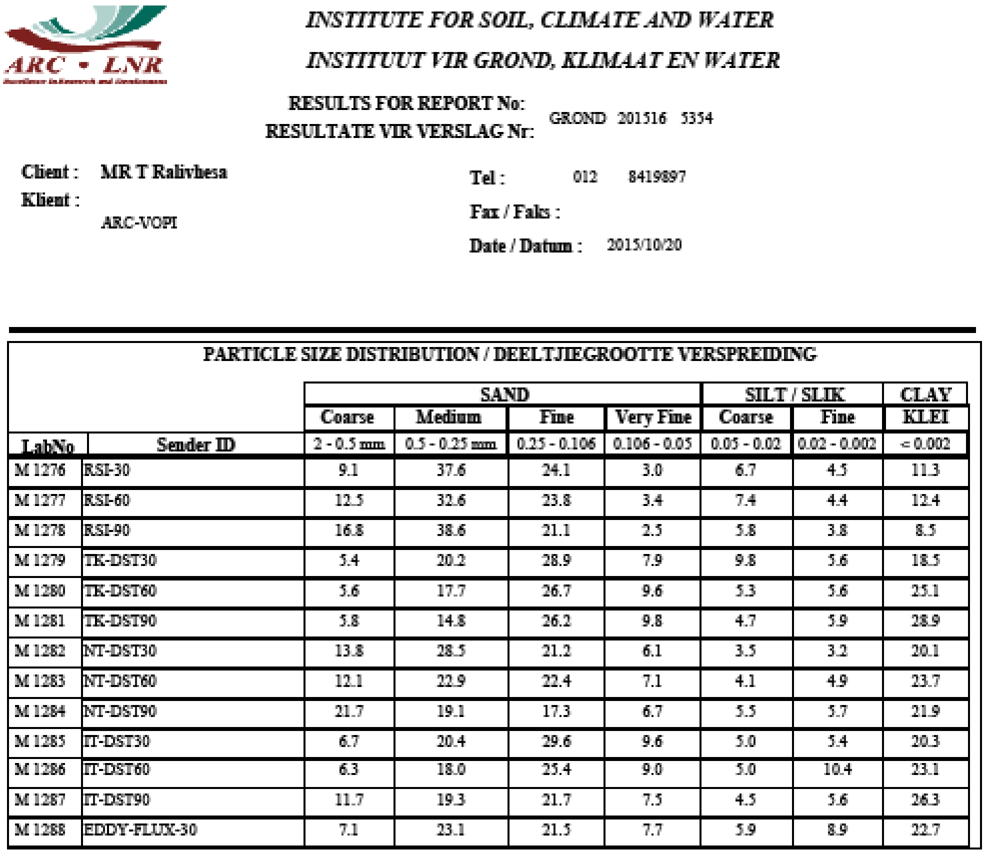
METHODS USED FOR ANALYSIS :

Serial	Method
1	KCL Extr
2	KCL Extr
3	Farmer soil analysis
4	Farmer soil analysis

Serial	Method
5	Farmer soil analysis
6	Farmer soil analysis
7	Farmer soil analysis
8	Farmer soil analysis

Serial	Method

Page 1 of 1



INSTITUTE FOR SOIL, CLIMATE AND WATER

INSTITUUT VIR GROND, KLIMAAT EN WATER

RESULTS FOR REPORT No:
RESULTATE VIR VERSLAG Nr: GROND 201516 5354

Client : **MR T Ralivhesa**
Klient :
ARC-VOPI

Tel : 012 8419897
Fax / Faks :
Date / Datum : 2015/10/20

PARTICLE SIZE DISTRIBUTION / DEELTJIEGROOTTE VERSPREIDING

		SAND				SILT / SLIK		CLAY
		Coarse	Medium	Fine	Very Fine	Coarse	Fine	KLEI
LabNo	Sender ID	2 - 0.5 mm	0.5 - 0.25 mm	0.25 - 0.106	0.106 - 0.05	0.05 - 0.02	0.02 - 0.002	< 0.002
M 1276	RSI-30	9.1	37.6	24.1	3.0	6.7	4.5	11.3
M 1277	RSI-60	12.5	32.6	23.8	3.4	7.4	4.4	12.4
M 1278	RSI-90	16.8	38.6	21.1	2.5	5.8	3.8	8.5
M 1279	TK-DST30	5.4	20.2	28.9	7.9	9.8	5.6	18.5
M 1280	TK-DST60	5.6	17.7	26.7	9.6	5.3	5.6	25.1
M 1281	TK-DST90	5.8	14.8	26.2	9.8	4.7	5.9	28.9
M 1282	NT-DST30	13.8	28.5	21.2	6.1	3.5	3.2	20.1
M 1283	NT-DST60	12.1	22.9	22.4	7.1	4.1	4.9	23.7
M 1284	NT-DST90	21.7	19.1	17.3	6.7	5.5	5.7	21.9
M 1285	IT-DST30	6.7	20.4	29.6	9.6	5.0	5.4	20.3
M 1286	IT-DST60	6.3	18.0	25.4	9.0	5.0	10.4	23.1
M 1287	IT-DST90	11.7	19.3	21.7	7.5	4.5	5.6	26.3
M 1288	EDDY-FLUX-30	7.1	23.1	21.5	7.7	5.9	8.9	22.7

APPENDIX 5: Developed relationship between volumetric water content (θ) measured with a neutron probe and soil water potential (ψ) measured with Chameleon soil moisture sensors. Soil depth used for calculations was 0.3 m

Scenarios	Soil profile water content (mm)	Chameleon colours (ψ)		Deficit to field capacity (mm)	Treatments
		0.15 m	0.30 m		
A	240–250	Blue	Blue	<10	No irrigation
B	233–239	Blue or Green	Green Blue	11–17	FI
C	220–233	Green	Green	18–30	
D	205–219	Blue or Red	Red Blue	31–45	
E	190–205	Green or Red	Red Green	45–60	
F	180–189	Red	Red	>60	SI