Water use efficiency of orange fleshed sweet potato

(*Ipomoea batatas* L. Lam.)

by

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DECLARATION

I, **Steve Masango**, 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.

Signed: ___________________________

Steve Masango

Date: July 2014

Place: Pretoria

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DEDICATION

In loving memory of my late:

twin brother STEVEN,

my Dad PHILLEMON &;

my Mom CHRISTINA

From thee I draw inspiration in challenging times

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ABSTRACT

The objectives of this research were to assess the yield response of orange fleshed sweet potato to water supply at different frequencies; to evaluate how beta carotene content and nutritional water productivity of orange fleshed sweet potato will be affected by water supply at different frequencies and; to calibrate and validate the Soil Water Balance (SWB) model for orange fleshed sweet potato.

A field trial was established in December 2011 at the University of Pretoria experimental Farm (Hatfield, Gauteng Province), under a rainshelter. The trial comprised of four irrigation regimes namely, T_{tw} (irrigated twice a week), T_{ow} (irrigated once a week), T_{otw} (irrigated once in two weeks) and T_{dryl} (rain and supplemental irrigation dependent). T_{dryl}, an independent field block, was established outside the rain shelter. Growth and yield analyses were carried out during the growing season. Irrigation was applied to field capacity (FC), depending on water required by each treatment, as determined with a neutron probe three times in a week.

Water use ranged between 298 mm (T_{dryl}) and as high as 478 mm (T_{tw}). Water use efficiency (WUE) (fresh mass basis) ranged from 64.8 kg ha^{-1} mm^{-1} to 97.5 kg ha^{-1} mm^{-1}. The results indicated that the less frequently watered treatments (T_{otw} and T_{dryl}) had the highest WUE. Generally, the total water use and WUE was within the values reported by other authors on sweet potato water use studies. Storage root yield of T_{ow} (6.5 t ha^{-1}) and T_{otw} (6.6 t ha^{-1}) were significantly lower compared to T_{tw} (7.1 t ha^{-1}) and T_{dryl} (7.6 t ha^{-1}). Harvest Index (HI) and total dry mass (TDM) was also determined. HI values ranged from 52 to 59 %. Beta carotene content of T_{dryl} (119.53 µg g^{-1}) as well as nutritional water productivity (1177 mg m^{-3}) was higher but not statistically different from the other treatments. The SWB model simulations revealed that Total dry matter (TDM), Harvestable dry matter (HDM), Leaf area index (LAI), Soil water deficit (SWD) and Fractional Interception (FI) compared reasonably well with measured data. The model can therefore be a useful tool for scenario modelling to assess the yield and water requirements of sweet potatoes in different environments.

Key words: beta carotene, harvest index, nutritional water productivity, orange fleshed sweet potato, storage root yield, total dry mass, water use efficiency.

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LIST OF ABBREVIATIONS AND SYMBOLS

∆SWC	Change in soil water storage
µg	Microgram
ARC	Agricultural Research Council
CDM	Canopy dry matter
DAP	Days after planting
Dr	Drainage
DWR	Dry matter-water ratio
ET	Evapotranspiration
ET_o	Reference evapotranspiration
FAO	Food and Agriculture Organisation
FI	Fractional interception
g	gram
Ha	Hectare
HI	Harvest index
I	Irrigation
K_c	Crop coefficient
K_s	Soil coefficient
kg	kilogram
kg/ha	kilograms per hectare
kJ	KiloJoules
kPa	Kilopascals
$\ell\ hr^{-1}$	litres per hour
LA	Leaf area

LAI	Leaf area index
LDM	Leaf dry mass
m	metre
m^2	metre square
m^2/m^2	metre square per metre square
mg	milligrams
mJ/m^2	milliJoules per metre square
mm	millimetres
MRC	Medical Research Council
OFSP	Orange fleshed sweet potato
P	Precipitation
PAR	Photosynthetically active radiation
PART	Stem-Leaf partitioning parameter
r	Run off
R	Solar radiation
RCBD	Randomized complete block design
RDM	Roots dry mass
SABS	South African Bureau for Standards
SAS	Statistical analysis system
SDM	Stem dry matter
SLA	Specific leaf area
SRY	Storage root yield
SWB	Soil water balance
t	ton
T_{tw}	Irrigation application twice in a week

T_{ow}	Irrigation application once in a week
T_{otw}	Irrigation application once in two weeks
T_{dryl}	Rain and supplemental irrigation dependent
TDM	Total dry matter
Tmax	Maximum temperature
Tmin	Minimum temperature
U	Wind speed at 2m height
VAD	Vitamin A deficiency
VDM	Vine dry mass
VPD	Vapour pressure deficit
WAP	Weeks after planting
WUE	Water use efficiency
β	Beta
ε	Epsilon

CHAPTER ONE

GENERAL INTRODUCTION

Orange fleshed sweet potato (OFSP) is an important crop in most developing countries. The increasing importance of this crop is mainly due to its relatively high yield output across a range of environments (Hagenimana & Low, 2000). It is predominantly a food security crop, as it offers essential nutritional value (Yanggen and Nagujja, 2006). The orange fleshed sweet potato has especially high levels of vitamin A, compared to ordinary white of cream fleshed sweet potatoes (Stathers *et al*., 2005).

Consumption of orange fleshed sweet potato has been shown to improve vitamin A status in children, due to its provision of natural β-carotene (van Jaarsveld *et al*., 2005). In sub Saharan African countries, including South Africa the orange fleshed sweet potato is already being promoted to combat vitamin A deficiency through community-based interventions (Kapinga *et al*., 1995; Laurie & Faber, 2008).

Sweet potato is often cultivated on communal land with marginal soils and limited irrigation water. South Africa has an average rainfall of approximately 497 mm; and this low rainfall is unevenly distributed (King *et al*, 2008). It is aggravated by climatic variation and makes the country more vulnerable to water shortages. This threatens food security and agricultural production (FAO, 2003).

Sweet potato is reported to be sensitive to both shortages and excess of water. In regions where rainfall is erratic, and during prolonged dry seasons, growers often plant sweet potato in areas where it can exploit residual soil water. During the rainy season, yield losses sometimes occur due to excessive soil water. In other areas, yields are reduced as a result of periods without rain (Gomes & Carr, 2003). Drought stress is detrimental during the crop establishment and storage root filling phases, as it alters the sink-source relationship by affecting photosynthate production, translocation and partitioning (Ekanayake, 2004). Generally, prolonged dry periods in the growing season reduce yield, root quality, and ultimately causes total crop failure, in some instances (FAO, 2003).

In South Africa, small holder farmers make up the majority of the country's rural poor; they often occupy marginal land and depend mainly on rainfall for crop production. Some small holder farmers successfully cultivate the sweet potato as an irrigated crop. However, little is known about the water requirements of specifically orange fleshed sweet potatoes, or its yield response to water supply (Gomes & Carr, 2003). Lack of information on the influence of water application levels on the β-carotene (the precursor of vitamin A) content of orange fleshed sweet potato is another major challenge for smallholder farmers (Laurie *et al*., 2012). To attain optimal production, the rural poor ought to be empowered with knowledge that will enable higher productivity.

Plants transpire several hundreds of times more water than is present in their tissues at any time. Under rainfed conditions, soil water may be lost through plant uptake and subsequently lost via stomata on plant leaves or from the soil surface through evaporation (Fletcher *et al*., 2007). This may result in a reduction in photosynthesis, total dry matter accumulation and yield, depending on time duration and severity of water loss. According to Doorenbos and Kassam (1979), to improve crop yield, not more than fifty percent of the total plant available soil water should be depleted. Growing more crop per drop of water use is therefore crucial to mitigate water shortages. This can be accomplished by advancing our understanding of the physiology of the plant and implementing current scientific knowledge to improve water use efficiency in agricultural production.

According to De Pascale *et al.* (2011), water use efficiency is the ratio of biomass accumulation, expressed as carbon dioxide assimilation, to water consumed by the plant, expressed as transpiration and evapotranspiration, over the growing season. Improving water use efficiency, especially in arid and semi-arid areas, depends on effective conservation of soil water and efficient use of limited water resources. In future, improving water use efficiency by forty percent on rainfed and irrigated lands will be required to compensate the need for additional withdrawals of irrigation to meet the demand for food production (Doorenbos & Kassam, 1979). Many researchers have acknowledged the importance of increasing crop productivity by means of increasing water use efficiency (Molden, 1997; De Pascale *et al*., 2011).

This study was conducted to assess the effects of different irrigation water management strategies on storage root yield, water use efficiency and nutritional water productivity of one orange fleshed sweet potato cultivar (Resisto) that is highly preferred by South African communities (Faber *et al.,* 2002). This knowledge will enable us to forecast the growth, yield and water requirements of this orange fleshed sweet potato cultivar under different environments.

The overall objectives of this study were as follows:

a. To assess the yield response of orange fleshed sweet potato to water supply at different frequencies.

b. To evaluate how β-carotene content and nutritional water productivity of orange fleshed sweet potato will be affected by water supply at different frequencies.

c. To calibrate and validate the Soil Water Balance model for orange fleshed sweet potato to enable accurate water use estimation under a range of conditions and for different environments.

CHAPTER TWO

LITERATURE REVIEW

2.1 Sweet potato

Sweet potato is an indeterminate, creeping dicotyledonous plant that belongs to the order of *Solanales*; under the family *Convolvulaceae* in the genus *Ipomoea* (Bovell-Benjamin, 2007). The world's average production of sweet potato is about 14.8 tons ha^{-1} (Assefa *et al*., 2007). Sweet potato ranks third in terms of world root and tuber crops after cassava and yam; and is considered as an important source of food (Yanggen & Nagujja, 2006). It is one of the most efficient food crops in terms of supplying substantial amounts of vitamins and minerals (Leighton, 2007).

Sweet potato is a hardy crop that has a relatively low demand for soil nutrients, with a growing season ranging from 90 to 360 days, depending on the cultivar grown (CIAD *et al*., 1996). In temperate areas of South Africa, sweet potato is planted between November and January; and harvested between May and October. In warmer areas, planting takes place in August and harvesting in November or January (Van den Berg *et al*., 2004)

A single sweet potato plant may produce up to 50 roots, with a length of up to 30 centimetres, weighing between 100g and 1000g (CIAD *et al*., 1996). There is a general observation that sweet potato roots can support more people per unit cropped area per unit time (Belehu, 2003). Leaves of the sweet potato are dark green and have nutritive values needed for human consumption (Ishida *et al*., 2000).

Sweet potato crop is very unique when it comes to adaptability. It is a drought tolerant crop, with a wide adaptability to various climates and farming systems (Low *et al*., 2000).

Practically, most production and consumption of sweet potato occur in developing countries (Khoury *et al*., 2014). In Africa, sweet potato cultivars commonly have white, cream or yellow flesh; while few are orange fleshed cultivars. Whereas white to yellow fleshed sweet potatoes have been reported to contain little or no provitamin A; the orange fleshed sweet potato cultivars contain good quantities of provitamin A, predominantly as β-carotene (Stathers *et al*., 2005). Promotion of consumption of locally available vitamin A-rich crops, which can be grown in home gardens, holds a promising future in many African countries; as they are practically possible to grow and are inexpensive (Low *et al*., 2000).

In South Africa, sweet potato crop can be produced in all the provinces. Major production areas include Limpopo (Marble Hall, Burgersfort and Levubu); Mpumalanga (Nelspruit); KwaZulu-Natal and the Western Cape provinces (Laurie & Van der Berg, 2004). From 2001 to 2003, the Agricultural Research Council (at Roodeplaat) conducted a survey on seven provinces of South Africa identified as major sweet potato growing areas. It was discovered that most of the households growing sweet potato for subsistence purposes regarded it as the third most vital source of food (Domola, 2003).

In African countries such as Uganda, Rwanda and Burundi where sweet potato is the staple food; consumption per capita is between 75 to 150 kg per year. In Malawi, Angola, DRC and Mozambique the sweet potato is considered as an additional food crop, after maize; and per capita consumption is about 5 to 50kg per person annually (Minde *et al*., 1996). The decrease in diversity of crop species contributing to the world's food supplies is gradually is becoming a potential threat to food security (Khoury *et al.,* 2014). Genetic pool of sweet potato crop, as an alternative crop to food security in Sub-Saharan Africa must therefore be preserved.

Until recently, there was rather a little consideration to using orange fleshed sweet potato as means to combat vitamin A deficiency in sub Saharan Africa. This was attributed to (a) limited support for sweet potato improvement programs; (b) limited understanding of the crop by crop researchers and farmers; (c) lack of information on the extent of vitamin A deficiency problem in Africa and the potential of orange fleshed sweet potatoes to help to improve the crisis; (d) perception by researchers that consumer preference for high root dry matter content could prevent the adoption of orange fleshed cultivars (Hagenimana *et al*., 2001), and/or (e) the lack of awareness in identifying orange fleshed cultivars with high dry matter content in the local germplasm or through breeding of new varieties (Von Oirschet, 2003)

2.1.1 Acceptability

Introduction and adoption of the orange fleshed sweet potato in regions where white fleshed sweet potato is traditionally dominant could be challenging. In South Africa, the white fleshed sweet potato is frequently consumed; and in some rural areas women cultivate the white flesh cultivar on small backyard plots as a food security crop. The white fleshed cultivar, however, contains insignificant quantities of the β-carotene; as a result it cannot contribute to the alleviation of Vitamin A Deficiency (Hagenimana *et al.*, 2001).

The Medical Research Council (MRC) of South Africa and the Agriculture Research Council (ARC) promoted the production of β-carotene rich foods; and home-based food production programme was launched at Kwa-Zulu Natal Province (Faber *et al*., 2002). Vigorous attempts to promote β-carotene contributed to the successful acceptance of the orange fleshed sweet potato cultivar. A study conducted in South Africa on nutrient and sensory quality of orange fleshed sweet potato cultivar, has proven successful in way that eighty five percent of the participants preferred the taste of orange fleshed sweet potato to that of the white fleshed sweet potato. Eighty six percent of consumers indicated willingness to buy the orange fleshed sweet potato if it was on the market (Leighton *et al.,* 2007).

In 1999, efforts to introduce the orange fleshed sweet potato at Central Uganda have proven to be successful. Overall, 43.5 % of all farmers that participated in the study ranked orange and yellow fleshed sweet potatoes as superior;

26 % ranked orange fleshed sweet potato inferior; and 30.5 % ranked it as similar to other cultivars (Tumwegamire, 2004). In Kenya, an action research project was implemented by the Kenya Agricultural Research Institute (KARI), in collaboration with Centro Internacional dé la Papa and CARE International to promote adoption of the early maturing orange fleshed cultivars. Results demonstrated that orange fleshed sweet potato cultivars were highly acceptable to producers and consumers, both when eaten alone and when used as ingredients in processed foods. Taste tests revealed that adults preferred the varieties with a high content of dry matter (greater than 27 percent), whereas children preferred weaning foods made from the varieties with low content of dry matter. The orange colour of the flesh is, thus, not in itself a barrier to acceptance (Low *et al*., 2000).

2.1.2 Classification of sweet potato according to flesh colour

Sweet potato flesh have a variety of colours. Generally, there is white, light-pink, dark-purple, red and cream, orange and yellow fleshed sweet potatoes (Leighton *et al*, 2007).

The two most common flesh colours are white and orange. Apart from the difference in the colour of the skin, there several specific differences with these sweet potatoes. White fleshed sweet potato is considered to be sweeter relative to the orange fleshed sweet potato; the orange sweet potato is known to contain more beta-carotene than the white sweet potato.

The white sweet potato has a softer skin compared to orange sweet potato. Unlike the white sweet potato, the orange sweet potato has a harder and solid texture. The orange sweet potato is dark skinned than the white sweet potato.

2.1.3 Sweet potato morphology

a. Above ground parts

The above ground part is made up of leaves and vines. Total number of leaves per plant varies from 60 to 300; and the leaves come in different shapes (Somda *et al*., 1991). Sweet potato genotype is made up of diverse classes of leaves ranging from erect, bushy, and intermediate to spreading; based on the length of the vines (Kays, 1985).

Leaves are rich in vitamin B, β-carotene, iron, calcium, zinc, and protein. A number of researchers have reported anti-oxidative and radical scavenging activities of sweet potato leaves (Ishiguro *et al*., 2004). In some parts of Africa and Japan, the leaves are eaten mainly for protein content that has been reported to be as high as 27 % on dry weight basis (Diop, 1998). The leaves and vines can yield between 20 to 80 tons per hectare (Laurie & van den Berg, 2004). Leaf petioles and vines provide channels to translocate carbohydrates throughout the plant.

Vines form a shallow and horizontal canopy that results into the crop growing very fast; covering a large ground area; thereby rapidly maximising interception of incoming solar radiation. Some cultivars also have stems with twining characteristics. The stems of erect cultivars are approximately 1 metre long, while the spreading stems can be more than 5 metres long (Huaman, 1992). The stem colour can be green, partially purple or entirely purple due to the presence of anthocyanin and cultivar type.

b. Root System

The root system absorbs water and nutrients (Waisel & Eshel, 2009). It also acts as the anchor of the plant. The root system absorbs excess energy not needed by the plant for maintenance and structural development, in a form of carbohydrates (Woolfe, 1992).

The sweet potato plant is made up of three root types, viz; fibrous, pencil and storage roots. When it is planted from stem cuttings, especially in moist soils, the sweet potato adventitious roots develop within few days (Laurie & Niederwieser, 2004). These roots grow rapidly and form fibrous roots. Fibrous roots are commonly less than 5 mm in diameter and may penetrate the soil to a depth of up to 1 metre. The deep penetration enables the plant to survive drought conditions as a result of the roots being capable to obtaining water from deeper layers of the soil (Onwueme & Charles, 1994).

Pencil roots develop from young thick adventitious roots under conditions such as soil compaction and drought, which are not conducive for the development of the storage roots (Bok, 1998). These are fairly thickened and lignified roots with a diameter of less than 2 centimetres (cm) (Loebenstein & Thottappilly, 2009). It is suggested that favourable conditions be maintained at the early stages of the growing season to encourage as many thick roots as possible to develop into potential storage roots (Laurie & Niederwieser, 2004).

The storage roots develop as a result of young adventitious roots differentiating into young thick roots. The initial sign of storage roots development is characterised by the accumulation of the photosynthates consisting mainly of starch (Chua & Kays, 1982). Under adequate moisture, air and mineral conditions, the young thick roots undergo secondary growth to form storage roots within the top 20 to 25 centimetres of the soil (Kays, 1985). Between 8 to 12 weeks after planting, the plant ceases to form new storage roots (Du Plooy, 1989). After this period, all the energy is channelled to the bulking of the storage roots.

2.1.4 Agro-climatic factors affecting growth and yield of sweet potato

Sweet potato storage root growth and yield are a result of agro-climatic conditions. In contrast to cereal grains, sweet potato storage roots can undergo periods of arrested growth during adverse climatic conditions and then proceed to grow when conditions improve (Ravi *et al*., 2009).

a. Soil water

The sweet potato crop performs best in regions where rainfall range from 750 to 1000 mm per annum. Average rainfall of 500 mm during the growing season is; otherwise; acceptable. The crop is considered fairly tolerant to drought conditions due to its low plant growth habit and the extensive root system (Belehu, 2003). Although sweet potato is a moderately drought tolerant crop, the plant is sensitive to water deficit, mainly during the establishment phase, including early vine development and storage root initiation (Gajanayake *et al*., 2013)

Water stress at early season is detrimental for sweet potato growth and development affecting final yield (Gajanayake *et al*, 2014). As the crop continue to grow, crop water requirement changes. Low water availability and dry spells retard storage root growth and yield may decrease significantly. This is common especially at the beginning of storage root formation (Thompson *et al*., 1992).

Jones *et al*. (1985) evaluated yield response of sweet potatoes to drought stress at various growth stages and found that water stress initiated at 30 days after planting resulted into significantly higher total root yield. It would have been apt to evaluate this finding. The current project applied it treatment from 79 days after planting due to some unforeseen circumstances.

During storage root initiation, sweet potato is intolerant to waterlogging, therefore, good drainage of the soil is essential (Belehu, 2003).

In the case of excess soil water, shoot growth may be good, but storage root formation could be poor, resulting into excess top growth (Laurie & Niederwieser, 2004). At harvest, wet soils cause increase in root rot and yield is affected adversely.

b. Temperature

Night temperatures between 15 and 25^{o}C encourage formation and growth of storage root. Night air temperatures between 14 and 22^{o}C may result in maximum sweet potato yield (Negeve *et al*., 1992). According to Du Plooy (1989) night air temperatures higher than 25^{o}C restrict tuber formation and promote shoot growth. Night air temperatures below 15^{o}C suppress storage root formation, growth and yield (Negeve *et al*., 1992). The higher temperatures above 28^{o}C divert photosynthates partitioning toward the fibrous roots than to storage roots (Eguchi *et al*., 2003). Cooler night air temperatures, ranging between 11.3 and 26.4°C (Mukhopadhyay *et al*., 1992) and irrigation at 5 to 13 week of growth period significantly increases the bulking rate of storage roots (Goswami *et al.,* 1995).

Soil temperatures between 20^{o}C and 30^{o}C support storage root formation and growth while soil temperature of 15^{o}C promotes fibrous root formation. Soil temperatures greater than 30^{o}C promote shoot growth (Spence & Humphries, 1972).

Sucrose content in the stem and the roots become lower at 20^{o}C soil temperature than at high temperatures (30^{o}C).

This implies that greater conversion of sucrose to starch in the storage root, at cooler soil temperature favours storage root development.

c. Frost

Sweet potato grows best between 20 and 30°C. A minimum frost free growing season of 4 to 6 months is desirable with cool (minimum), cloudy weather. Plant growth is restricted below 10°C and plants are physically damaged at 1°C (Spence & Humphries, 1972).

In cold regions of South Africa, it is important that planting of vines is established at least two months before the first frost. As frost begins, it is essential that irrigation is suspended to reduce chances of top growth dying earlier than expected; otherwise tuber rotting could be severe. In areas with light frost, planting may be initiated early October. Yield and quality of sweet potato crops established in January or February are usually poor due to the timing of planting.

2.2 Nutritional value of the sweet potato

Sweet potato has a huge role in human nutrition, food security and poverty alleviation, especially in developing countries because of its nutritional composition and unique agronomic features (Bovell-Benjamin, 2007). The crop is valuable in addressing vitamin A deficiency (VAD); which is a severe public health problem in many developing countries, including South Africa (Woolfe, 1992).

A study conducted by Khoury *et al*. (2014), examining how national food supplies changed over the past 50 years, reported that there was a decrease in demand for important root crops such as cassava, sweet potato; and yam crops, as a result of dietary changes of about 98% of the world population. Lack of information on nutritional composition of these crops may be another resulting factor (Kays, 2005).

Sweet potato is rich in carotenoids (especially β-carotene), proteins, carbohydrates, minerals (calcium, iron, and potassium), dietary fiber, vitamins (especially C, folate, and B6), antioxidants (such as phenolic acids), anthocyanins, tocopherol and sodium (Woolfe, 1992).

Orange fleshed sweet potato contributes 28 percent of vitamin C, 13 percent calcium, 15 percent magnesium and 75.6 percent zinc which is required by children between 4 and 8 years of age in their daily diets (Leighton, 2007).

In some parts of West, Central and East Africa, orange fleshed sweet potato is regarded an important source of calories (Hagenimana *et al*., 1998). In China, Vietnam, Korea and Taiwan, and the Philippines sweet potato is an important source of starch (Collado *et al*., 1999). According to Woolfe (1992), sweet potato dry matter consists of approximately 70 percent starch.

The storage roots have average contents of minerals and vitamins in the recently developed sweet potato cultivar 'Suioh' are 117 milligrams (mg) calcium, 1.8 mg iron, 3.5 mg carotene, 7.2 mg vitamin C, 1.6 mg vitamin E, and 0.56 mg vitamin K per 100 g fresh weight basis. In Korea, sweet potato leaves are valued as a tasty vegetable. In many parts of Mozambique, up to twenty-three percent of the Mozambican population consume sweet potato leaves at least once a week (Low *et al*., 2000).

a. Carotenoids

Carotenoid pigments are regarded as fundamental components in all photosynthetic organisms (Britton *et al*., 2004). These are isoprenoid molecules common in all photosynthetic tissues; and are divided into the hydrocarbon carotenes, such as lycopene, β-carotene and xanthophyll (Bramley, 2002). The carotenoids are mainly 40-carbon isoprenoids, which consist of eight isoprene units.

More than 700 naturally occurring carotenoids have been identified (Britton *et al*., 2004). In the chloroplast, carotenoids assist in harvesting light energy; and protect the photosynthetic apparatus against harmful reactive oxygen species by quenching the triplet chlorophylls, superoxide anion radicals and singlet oxygen (Niyogi, 1999).

In the sweet potato plant, carotenoid pigments are responsible for the cream, yellow and the orange flesh colour of the root (Woolfe, 1992). The yellow and orange colour of sweet potato cultivars indicate high β-carotene content, whereas white cultivars may contain little or no β-carotene (Ameny & Wilson, 1997).

Carotenoids, other than β-carotene, identified in the orange fleshed sweet potato, include alpha, zeta and gamma carotenes, phytoene and phytofluence (Young, 2001). These carotenes contribute more or less one percent of the total carotenoids.

In several white fleshed cultivars, either β-zeacarotene or neurosporene dominates (Woolfe, 1992). The importance of the β-carotene and other active carotenes is characterised by the provitamin A activity (Mazuze, 2007). The provitamin A carotenoids are enzymatically converted in the intestinal mucosa of human body to give up the retinal and eventually the retinol (Faber *et al.,* 2001). The retinol (vitamin A) is essential for vision, maintenance of differentiated epithelia, mucus secretion, and reproduction in humans (Mayne, 1996).

b. β-carotene

In many developing countries, sweet potato is a secondary staple food. Several recent studies have shown that sweet potatoes have superior ability to contribute to the reduction of Vitamin A deficiency in most developing countries. More than 80 percent of the dietary vitamin A, in these countries, is supplied by carotenoids present in plant foods; and the most predominant and active carotenoid in these foods is β-carotene (Bhaskarachary *et al*., 1995).

β-carotene rich orange-fleshed sweet potato (OFSP) is an excellent source of provitamin A. Provitamin A of orange fleshed sweet potato appears to be more bioavailable than that from most vegetables (Hess *et al*., 2005). Production and consumption of orange fleshed sweet potato is considered a sustainable long-term approach to address vitamin A deficiency and is used in many parts of the developing world. In South Africa, OFSP is currently being promoted to low income households as an alternative to source of β-carotene (Laurie & Faber, 2008).

2.2.1 Other nutrients

a. Vitamins

The storage roots constitute essential vitamins such as pantothenic acid (vitamin B5), pyridoxine (vitamin B6), thiamine (vitamin B1), niacin and riboflavin. These vitamins are essential in the way that the human body requires them from external sources to replenish. They have also been reported to contain reasonable amounts of Vitamin E (Wolfe, 1992).

These vitamins function as co-factors for various enzymes during metabolism. In a human body, Vitamin B6 break down homocysteine, a substance that contributes to the hardening of blood vessels and arteries.

Mineral content

The orange fleshed sweet potato contains a high calcium concentration than other sweet potato cultivars (Kruger *et al*., 1998). Magnesium content of the orange fleshed sweet potato is 19.3 mg/1009 when compared to other cultivars. A 100 grams of cooked portion of the orange fleshed sweet potato could contribute 15% (19.6mg/100g) of the daily requirements, in comparison to white fleshed which could contribute 10% (13mg/100g), followed by 8.5% from carrots (11mg/100g) for children under the age of four to eight years (Leighton *et al.*, 2007).

Potassium is another vital mineral to the human body. Potassium concentration has been reported as the most abundant (324mg/100g) in sweet potato roots compared to the other white fleshed sweet potato (Leighton *et al.*, 2007). Other minerals in low amounts include manganese (8.8 mg/100g); iron (14.0 mg/100g), copper (1 to 5.0 mg/100g) and zinc (0.3mg/100g) (Bovell-benjamin, 2007).

2.3 Nutritional water productivity

The largest water quantity is consumed by irrigation in South Africa. Data published in the year 2000 showed that irrigation extract 63% of the country's available surface water (Water Accounts for South Africa, 2000); and the prospect of expanding the irrigated areas is increasing, which could result to depletion of water sources. Improving productivity within the existing irrigated and rainfed agriculture is, therefore crucial (Renault and Wallender, 2000).

The increase in water productivity is likely to play a dynamic part in dealing with the additional requirement for food production. The concept of water productivity in agriculture is now shifting from harvest index per unit of land and water to nutrients produced per unit of water; viz, nutritional water productivity. Nutritional water productivity refers to producing more nutrients per millimetre of water used; and is a vital concept as it attempts to alleviate the problem of malnutrition particularly in the developing African countries (Renault and Wallender, 2000). Nutritional water productivity can promote production of healthy foods, in a cheaper way, to help close nutrient gaps of vulnerable South Africans.

2.4 Crop water use

Crop water use is also known as evapotranspiration (ET). It is the combination of water evaporation from soil and plant surfaces along with water used by plants for growth and transpiration. By definition, transpiration refers to water lost to the atmosphere through stomata as processes to avoid heat stress taking place in the plant. Transpiration is the water used by a crop for growth and cooling purposes. It is extracted from the soil root zone by the root system, and is no longer available as stored water in the soil (Molden, 1997).

Adequate soil water during the growing season is essential to obtain optimal yield; as optimal yield is highly affected by the availability of water stored in the soil profile (Al-Kaisi & Broner, 2009). As the soil dries, it becomes more difficult for a plant to extract water. At field capacity plants use water at the maximum rate. When soil water content drops below the field capacity, plants use less water (FAO, 2003). When a crop is exposed to water stress conditions, reduction in the growth rate of leaves and stems take place. This is similar to exposing a plant to limited water supply conditions, as process of cell expansion and division in the plant become retarded. This affects the production of enzymes and proteins by the plant needed for growth. As soil water deficit increases; the plant roots’ capacity to pull adequate water from the root zone and to fulfil the transpiration demand are reduced. This causes the crop to respond by closing their stomata, thereby reducing crop water use (FAO, 2005).

Different crops have different water requirements and respond differently to water stress. It is therefore important to maintain the water content in the root zone above the allowable depletion level, to ensure that the crop will not suffer from water stress, compromising maximum potential yield (FAO, 2002).

2.5 Water use efficiency

Water use efficiency is usually referred to as the total dry matter production per unit of transpiration, or evapotranspiration (in m^3 or mm of water) by the crop during the growing season; and is important in all areas of plant production (Molden, 1997). This concept is considered to be a measure of the plant's efficiency to use water applied or used over the growing season.

According to Atwell *et al* (1999) water use efficiency is the outcome of the entire collection of plant and environmental processes functioning over the life of a crop to determine both yield and evapotranspiration. This include the ability of soil to capture and store water; the ability of the crop to access water stored in the soil; the ability of the crop to convert water into biomass; and the ability of the crop to convert biomass into economic harvest index.

Agronomic methods aimed at reducing water losses and effectively conveying water to the root zone will increase water use efficiency. Equally, any agronomic practice that increase crop yield will eventually improve water use efficiency. Furthermore, criteria to improve water use efficiency may involve controlling physiological processes that affects plant transpiration and yield (De Pascale *et al*., 2011).

Deficit irrigation is in some cases beneficial in the improvement of the water use efficiency, especially if coincided with the less sensitive stages of plant growth (i.e., during tuber bulking) (Dalla Costa & Giovanardi, 2000).

Limited water supply to meet the requirements of evapotranspiration requirements is a very significant tool to increase water use efficiency. Deficit irrigation involves a gradual increase in crop water stress through uniform reduction of the amount of water applied at a given point (Fereres & Soriano, 2007).

Improving water use efficiency requires correct timing of irrigation application based on crop water requirements. This can be achieved by estimating soil moisture through visual observation of the soil; application of relevant devices/instruments; e.g., tensiometers, soil moisture sensors and neutron probes; measuring plant water stress and; assessing and measuring parameters such as evapotranspiration and the use mathematical models. Adoption of such methods for control of plant water stress levels can reduce water application amounts significantly (De Pascale *et al*., 2011). Nowadays, computer models have also been developed for constant monitoring of crop specific parameters and irrigation scheduling (Ines *et al*., 2001). Generally, water use efficiency can be improved through selection of specific cultivar, time of cultivation and the specific environment for plant growth.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Site Description

The trial was conducted at the University of Pretoria Experimental Farm (S 25°44'49" E 28°15'40", altitude 1 327 m a.s.l.) located at Hatfield, Pretoria, Gauteng. The study area receives an average rainfall of 670 mm per annum. The soil pH (water), according to the soil analysis report was between 5.6 and 6.0 (refer to Appendix 8) before planting, and the soil has a clay content of 26%. The trial was conducted under a movable rain shelter and a dryland block outside the rainshelter was established for the purpose of destructive sampling and model calibration.

3.2 Cultural practices

The trial was planted on the 1st of December 2011 and harvested on the 5th of May 2012. The purpose of establishing the trial under a movable rain shelter was to minimize the interference of rainfall on the water treatments.

Cuttings of the orange fleshed sweet potato (OFSP) cultivar Resisto, with six nodes each and without roots, were sourced from ARC-Roodeplaat for the purpose of this study. The cultivar Resisto was selected on the basis of its wide use for many home-gardening and nutrition projects in South Africa and the general observation that Resisto is highly preferred by communities (Faber *et al.,* 2002).

At planting, NPK 5:1:5(36) fertiliser mix was broadcasted on the trial, at a rate of 489 kg ha^{-1} (which represents 80 kg ha^{-1} N, 16 kg ha^{-1} P and 80 kg ha^{-1} K) as recommended by the soil analysis test results. Sweet potato cuttings, with six nodes, were manually planted on ridges after fertiliser was incorporated into the soil. Cuttings were spaced 0.3 m apart within the rows and 0.75 m between rows.

A once-off uniform irrigation of 20 mm, using a sprinkler, was applied directly after cuttings were planted. Weeds were controlled manually between the rows just before the ground area was covered by the vigorous canopy growth. Irrigation water of the same amount (50 mm) was applied once weekly, to ensure stimulation of good crop establishment before trial data was collected. During the growing period, the crop did not show any sign of nutrient deficiencies.

3.3 Experimental design and treatments

The experiment comprised of four water supply regimes. Irrigation treatments were applied at 79 days after planting as follows:

a) T_{tw} - irrigation application twice in a week
b) T_{ow} - irrigation application once in a week
c) T_{otw} - irrigation application once in two weeks
d) T_{dryl} – dryland model calibration block (rain and supplemental irrigation dependent)

Irrigation was applied to refill the soil to field capacity according to neutron probe measurements, taken three times a week, for soil water deficit of each treatment. Each treatment was equipped with a water meter and valve that were used to control irrigation amount.

Under the rainshelter, the trial was arranged in a randomised complete block design (RCBD), with four replicates for each treatment. Each plot was five rows wide and 5.4 m long, giving a total plot area of 4.05 m^2 each. Blocks and plots were separated by 1 m paths. For each treatment, 360 cuttings were used (18 plants per row x 5 rows = 90 x 4 replications per treatment). The dryland (model calibration) block was made up of four plots and the plot size and spacing were similar to that of the rainshelter trial (refer to Appendix 6).

A drip system was used for irrigation application. One dripper line was installed on each row with one dripper per plant. The drip irrigation system was pressure compensated and had a delivery rate of 2.5 ℓ hr^{-1} at a pressure range of 100-150 kPa.

3.4 Data collection

3.4.1 Soil water content, water use and water use efficiency

Soil water content was monitored with a neutron probe Model 503DR CPN Hydroprobe (Campbell Pacific Nuclear Inc., California, USA). The neutron probe was calibrated for the specific site and measurements were recorded three times weekly to determine the water depletion levels before irrigating to field capacity.

The measurements were recorded, during the afternoon, a day before the irrigation was applied. Soil water status was monitored by taking neutron probe readings at 0.2 m increments down to a soil depth of 1 m by lowering the radioactive source through an access tube which was installed in the middle of each plot. Irrigation was based on the neutron probe data collected on Mondays and Thursdays. Irrigation for T_{tw} was applied on Tuesdays and Fridays, T_{ow} was irrigated on Tuesdays; and T_{otw} on Fridays of every second week. T_{dryl} received supplemental irrigation of 50 mm only during hot, dry periods when rainfall was insufficient throughout the season.

Water use (ET in mm) and water use efficiency (WUE in kg ha^{-1} mm^{-1}) on storage root fresh mass basis were calculated at final harvest. Equations 3.1 and 3.2 were used to calculate ET and WUE:

$$ET\ (mm) = I+P-Dr-\Delta S-R \qquad \textbf{(3.1)}$$

where:I = Irrigation (mm), P = Precipitation (mm), Dr = Drainage (assumed to be zero), ΔS = change in soil water storage (mm) and R = run off (assumed to be negligible)

$$WUE\ (kg\ ha^{-1}\ mm^{-1}) = SRY/ET \qquad \textbf{(3.2)}$$

where: SRY is Storage Root Yield in kg ha^{-1} (fresh mass)

ET is evapotranspiration (mm)

3.4.2 Crop growth analysis

During the growing season, crop growth analysis was carried out by sampling the above-ground and harvestable (storage root) plant material from a ground surface area of 0.675 m^2 from the dryland block (T_{dryl}) only. Harvested samples were separated into leaves, stems and storage roots, whereafter the fresh mass of samples was determined by weighing. Leaf area was measured with an LAI 3100 belt driven leaf area meter (LiCor Lincoln, Nebraska, USA) and leaf area index was calculated from the data using equation 3.3:

$$\text{LAI } (m^2\ m^{-2}) = \text{measured total leaf area/sampled ground area} \quad \textbf{(3.3)}$$

Leaf, stem and storage root samples were then oven-dried at 80^{o}C for 48 hours to determine the dry matter content of the different plant parts. Sampling was performed every two weeks throughout the growing season.

Fractional interception (FI) of photosynthetically active radiation (PAR) was measured with a Decagon Sunfleck Ceptometer (Decagon, Pullman, Washington, USA). One reference reading was taken above the canopy of each plot and 3 readings below the canopy.

3.4.3 Yield and β-carotene

Total biomass yield was determined at final harvest (at the end of the season) by weighing the top growth (vines) and storage roots of each plot separately. Harvest data was recorded from the three middle rows of each plot. Data was recorded, grouped according to the treatments and statistically analysed.

Roots for β-carotene was obtained by randomly selecting five medium sized storage roots from each plot at final harvest. The storage roots were packed in clearly marked bags and sent to the SABS laboratory, at Pretoria, for beta carotene analysis. (refer to Appendix 7)

3.4.4 Nutritional water productivity

Nutritional water productivity of orange fleshed sweet potatoes was calculated from equation 3.4, as defined by Wallender and Renault (2000):

$$NWP\ (mg/m^3) = (Ya/Eta)*NP \qquad \textbf{(3.4)}$$

where: Ya is actual harvested yield (kg ha^{-1})

ETa is the actual evapotranspiration ($m^3\ ha^{-1}$)

NP is the nutrition unit per kg of roots

3.4.5 Statistical analysis

Analysis of variance (ANOVA) was performed using SAS (Statistical Analysis Systems v9.3). Means were compared using the LSD (Least Significance Test) at a 5% probability level. (refer to Appendix 5)

3.4.6 Weather data

Weather data was sourced from an automatic weather station which was located about 100 m from the trial site. Meteorological data were recorded, using a CR10X data logger (Campbell Scientific, Inc., UT, USA) and the following electronic sensors:

- Daily minimum and maximum relativity humidity and air temperature using a CS-500 Vaisala temperature and relative humidity probe.
- Total daily solar radiation using an LI-200 (Li-Cor) pyranometer.
- Rainfall amount and intensity, using an TE525 tipping bucket rain gauge (Texas Instruments Inc.)
- Wind speed was measured using R.M Young (Michigan, USA) cup anemometer.
- Vapour pressure deficit was calculated using equation 3.5

$$\text{VPD (kPa)} = (e_s - e_a) \qquad \textbf{(3.5)}$$

where: e_s is the saturation vapour pressure of the air

e_a is the actual vapour pressure of the air

3.5 Soil Water Balance (SWB) model calibration and validation

The key strength of the SWB model relative to other models that are more detailed is that it requires fewer crop input parameters, while still predicting the crop growth and soil water balance reasonably well. Its generic nature further allows growth and water balance simulation of several crops with the same user-friendly software package, unlike species specific models (Jovanovic *et al*., 2000).

The SWB model was calibrated using the growth analysis, water balance and weather data collected over the growing season. Calibration was based on measured values of leaf area, dry biomass yield, dry storage root yield, calculated crop water use and soil water deficit measurements.

The calibrated model was validated on the remaining independent experimental data set from the model calibration field block (T_{dryl}). Predictions of the SWB model were assessed using statistical norms as recommended by de Jager (1994). Details on the statistical norms are presented in Chapter 5. (refer to Appendix 1 - 4)

Crop-specific model parameters were calculated from the field data collected other parameters were obtained from literature or estimated as follows:

- Canopy radiation extinction coefficient[a]
- Corrected dry matter water ratio (Pa) [b]
- Radiation conversion efficiency (kg MJ^{-1}) [c]
- Base Temperature (^{o}C)[d]
- Temperature for optimum crop growth (^{o}C) [d]
- Cut-off temperature (^{o}C) [d]
- Emergence day degrees (^{o}C) [e]
- Flowering day degrees (d ^{o}C) [e]
- Day degrees for maturity (d ^{o}C) [e]
- Day degree transition period (d ^{o}C) [e]
- Day degrees for leaf senescence (d ^{o}C) [e]
- Maximum crop height (m)[f]
- Maximum root depth (m)[g]
- Fraction of total dry matter translocated to the roots[h]
- Canopy storage (mm)[h]
- Leaf water potential at the maximum transpiration (kPa) [g]
- Maximum transpiration (mm d^{-1})[h]
- Specific leaf area (m^2 kg^{-1}) [i]
- Leaf-stem partition parameter (m^2 kg^{-1})[h]
- Total dry matter at emergence (kg m^{-2})[h]
- Root fraction[h]
- Root growth rate (m^2 $kg^{-0.5}$)[h]
- Stress index[h]

[a] k = [loge (I/I0)] /LAI (Sheehy & Cooper (1973), where: I is the irradiance values upon the canopy and I_0 is the irradiance values under the canopy); [b] refer to 5.7, [c] refer to 5.3.1.1; [d] Somasundaram & Mithra (2008); [e] GDD = (Tmax +Tmin)/2 – Tbase (where: Tmax is maximum daily temperature,Tmin is the minimum daily temperature, Tbase is the base temperature; [f] Measured; [g] FAO (1998); [h] Estimated; [I] SLA (cm^2/g) = Total leaf area (cm^2)/leaf dry weight (g).

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Climatic parameters

The climatic parameters (temperature, wind speed, radiation, vapour pressure deficit and rainfall) recorded during the experiment are presented in Table 4.1 and Figure 4.1. The treatment outside the rainshelter (T_{dryl}) was mostly dependant on rainfall. A total of 50 mm supplemental irrigation was also applied to this treatment, especially during hot, dry periods in the season. Although December was the wettest month (92 mm rainfall), the data shows that the rainfall pattern throughout the season was irregular, with April being the driest month with only 24 mm of rainfall.

Table 4.1: Mean monthly climatic variables recorded throughout the sweet potato growing season.

	Tmax (°C)	**Tmin** (°C)	**U** (m s^{-1})	**R** (MJ d^{-1})	**VPD** (kPa)	**Rain** (mm)	**ET_o** (mm/month)
Dec	28	16	1.47	20	1.10	92	151
Jan	30	16	1.77	23	1.06	68	167
Feb	31	17	1.22	22	1.18	85	143
March	30	15	1.54	20	1.24	32	149
April	26	10	1.7	18	1.60	24	106
Average	*29*	*15*	*1.54*	*21*	*1.23*	*63*	*143*

Tmax - maximum temperature, Tmin - minimum temperature, U - wind speed at 2 m height, R - solar radiation, VPD - vapour pressure deficit, ET_o - Reference evaporation

- Planting date for the trial was 01 December 2011; treatments of this study were applied from 79 days after planting (19 February 2012). Data for climatic parameters (4.1) include December and January. Results discussed after climatic parameters begin from the 79th day after planting.

Orange fleshed sweet potato cultivars are generally less tolerant to drought, compared to the white fleshed cultivars (Tumwegamire *et al*., 2004). Under rain-fed conditions, erratic rainfall can result in drought stress that retards root growth and negatively affects crop yield (van Heerden & Laurie, 2008).

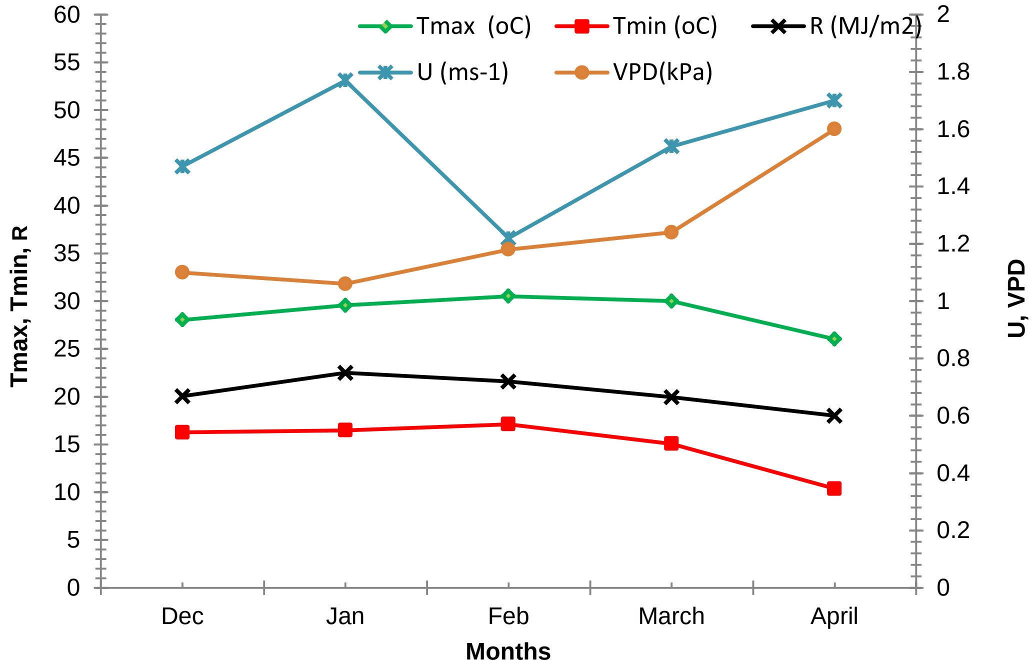

FIGURE 4.1: Graphic representation of climatic parameters over the growing season *(Tmax - maximum temperature, Tmin - minimum temperature, U - wind speed at 2 m height, R - solar radiation, VPD - vapour pressure deficit, ETo - Reference evaporation)*

Optimum temperature (T*opt*) for the growth of sweet potato is 25°C; base temperature (T*base*) is 8.1°C and the highest temperature at which sweet potato can grow (T*high*) is 38°C (Somasundaram & Mithra, 2008). The observed temperature range varied from month to month, with January and February having higher maximum temperatures (Figure 4.1). April was characterised by lower minimum and maximum temperatures, which could have resulted in a decline in leaf growth rate and leaf area reduction due to the onset of frost.

Generally, the average minimum and maximum temperatures were optimal for sweet potato growth during the growing season. The month of March was characterised by high evaporative demand (ET_o), increasing vapour pressure deficits, and low rainfall levels which could have resulted to high soil water depletion levels. The average solar radiation was relatively lower in April, causing the reduction in evaporative demand thus allowing the reduction in depletion levels (Table 4.1).

4.2 Soil water deficits

Soil water deficits for the entire growing season as measured with the neutron probe, three times in a week, are graphically presented in Figure 4.2(A). Soil water deficits for treatment T_{dryl} were higher compared to treatments under the rain shelter (T_{tw}, T_{ow} and T_{otw}). The highest water deficit for treatment T_{dryl} was observed at 106 DAP (108 mm), and deficit levels declined from 110 DAP to 147 DAP due to the occurrence of substantial rainfall (Figure 4.2B). During this period, the water depletion level for treatment T_{dryl} was reduced by 40% and was maintained at an average of 68 mm.

The wet period, due to rainfall, between 107 DAP and 122 DAP (*Table* 4.2) made a significant impact in increasing the profile soil water content, by reducing the deficits associated with treatment T_{dryl}. An almost similar pattern was observed at the beginning of the season where rainfall reduced deficit levels effectively (Figure 4.2B).

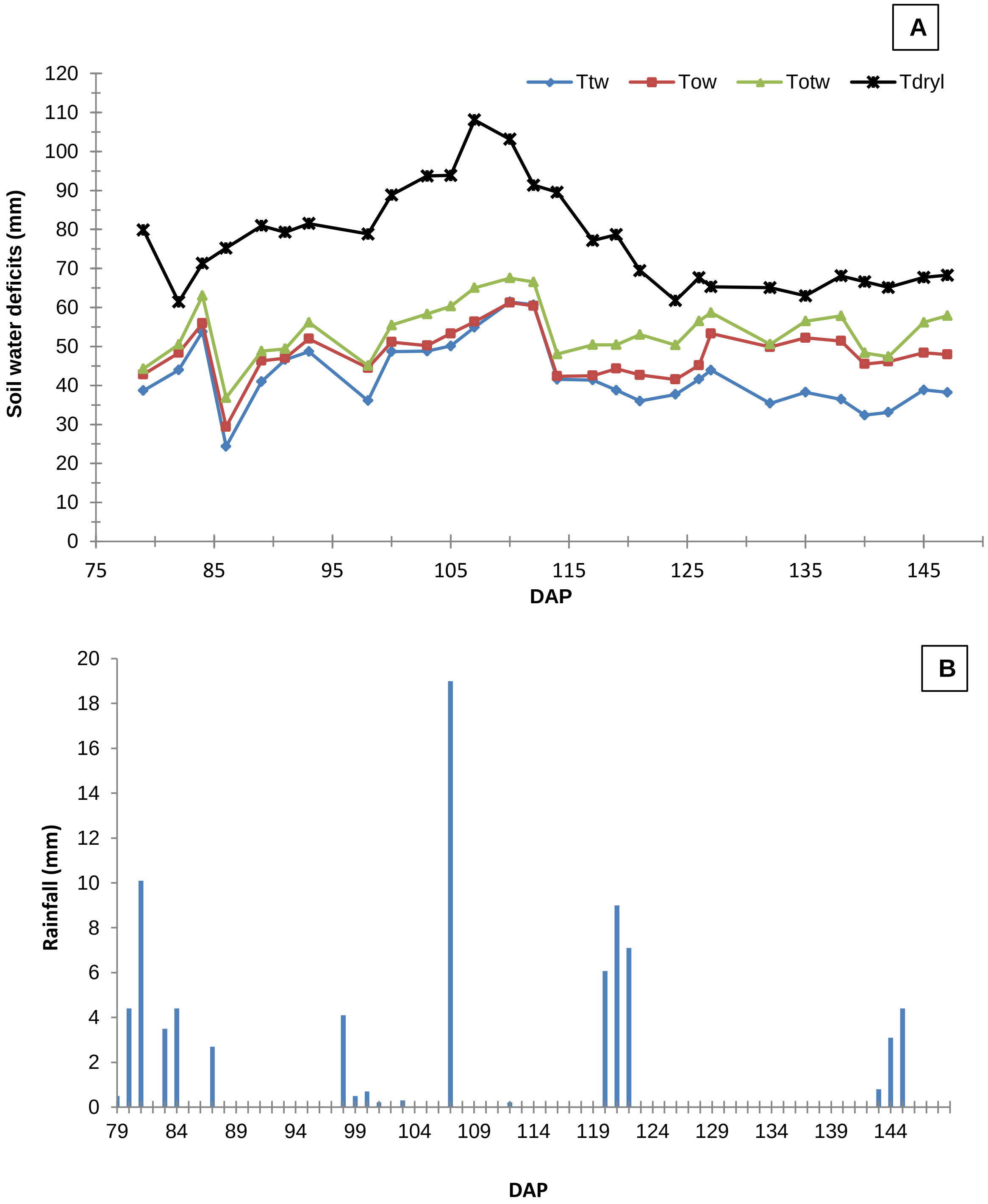

FIGURE 4.2: Soil water deficit (A) and daily rainfall (B) recorded over the cropping season. *(T_{tw} was irrigated twice in a week, T_{ow} was irrigated once in a week, T_{otw} was irrigated once every two weeks and T_{dryl} was rainfall and supplemental irrigation dependent)*

Under the rain shelter, the soil water deficit of treatment T_{tw} was lower, compared to treatment T_{ow} and T_{otw}, throughout the measured intervals in the season. Frequently applied irrigation to treatment T_{tw} accounted for the lower deficits. Under ideal conditions, deficit for treatment T_{tw} are supposed to be lower relative to the values found in this experiment; however, the field capacity (FC) value used (FC of 250 mm used, which was probably higher than the actual FC, resulting in higher calculated deficit values) and other unforeseen irrigation discrepancies during the growing season could have resulted in the rather high deficits.

Table 4.2: Rainfall data over the growing season, for each day after planting (DAP)

Date	DAP	Rain (mm)
2012-02-19	79	0.5
2012-02-20	80	4
2012-02-21	81	10
2012-02-23	83	3
2012-02-24	84	4
2012-02-27	87	2
2012-03-09	98	4
2012-03-10	99	0.5
2012-03-11	100	0.7
2012-03-12	101	0.2
2012-03-14	103	0.3
2012-03-18	107	19
2012-03-23	112	0.6
2012-03-31	120	6
2012-04-01	121	9
2012-04-02	122	7
2012-04-23	143	0.8
2012-04-24	144	3
2012-04-25	145	4

(Table excludes rainfall from 1 to 78 DAP as treatments were applied from 79DAP)

From 114 DAP to 147 DAP; there was a general observation that the water depletion pattern of the treatments under the rainshelter (T_{tw}, T_{ow} and T_{otw}) stabilized. During that period, average deficit for T_{tw} was 38 mm, T_{ow} was 47 mm; and T_{otw} was 53 mm.

4.3 Water use (Evapotranspiration)

Total water use by the crop over the season was estimated using the soil water balance equation (*Equation 3.1*), described under the materials and methods. The water balance data presented in Table 4.3 estimates the quantity of water that entered and exited the trial over the growing season, through the various hydrological pathways. Components of the water balance were estimated using data collected during the growing season. Monthly water balance values, for each treatment were totalled to get the seasonal value of each component.

Table 4.3: Water balance components per treatment over the growing season.

Treatments	Irrigation(mm)	Rainfall (mm)	ET (mm)	ΔSWC (mm)
T_{tw}	447	-	478	31
T_{ow}	282	-	365	83
T_{otw}	232	-	321	89
T_{dryl}	50	301*	298	(-7)

(T_{tw} was irrigated twice in a week, T_{ow} was irrigated once in a week, T_{otw} was irrigated once every two weeks and T_{dryl} was rainfall and supplemental irrigation dependent)

** Total rainfall throughout the season.*

***ΔSWC** = change in soil water storage.*

ET = evapotranspiration

Water use by the treatment irrigated twice in a week during the entire growing season (T_{tw}) was 38% greater as the water use by treatment T_{dryl} which was dependant on rain fall and supplemental irrigation (Figure 4.3).

After irrigation, the ET becomes higher; and when the soil or crop surface becomes wet, the evaporation portion of ET increases considerably, resulting in a higher evapotranspiration (Doorenbos & Kassam, 1979). The relatively high water use by treatment T_{tw} is equally explained by this phenomenon.

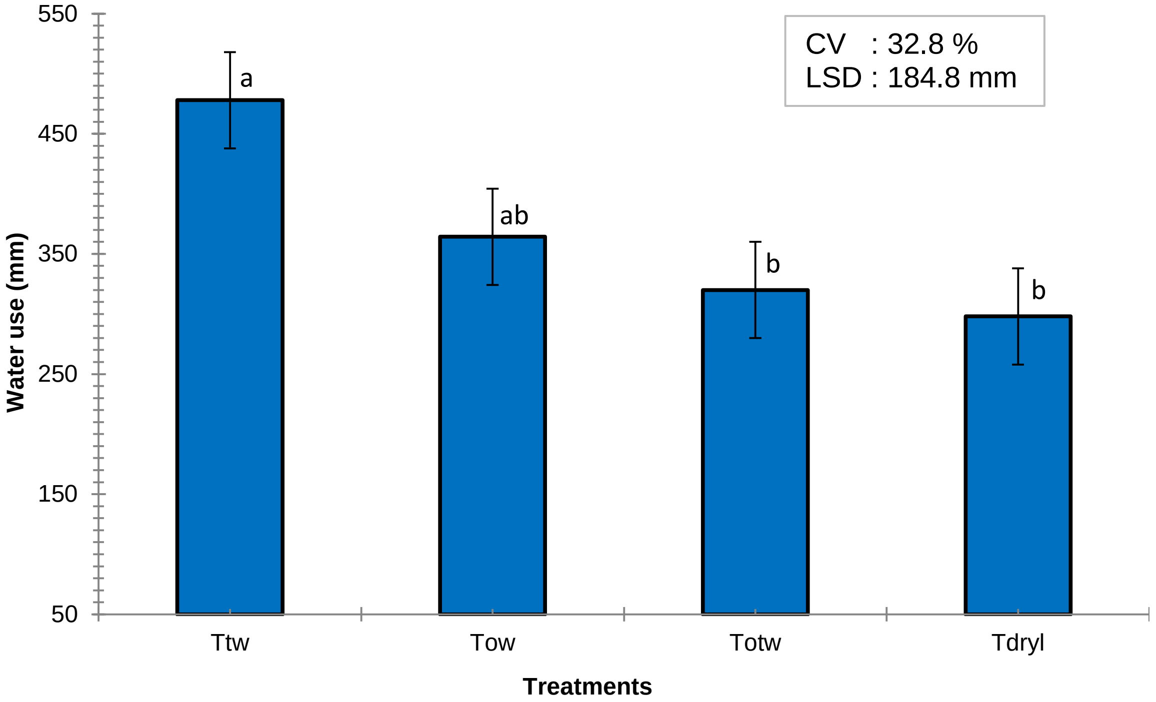

Figure 4.3: Evapotranspiration of treatments over the cropping season. *(T_{tw} was irrigated twice in a week, T_{ow} was irrigated once in a week, T_{otw} was irrigated once every two weeks and T_{dryl} was rainfall and supplemental irrigation dependent)*

Although foliage growth was not measured, it was observed that foliage cover occurred more rapidly with the treatments under the rainshelter especially, treatment T_{tw} thereby resulting into the crop using water at maximum rate comparative to treatments T_{otw} and T_{dryl}. Karanja (2006) reported sweet potato maximum crop water use of 458 mm in Kenya. For the same locality in South Africa as the current study, Bok (1998) reported a range of 400 mm to 500 mm.

4.4 Yield

4.4.1 Storage root yield (Fresh)

The storage root of sweet potato is considered the economic yield of the crop. In literature, numerous reports show that frequency of water application and/or irrigation may significantly reduce or increase the storage root yield (Ravi *et al.*, 2009). There was a 6% difference in storage root yield of treatment T_{tw} (31020 kg ha^{-1}) and T_{dryl} (29251 kg ha^{-1}) (Figure 4.4). Owing to the significant differences in water use of treatment T_{tw} and T_{dryl}, it was generally expected that both treatments differ greatly in terms of storage root yield. However, significant differences were not found between these treatments. According to FAO (2002) crop growth and the degree of yield reduction by water deficit or water improvement through irrigation depend on a variety of factors, viz; the degree of water deficit duration, timing of the deficit and the proportion of the total yield that comprises the economic yield of the crop.

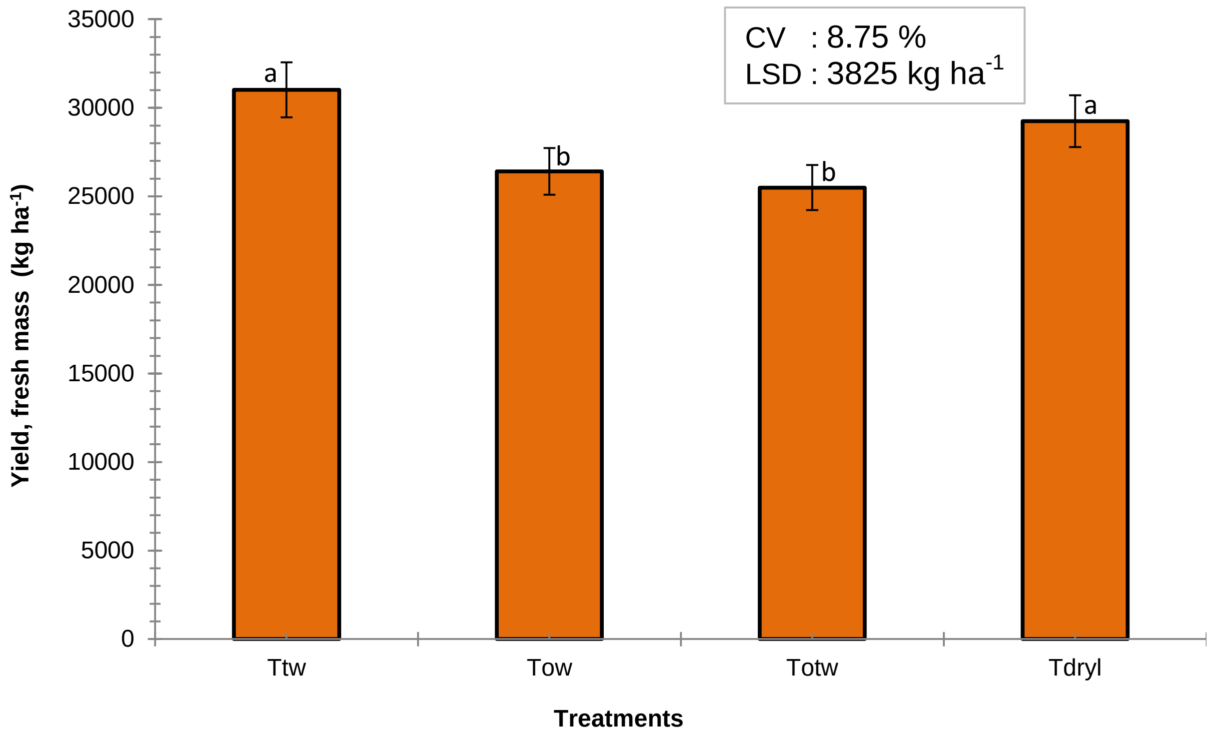

FIGURE 4.4: The impact of irrigation levels on storage root yield (fresh mass) of sweet potato. *(T_{tw} was irrigated twice in a week, T_{ow} was irrigated once in a week, T_{otw} was irrigated once every two weeks and T_{dryl} was rainfall and supplemental irrigation dependent)*

Nedunchezhiyan *et al*. (2012) reported an average sweet potato root yield of between 20 and 25 t ha $^{-1}$, while Mbwaga *et al*. (2007) found that 27.3 t ha^{-1} (27330 kg ha^{-1}) was the highest storage root yield in the different agro-ecological zones of Tanzania. Somasundaram & Mithra (2008) reported an average root yield of 31.05 t ha^{-1} in an experiment to determine variation in yield at different levels of soil water. At Mozambique, Gomes & Carr (2001) conducted an experiment to determine the effect of water availability on sweet potato yield and root yield of 34.2 t ha^{-1} was achieved at final harvest. In South Africa, Laurie *et al.* (2012) reported total storage yield of between 7.5 and 48.9 t ha^{-1}.

Values of storage root yield (fresh mass) attained from this study were therefore comparable to other literature.

4.4.2 Storage root yield (Dry)

Similar to fresh storage root yield, different irrigation frequencies influenced sweet potato yield as expressed on dry mass basis (Figure 4.5). Root yield of treatment T_{ow} (6.5 t ha^{-1}) and T_{otw} (6.6 t ha^{-1}) were significantly lower compared to treatment T_{tw} (7.1 t ha^{-1}) and T_{dryl} (7.6 t ha^{-1}). The storage root yield of treatment T_{tw} was 6% higher compared to T_{dryl}; but both treatments were statistically not different to another.

The storage root yield results demonstrates the importance of sweet potato crop growth under different growing conditions; it also provides an indication of the possible yield responses of the orange fleshed sweet potato to different water supply scenarios. These results are supported by a study from Teshome-Abdissa & Nigussie-Dechassa (2012) who reported storage root dry mass yield ranging between 4.7 t ha^{-1} and 10 t ha^{-1}.

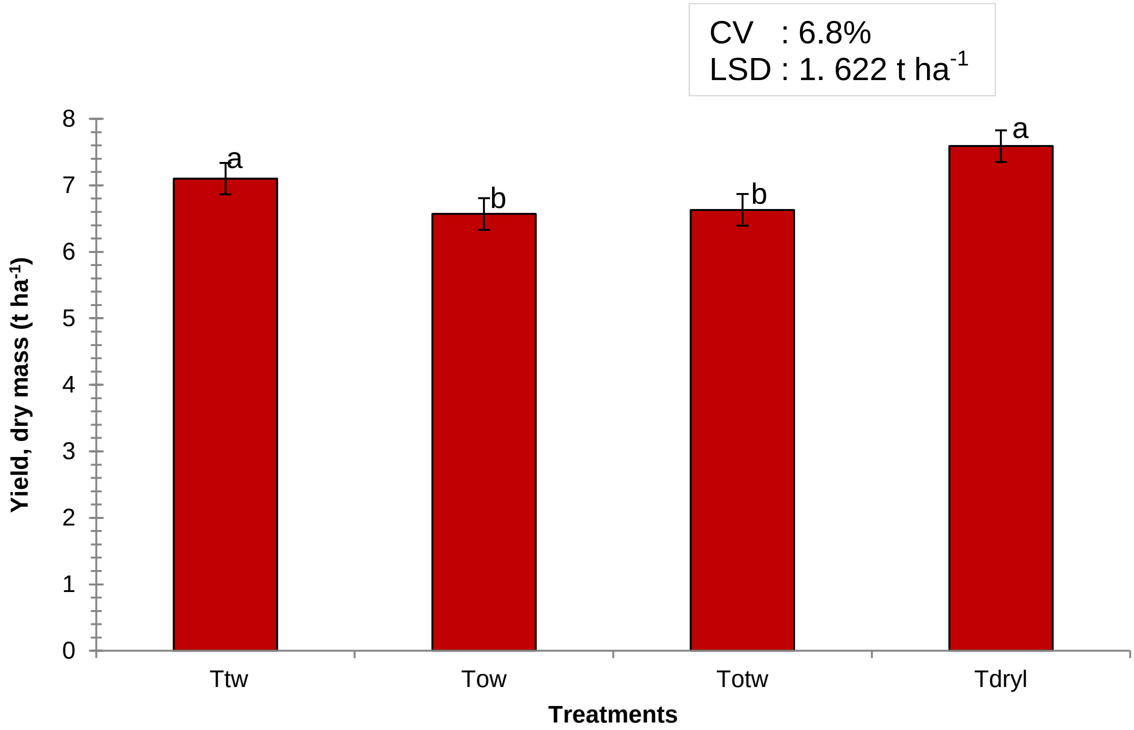

FIGURE 4.5: Storage root yield (dry mass basis) of sweet potato as influenced by irrigation levels. *(T_{tw} was irrigated twice in a week, T_{ow} was irrigated once in a week, T_{otw} was irrigated once every two weeks and T_{dryl} was rainfall and supplemental irrigation dependent)*

4.5 Total Dry Matter (TDM) Yield

At final harvest, significant differences in total dry matter yield, between the treatments, due to frequency of water application were found (Figure 4.6). Treatment T_{dryl} had significantly higher TDM yield (13.95 t ha^{-1}) and was followed by T_{tw} (12.47 t ha^{-1}). Treatments T_{otw} (10.86 t ha^{-1}) and T_{ow} (10.31 t ha^{-1}) produced lowest TDM yields. Lewthwaite & Triggs (2012) found that prolonged soil water deficit showed a significant increase in root dry matter content of sweet potato; whereas a reduction in root dry mass under water stress conditions was reported by Ekanayake *et al* (2004).

The discrepancies in literature on the effects of irrigation/water frequency on the total dry matter content can be attributed to water stress intensities, climate, as well as the difference in species among studies (Rosei & Vasanthakalam, 2011). The significantly higher TDM produced by treatment T_{dryl} was, therefore, consistent with the findings by Lewthwaite & Triggs (2012). It is thus important to study how crops modify their dry mass distribution under different conditions of different water frequencies.

Values of TDM yield from this study confirms previous research by Oboh *et al* (1989) who reported TDM yield of 11.20 t ha^{-1} for sweet potato.

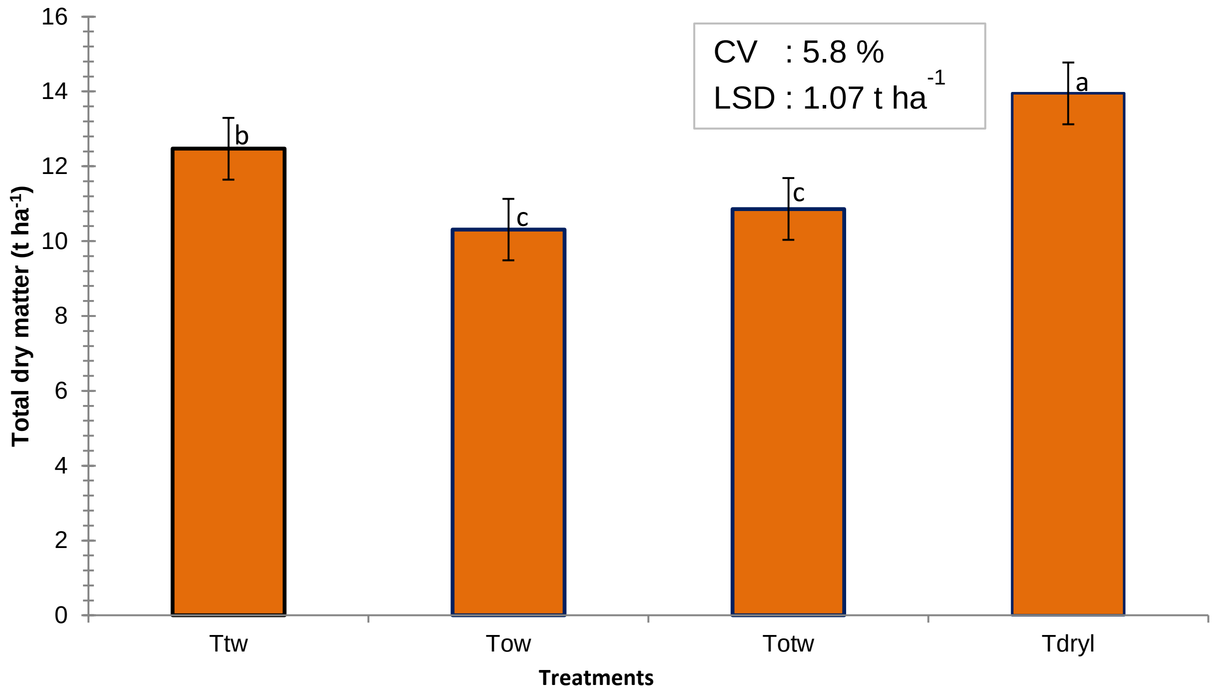

FIGURE 4.6: The total dry matter production as a function of irrigation intervals of sweet potato. *(T_{tw} was irrigated twice in a week, T_{ow} was irrigated once in a week, T_{otw} was irrigated once every two weeks and T_{dryl} was rainfall and supplemental irrigation dependent)*

4.6 Harvest index (HI)

At final harvest, the harvest index was calculated as the ratio of the dry storage root yield (economic yield) over the total biological yield (dry vines and leaves + dry storage root mass) from the same area multiplied by 100; and these results are presented in Figure 4.7. HI values of this experiment ranged from 56 % to 59 %.

The order of treatments from highest to lowest was as follows: Treatment T_{ow} (59.3 %), T_{otw} (56.5 %), T_{tw} (52.9 %) and T_{dryl} (52.7 %).

A wide variation in HI values of the sweet potato crop has been reported by different authors in the past. HI values of this experiment were comparable to the range of 48 % to 52 % reported by Yeng *et al.* (2012) and are equally consistent with the findings by Bhagsari (1990), who reported a range of 43 % to 77 % at final harvest.

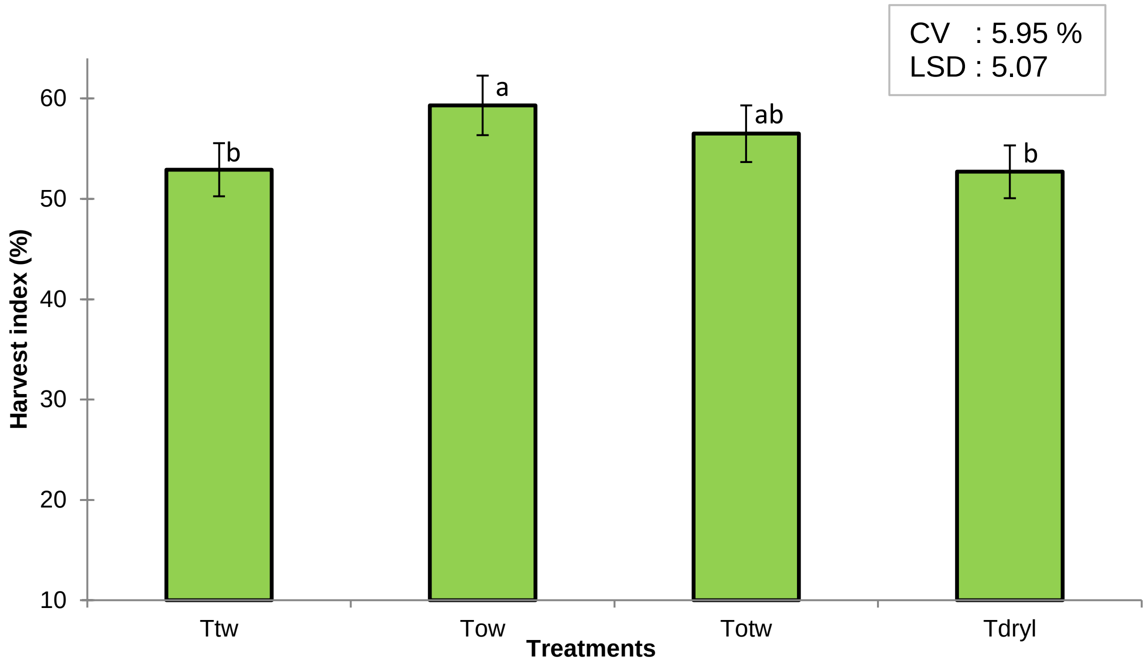

FIGURE 4.7: The influence of irrigation intervals on Harvest Index of sweet potato. *(T_{tw} was irrigated twice in a week, T_{ow} was irrigated once in a week, T_{otw} was irrigated once every two weeks and T_{dryl} was rainfall and supplemental irrigation dependent)*

Harvest index is one of the most important components in crop growth and can be used to evaluate the water productivity under varying conditions. Kawano (1990) stated that harvest index represents the efficiency of the conversion of photosynthetic products into economically valuable forms.

The less frequently irrigated treatments (T_{ow} and T_{otw}) produced relatively higher harvest index values, demonstrating that more assimilates were translocated efficiently to the main sink of photosynthates, compared to other plant parts (Bhagsari & Doyle, 1990). According to Bok (1998), the translocation pattern of assimilates determines dry matter partitioning; and the portion of the photosynthates channelled to the economically important tuberous roots. Once water stress becomes prolonged, it is capable of limiting biomass production of a plant and can change the allocation pattern of biomass to the storage roots (Rodiyati *et al*., 2005).

4.7 Growth analysis data

Data for growth analysis was collected earlier before treatments were applied and was collected from outside the rainshelter only (Treatment T_{dryl}). Results of leaf dry mass (LDM), vine dry mass (VDM) and total dry mass (TDM) measured over the growing season are presented in Figure 4.8. When a plant is exposed to a certain water stress level, a sign of decrease in growth rate manifest, as growth rate is a function of transpiration rate and leaf area (Chartzoulakis *et al*., 1993).

From 68 days after planting (DAP), the graph show differences in partitioning of assimilates to the different plant parts. At 97 DAP, a large proportion of the dry matter began to be channelled to the storage root, as the main sink. Translocation of a larger proportion of assimilates to the storage roots resulted in a reduction of assimilate partitioning to LDM, which was observed from 104 DAP, followed by a decline in VDM at a later stage (116 DAP).

This was consistent with the observations by Belehu (2003) that once the crop reached its final stages towards maturity a high percentage of dry matter is partitioned to the storage roots.

From 116 DAP, a sharp decline in LDM and VDM was observed. RDM continued to increase linearly; while rates of LDM and VDM accelerates during growth and drop off as the crop approached maturity. This observation was similar to that of Al-Jamal *et al* (2001) who found that root yield increases linearly throughout the growing season resulting to LDM and VDM initially accelerating and then dropping at maturity.

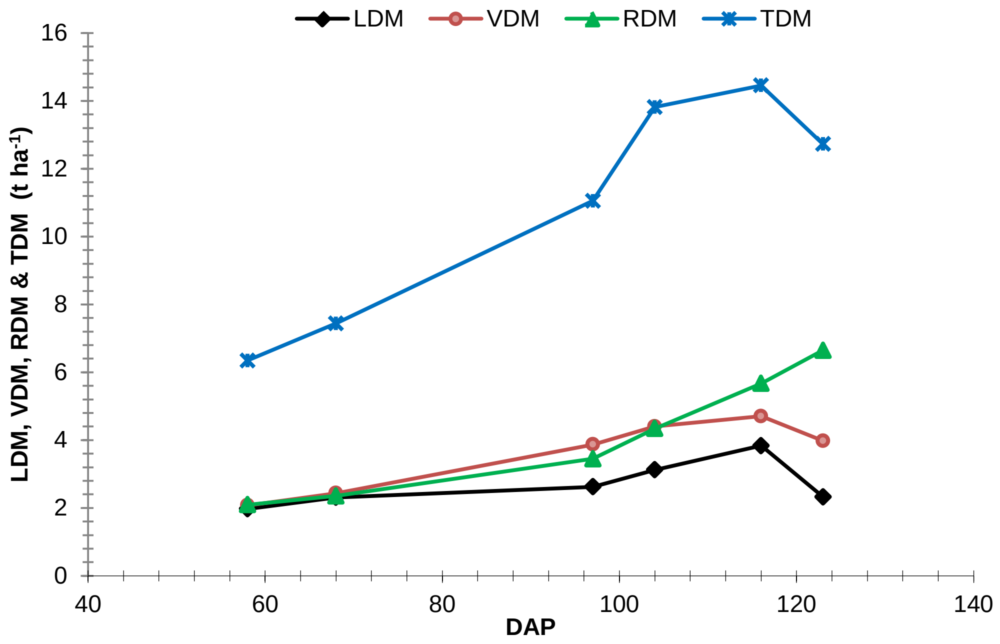

FIGURE 4.8: Changes in Leaf dry mass (LDM), Vine dry mass (VDM), Roots dry mass (RDM) and Total dry mass (TDM) of treatment T_{dryl} over the growing season. *(Treatment T_{dryl} was the independent field block outside the rainshelter from which growth analysis data was collected)*

Values of total dry mass collected at different intervals over the growing season were in the range of between 6.43 t ha^{-1} and 14.4 t ha^{-1}. TDM exhibited a sigmoidal curve over the growing season. This confirmed the findings of Oswald *et al* (1994) that the increase in total dry mass of sweet potato exhibits a sigmoidal pattern over the growing season.

From 58 to 68 days after planting (DAP), the TDM curve exhibited a gentle linear increasing pattern, followed by a sudden increase in TDM from 97 DAP up to 104 DAP. TDM then peaked at 116 DAP, whereafter a decline was observed, probably due to leaf drop as senescence set in.

4.8 Leaf area index (LAI)

Data for LAI was collected from treatment T_{dryl}, outside the rain shelter. Figure 4.9 presents the leaf area index (LAI) data for treatment T_{dryl} collected between 20 and 125 days after planting. The highest LAI value was 3 m^2 m^{-2}; this value was recorded at 107 DAP.

There was a steady increase in LAI values between 40 and 89 DAP. The steady increase in LAI indicated that the crop was able to intercept increasingly more photosynthetically active radiation as the season progressed.

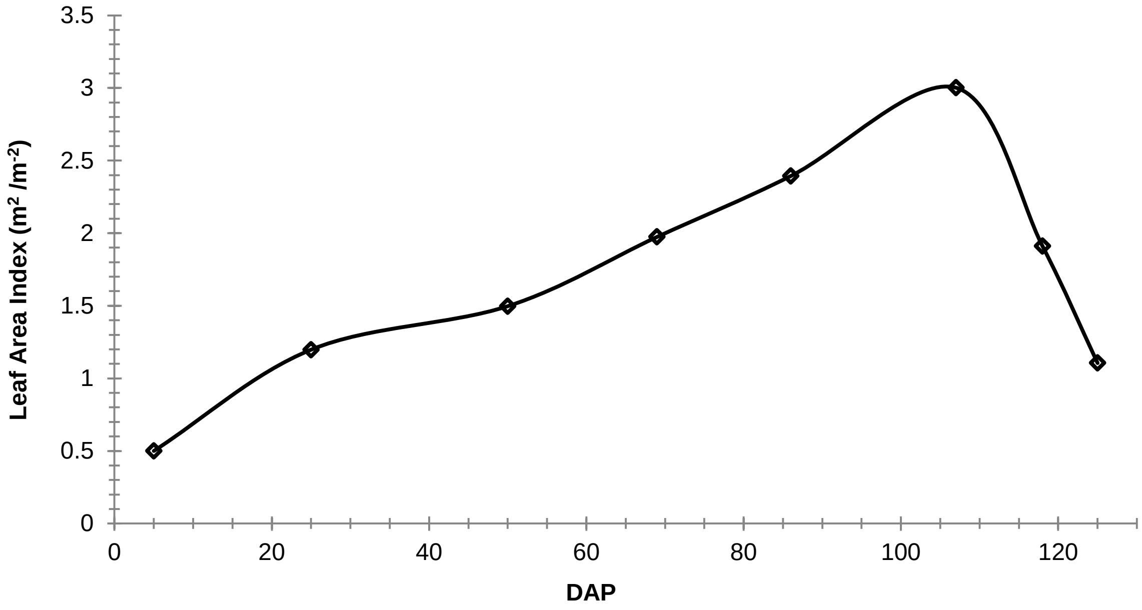

FIGURE 4.9: Leaf area index (LAI) of treatment T_{dryl} over the growing season. *(Treatment T_{dryl} was the independent field block outside the rainshelter from which growth analysis data was collected)*

During the storage root bulking period (50 DAP to 112 DAP), the crop had LAI values between 1.4 m^2 m^{-2} and 3 m^2 m^{-2}. This is in line with the report by Brown (1992), that at LAI value of 3, the sweet potato crop will intercept 95% of incoming photosynthetically active radiation. According to several authors sweet potato LAI varied between 2 and 11 (Mukhopadhyay *et al*., 1992; Nair & Nair, 1995). The sharp decline observed after 117 DAP was attributed to the fact that there was a lot of rain which caused leaf rot, which possibly resulted in senescence of leaves, and also in lower TDM values (Laurie & Niederwieser, 2004).

The duration that storage root crops are able to maintain active leaves is very important as it determines the total storage root dry matter accumulation (Bourke, 1984). Van Delden *et al* (2001) indicated that total biomass production and accumulation is dependent on the absorbed photosynthetically active radiation (PAR), which is directly proportional to plant canopy cover (LAI).

4.9 Water use efficiency

Water use efficiencies (expressed on fresh mass basis) for each treatment, over the entire season were estimated using equation 3.2 in the methodology chapter. Values used to calculate WUE of each treatment are presented in Table 4.4 and water use efficiencies are presented in Figure 4.10. Treatment T_{dryl} recorded the highest WUE value of 98 kg ha^{-1} mm^{-1}. Treatment T_{tw} had a WUE value of 65 kg ha^{-1} mm^{-1}, which was lowest of all treatments. A WUE of 73 kg ha^{-1} mm^{-1} was recorded from treatment T_{ow} and 80 kg ha^{-1} mm^{-1} from T_{otw}.

The highest WUE recorded by treatment T_{dryl} was generally a response mechanism of the crop to survive the severe soil water deficits (Kuslu *et al*., 2010). Water use efficiency (WUE) considers the harvestable yield that a crop has produced per unit of water consumed. It is not only crop based but is the outcome of an entire collection of plant and environmental processes operating over the life of a crop during its growth (Atwell *et al*., 1999).

Water use efficiency values of this study were within the range of values reported by Bok (1998), which were between 69.83 kg ha^{-1} mm^{-1} and 131.78 kg ha^{-1} mm^{-1}; when conducting an experiment in Pretoria (Gauteng province of South Africa) on the response of sweet potato to different soil water regimes. In another experiment by Gomes and Carr (2001) in Mozambique, irrigation WUE values of 11.2 kg ha^{-1} mm^{-1}

(rainy season) and 19.0 kg ha^{-1} mm^{-1} (dry season) were reported on dry mass basis; while Laurie *et al* (2012) reported values between 54 kg ha^{-1} mm^{-1} and 70.5 kg ha^{-1} mm^{-1} for Resisto variety.

Table 4.4: Storage root yield, evapotranspiration and water use efficiency for all the treatments.

Treatments	Storage root yield (kg/ha)	Evapotranspiration (mm)	Water use efficiency (kg ha^{-1}mm^{-1})
T_{tw}	31020a	478a	65b
T_{ow}	26415b	364ab	73b
T_{otw}	25497b	320b	80ab
T_{dryl}	29251a	298b	98a
LSD	3825	184.8	22.2

Means in a column followed by the same letter is not significantly different. (T_{tw} was irrigated twice in a week, T_{ow} was irrigated once in a week, T_{otw} was irrigated once every two weeks and T_{dryl} was rainfall and supplemental irrigation dependent)

Other authors (Chua & Kays, 1982; Larenas de la & Accatino, 1994) suggested that sweet potato require a continuous supply of water throughout the growing season. Continuous water supply may, however, be detrimental, as it may result in poor soil aeration, thereby causing poor storage root development (Chua & Kays, 1982).

In this study, it was generally observed that water use efficiencies increased with decreasing water use by the sweet potato crop. These observations were supported by the findings of Hedge (1987), who also found that water use efficiency of crops significantly increased by decreasing irrigation levels. The results are also consistent with the findings of Jones (1992) who reported that plants exhibit higher water use efficiency with a lower water supply.

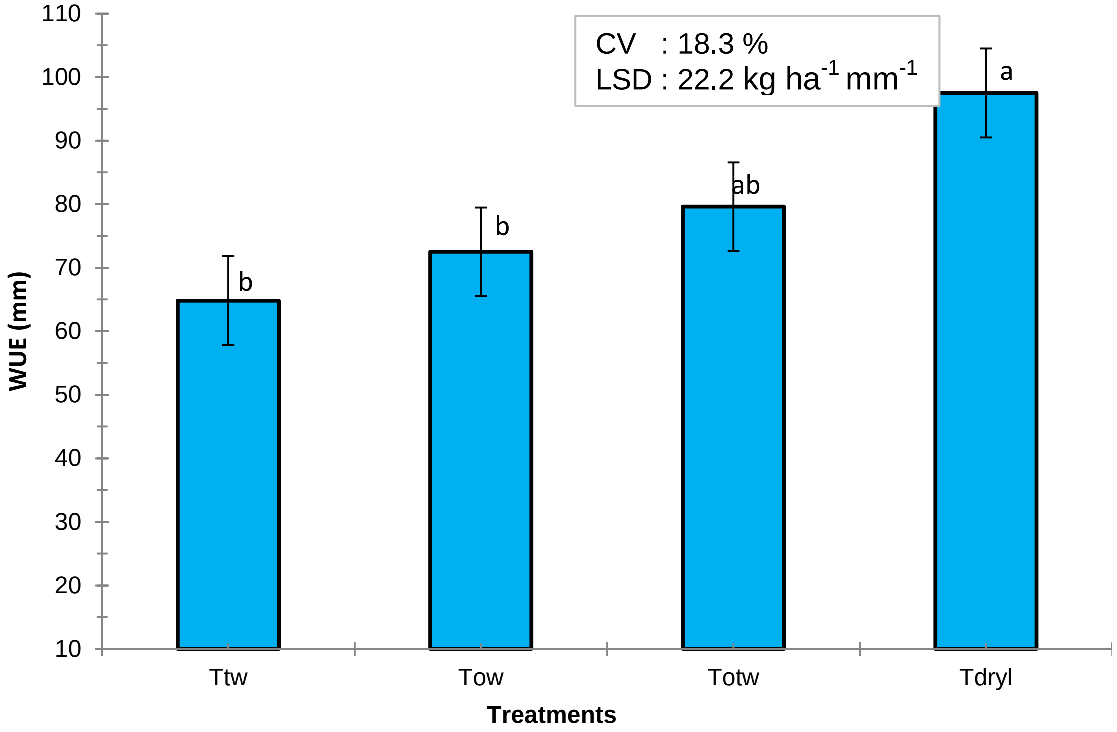

Figure 4.10: Water use efficiencies (fresh mass) of the treatments throughout the growing season. *(T_{tw} was irrigated twice in a week, T_{ow} was irrigated once in a week, T_{otw} was irrigated once every two weeks and T_{dryl} was rainfall and supplemental irrigation dependent)*

4.10 Nutritional Quality

Carotenes, predominantly, beta carotene (β-carotene) is the most important quality component of orange fleshed sweet potato, due to the fact that it is the precursor of Vitamin A, a very important nutrient to humans (Szpylka & DevRies, 2005). As one of the objectives of this study, water supply at different frequencies and quality was evaluated to determine beta carotene content and nutritional water productivity of orange fleshed sweet potato.

The objective was to establish a better understanding in the subject of beta carotene accumulation on the storage roots of the orange fleshed sweet potato; and to assist in establishing whether the crop could be grown under irregular water supply conditions but still yield sufficient beta carotene to meet requirements for human consumption.

The beta carotene content results as presented in Figure 4.11 showed that water frequencies had no effect on the β-carotene content of the sweet potato roots. A variety of environmental factors and cultural management practices factors such as exposure of storage roots to intense sunlight for a long period of time, high soil temperatures, high air temperature, farming site, cultivar type, fertilization, and age of the roots can all affect beta carotene content (Bartoli *et al*., 1999; K'Osambo *et al*., 1998).

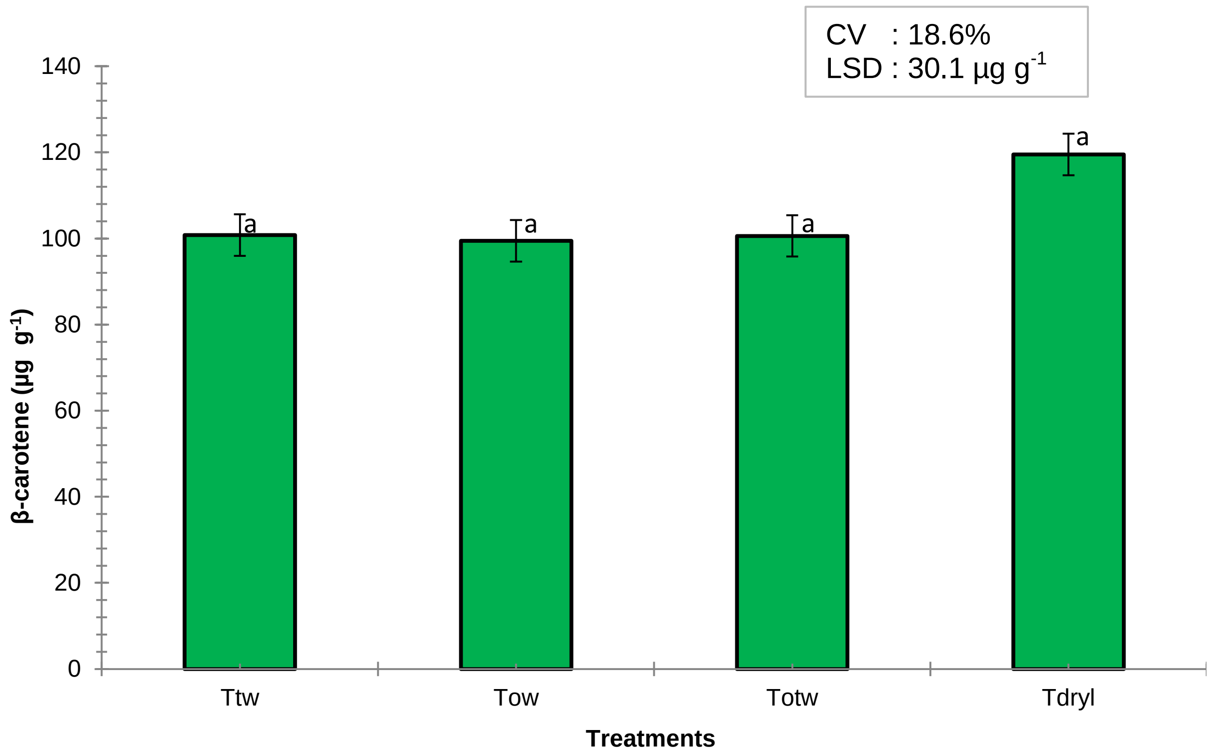

Figure 4.11: Beta carotene content for the irrigation treatments. *(T_{tw} was irrigated twice in a week, T_{ow} was irrigated once in a week, T_{otw} was irrigated once every two weeks and T_{dryl} was rainfall and supplemental irrigation dependent)*

Soil type is another element that has an influence on the β-carotene content (Lester & Eischen, 1995). Lester & Eischen (1995) conducted an experiment to determine the effect of soil type on the beta carotene content of muskmelon and found that sandy loam soil produced fruit with less beta carotene when compared to silty clay loam soils; which produced higher beta carotene content levels. Post-harvest handling and storage are other factors influencing the beta carotene content of crops (Rodriguez-Amaya, 2001).

Although there were no significant differences amongst the treatments of this study, beta carotene content of treatment T_{dryl} (119.53 µg g^{-1}) was relatively higher than the treatments under the rain shelter (T_{tw}, T_{ow} and T_{otw}). Faber *et al*. (2013) attributed to different water applications as contributing factors to the differences in beta carotene when comparing sweet potato crop that received regular water application to that which was exposed to erratic water supply.

It is therefore, against this background that treatment T_{dryl} produced higher β-carotene content compared to the other treatments. Values attained in the present study were consistent with 79.8 µg g^{-1} reported by Ben-Amotz & Fishler (1998).

4.11 Nutritional water productivity (NWP)

Nutritional water productivity (NWP) is an emerging concept that takes water productivity a step closer to human nutrition (Wenhold *et al*., 2012). The main interest of the NWP is to produce more nutrition per drop of water (Renault & Wallender, 2000).

Most studies focus on nutritional productivity or water productivity as isolated concepts. In this study the focus was based on the concept of NWP as a holistic term that looks at producing more nutrients (beta carotene) per millimetre of water used.

NWP of orange fleshed sweet potato was calculated as the ratio of actual harvested storage root yield (kg ha^{-1}), at final harvest, over the actual evapotranspiration

(m^3 ha^{-1}) of the entire growing season, multiplied by the nutritional content; which in this context, is the beta carotene content of the harvested roots.

Comparatively, nutritional water productivity value for treatment T_{dryl} was higher (1177 mg m^{-3}) but not statistically different to the other treatments (Table 4.5)

Table 4.5: Nutritional water productivity values of the orange fleshed sweet potato

Treatments	NWP (mg m^{-3})
T_{tw}	656
T_{ow}	718
T_{otw}	796
T_{dryl}	1177

Wenhold *et al*. (2012) reported NWP values of 681 mg m^{-3} for OFSP, which compares well with the values recorded in the present study. From this study, T_{dryl} was the most efficient treatment in promoting nutritional water productivity (producing high beta carotene with less water). This is attributed to the fact that T_{dryl} was exposed to a different planting setting; and relied on erratic rainfall and supplemental irrigation for water supply throughout the season. Attaining high nutrient content with less water appears to be the most important consideration in food security (Wenhold *et al*., 2012).

CHAPTER FIVE

CALIBRATION AND VALIDATION OF THE SWB MODEL FOR ORANGE-FLESHED SWEET POTATO (*Ipomoea batatas*)

Abstract

The Soil Water Balance (SWB) model is a generic crop growth and irrigation scheduling model used to simulate the soil water balance of crops. In this study, simulating the growth and water use of orange fleshed sweet potato (OFSP) (*Ipomoea batatas Lam*.) was undertaken using the Soil-Water Balance model. In order to be able to use the Soil Water Balance model, crop specific parameters for each crop are required.

The objectives of this study were to determine crop-specific model parameters for OFSP and; to calibrate and validate the SWB model for this crop. Detailed soil, water and crop growth data were collected from a field trial conducted in the 2011/12 growing season at the Hatfield Experimental Farm, University of Pretoria, to determine model parameters and calibrate the SWB model for OFSP. Independent data was collected from a different (rainshelter) trial that was conducted simultaneously to validate the model.

The SWB model simulation results revealed that the Total Dry Matter (TDM), Harvestable Dry Matter (HDM), Leaf Area Index (LAI), Soil Water Deficit (SWD) and Fractional Interception (FI) simulations fitted the measured data reasonably well. It is therefore concluded that the model can be a useful tool for scenario modelling to assess the yield and water requirements of the sweet potato crop under different environments.

Key words: crop growth, crop specific parameters, simulating growth, irrigation scheduling, orange fleshed sweet potato.

5.1 Introduction

The role of simulation models in appreciating the processes in the soil-plant-atmosphere system has considerably improved significantly in recent years. This is attributed to increase in computing abilities present today (Ines *et al*., 2001). Scheduling irrigation with the aid of computer crop growth models has rapidly become widespread, as well (Bruno *et al.,* 2007).

Computer models could simplify irrigation water management by reducing the frequency of field visits and measurements. However, model simulations of crop growth and development need to be accurate and reliable for irrigation scheduling purposes (Jovanovic & Annandale, 2000)

Several mechanistic irrigation management models have been developed and are available (Crosby, 1996; Campbell & Stockle, 1993; Singels & De Jager, 1991). Annandale *et al.* (1999) however noted that most of the existing models are either crop specific or do not simulate daily crop water use, while some are only relevant for planning purposes and do not allow real-time scheduling. Other models are suitable for research purposes, but may generally not be applicable in practice, as large amounts of input data is required and such models lack a user friendly interface. The most idealistic approach must be able to assist the user to appreciate the soil-root continuum as mechanistically as possible; taking into account the optimisation of irrigation water management (Jovanovic *et al.,* 1999).

The SWB model is an example of such a mechanistic model. The SWB model is a real-time, generic crop, soil water balance, irrigation scheduling model. It is based on the improved generic crop version of the NEW Soil Water Balance (NEWSWB) model (Annandale *et al.,* 1999). The SWB model gives a detailed description of the soil-plant-atmosphere continuum, making use of weather, soil, and crop growth management data. It calculates the water balance and crop growth with weather, soil and crop units (Annandale *et al.,* 1999).

SWB uses thermal time to describe crop development, thereby eliminating the need to use different crop factors for different planting dates and regions. Evaporation and transpiration are split to solve the problem of taking irrigation frequency into account, particularly during the initial stage of the crop, when canopy cover is low and the soil evaporation component is large (Villalobos & Fereres, 1990). Strategies of deficit irrigation, where water use is supply limited, can be described more accurately, with SWB model (Jovanovic & Annandale, 2000).

PenMan-Monteith reference crop evapotranspiration, together with a mechanistic model, which uses soil water and grows a realistic canopy and root system, provide the best possible estimate of the soil water balance (Allen *et al*, 1998). This approach, however, could not be used in the past as it required specialised knowledge and high management costs. The SWB model is packaged in a user-friendly format and has increased benefits due to its accuracy (Annandale *et al*, 1999). Although SWB was primarily developed for real-time irrigation management, it is also suitable for scenario modelling purposes.

Since SWB is a generic crop growth model, specific parameters for each crop need to be determined experimentally before it can be used for irrigation scheduling or scenario simulations (Annandale *et al.,* 1999). A recent study by Piedallu *et al.,* (2013) reported that SWB indices performed better than climatic proxies in a study to determine if the soil water balance model performs batter than climatic water variable in tree species distribution modelling. In another publication, Ines *et al* (2001) appreciate the models by mentioning the promising potential to explore solutions to water management problems using soil water balance models.

The objective of this part of the study was to generate growth model parameters for orange fleshed sweet potato to be included in the SWB model database, with the ultimate aim of creating a user-friendly irrigation scheduling and planning tool for practical application.

5.2 Materials and Methods

5.2.1 Model description

The sub-components of the SWB model include the soil, weather and crop units. These units will be discussed briefly in this chapter. Further details are described by Annandale *et al.* (2000).

According to Annandale *et al.* (2000) SWB model consist of two components; viz:

- The mechanistic crop growth model (calculates crop growth and soil water balance components) and;

- The FAO type crop factor model (calculates the soil water balance without simulating dry matter production mechanistically)

The weather unit of SWB calculates daily Penman-Monteith grass reference evapotranspiration (ET_o) as per the recommendations by the FAO (Smith, 1992).

In the weather unit of SWB, the potential evapotranspiration (PET) is divided into potential evaporation and potential transpiration by calculating radiant interception from simulated leaf area (Ritchie, 1972). Under conditions where actual transpiration is less than potential transpiration, the crop undergoes stress that reduces leaf area development. This makes the crop growth model appropriate for predicting crop water requirements when deficit irrigation strategies are applied (Annandale *et al*., 1999). The SWB model calculates potential evapotranspiration (PET) according to equation 5.1

$$PET = ET_{o\ X}\ Kc_{\ max} \qquad \textbf{(5.1)}$$

where

ET_o is the Penman-Monteith grass reference evapotranspiration

$Kc_{\ max}$ represents the maximum Kc value following rain or irrigation (Allen *et al.,* 1998)

Transpiration rate depends on the atmospheric demand, soil water potential and the FI of solar radiation by the crop canopy. FI is calculated from LAI using equations 5.2 and 5.3

$$FI = 1-\exp(-k \times LAI) \qquad \textbf{(5.2)}$$

hence $$k = \mathrm{Ln}(1 - FI) / (-LAI) \qquad \textbf{(5.3)}$$

where

k is the canopy extinction coefficient.

k values are calculated using LAI and FI measurements. Data for FI measurements is collected with a ceptometer which, measures the canopy interception of photosynthetically active radiation (PAR).

The canopy extinction coefficient for PAR (K_{PAR}) can be used to calculate photosynthesis as a function of intercepted PAR. K_s is required for predicting radiation-limited dry matter production (Monteith, 1977) and for partitioning of ET into evaporation from the soil surface and crop transpiration (Ritchie, 1972). The procedure recommended by Campbell & van Evert (1994) is used to convert K_{PAR} into K_s)

$$K_s = K_{bd}\sqrt{a_s} \qquad \textbf{(5.4)}$$

$$K_{bd} = K_{PAR}\sqrt{a_p} \qquad \textbf{(5.5)}$$

$$a_s = \sqrt{a_p\, a_n} \qquad \textbf{(5.6)}$$

where

K_{bd} - Canopy radiation extinction coefficient for leaves

a_s - Leaf absorptance of solar radiation

a_p - Leaf absorptance of PAR

a_n - Leaf absorptance of near infrared radiation (NIR, 07-3 µm)

In the crop unit, the SWB model calculates crop dry matter (DM) production in direct proportion to transpiration corrected for VPD (Tanner & Sinclair, 1983). It also calculates radiation limited growth (Monteith, 1977) and takes the lower of the two values. This DM is partitioned into roots, stems, leaves and grains or fruits. Partitioning depends on the phenology which is calculated with thermal time and modified by water stress.

The specific crop growth parameters required by SWB are generated to enable simulation of growth and water use of crops (refer to Table 5.3). According to Tanner & Sinclair (1983) the relationship between dry matter production and crop transition needs to be corrected to account for atmospheric conditions, particularly the vapour pressure deficit (VPD). In this regard the dry matter-water ratio (DWR) is calculated as:

$$DWR = (DM \times VPD)/ET \qquad \textbf{(5.7)}$$

where

DM (kg m^{-2}) is the total dry matter yield measured at harvest

VPD represents the average vapour pressure deficit (Pa) of the season,

ET represents seasonal crop evapotranspiration in mm, which is equivalent to kg m^{-2}. Refer to equation 3.1 on how ET is obtained

Since radiation conversion efficiency (E_c) is a crop specific parameter, the dry matter production can be calculated using E_c under conditions of radiation-limited growth (Monteith, 1977), as follows:

$$DM = E_c \times FI \times R_s \qquad \textbf{(5.8)}$$

where

DM is the dry matter yield in kg m^{-2}

R_s is the total seasonal intercepted solar radiation (MJ d^{-1})

FI is the fractional interception

The SWB model calculates daily increments of DM production and the partitioning of assimilates to the reproductive sinks and roots as either transpiration-limited (eq. 5.7) or radiation limited (eq. 5.8). The remaining DM is then partitioned to the canopy dry matter (CDM). Leaf dry matter (LDM) and stem dry matter (SDM) are calculated using the equations below:

$$LDM = CDM / (1 + PART) \qquad \textbf{(5.9)}$$

$$SDM = CDM – LDM \qquad \textbf{(5.10)}$$

LAI is also calculated using LDM as follows:

$$LAI = SLA \times LDM \qquad \textbf{(5.11)}$$

where

SLA represents the specific leaf area in m^2 kg^{-1}

LDM is the leaf dry matter in kg m^{-2}

The input data required in order to run the model are detailed in sections 5.2.2 to 5.2.5.

5.2.2 Crop management data

Table 5.1 presents crop management input data and measurements that were collected during the growing season. The data was required to enable simulation of the SWB model

Table 5.1: Crop management data used for simulations

Factor	Value/type
1.Trial planting date	01 December 2011
2. Irrigation system type	Sprinkler/ drip
3. Irrigation delivery (mm/h)	15.0
4. Irrigation system efficiency (%)	95/85
5. Plot size (m^{-2})	15

5.2.3 Soil data

Soil data used by the SWB balance model for simulation is summarized in Table 5.2 below.

Table 5.2: Summarized soil profile data used for simulations

Factor	Value
1. Layer thickness (m)	0.79
2. Bulk density (Mg m^{-3})	1500
3. Field capacity (m/m)	0.25
4. Permanent wilting point (m/m)	0.13
5. Drainage factor	0.60
6. Drainage rate (mm/day)	80

5.2.4 Weather data

The weather data used for the simulation period is tabulated in Table 4.1 under Chapter 4.

5.2.5 Crop parameters

The crop parameters determined for the purpose of the simulation is comprehensively tabulated in Table 5.3.

Table 5.3 presents a summary of crop growth parameters that were determined from the measured data. Data for model parameter determination was collected from treatment Tdryl, which was an independent field block. These parameters were also used to calibrate the model. Some of the parameters tabulated on the table were calculated from the data collected throughout the season. Other values were estimated while some were sourced from the literature.

Table 5.3: Summary of crop growth parameters determined for orange fleshed sweet potato to calibrate the SWB model

Crop growth parameter	Value	Source
Canopy radiation extinction coefficient	0.85	Calculated
Corrected dry matter water ratio (Pa)	6.5	Calculated
Radiation conversion efficiency (kg MJ^{-1})	0.00121	Calculated
Base Temperature (^{o}C)	8	Somasundaram & Mithra (2008)
Temperature for optimum crop growth (^{o}C)	28	Somasundaram & Mithra (2008)
Cut-off temperature (^{o}C)	38	Somasundaram & Mithra (2008)
Emergence day degrees (^{o}C)	25	Calculated
Flowering day degrees (d ^{o}C)	650	Calculated
Day degrees for maturity (d ^{o}C)	1950	Calculated
Day degree transition period (d ^{o}C)	480	Calculated
Day degrees for leaf senescence (d ^{o}C)	1650	Calculated
Maximum crop height (m)	0.60	Measured
Maximum root depth (m)	1.5	FAO (1998)
Fraction of total dry matter translocated to the roots	0.45	Estimated
Canopy storage (mm)	1	Estimated
Leaf water potential at the maximum transpiration (kPa)	-1500	FAO (1998)
Maximum transpiration (mm d^{-1})	8	Estimated
Specific leaf area (m^2 kg^{-1})	9.8	Calculated
Leaf-stem partition parameter (m^2 kg^{-1})	1.0	Estimated
Total dry matter at emergence (kg m^{-2})	0.03	Estimated
Root fraction	0.15	Estimated
Root growth rate (m^2 $kg^{-0.5}$)	3.5	Estimated
Stress index	0.90	Estimated

5.2.6 Statistical norms

The predictions of the SWB model are assessed using statistical norms that were recommended by De Jager (1994). The norms are as follows: the index of agreement (d), root mean square error (RMSE) and coefficient of determination (r^2) and mean absolute error (MAE). According to De Jager (1994), d and r^2 ought to be >0.8 and MAE <0.2. These norms were used to determine the model accuracy. RMSE reflects the magnitude of the mean difference between predicted and measured values.

5.3 Results and Discussion

5.3.1 Determination of model parameters

5.3.1.1 Radiation conversion efficiency

Figure 5.1 represents total dry matter production of sweet potato as a function of the cumulative product of fractional interception and solar radiation (FI x R_s). The slope of the regression line represents radiation conversion efficiency of the crop. The high coefficient of determination (r^2) indicates that radiation conversion efficiency is a relatively conservative and predictable parameter under conditions of sufficient water supply (Jovanovic *et al*., 1999).

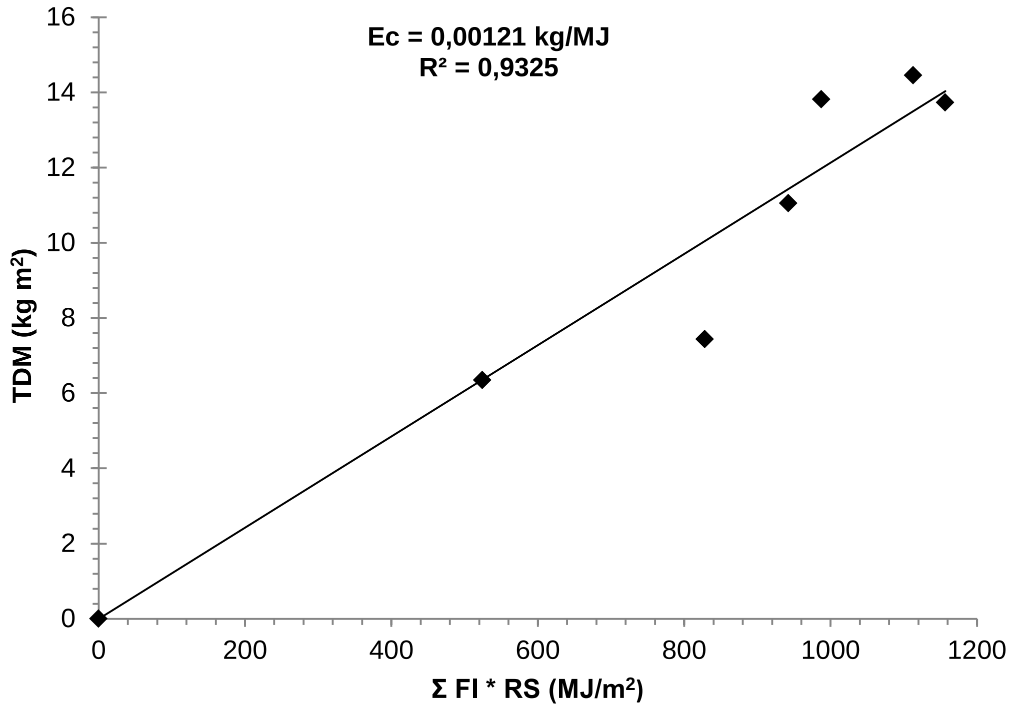

FIGURE 5.1: Total dry matter production of sweet potato as a function of cumulative product of fractional interception and solar radiation (FI x R_S). Radiation conversion efficiency (E_C) and the coefficient of determination (r^2) of the linear function are shown.

5.3.1.2 Specific Leaf Area

Specific leaf area (SLA) is known as the ratio of leaf area to leaf mass and is a parameter used to determine the morphology of a specific crop. It is an important trait in plant physiology as it is associated with many critical aspects of plant growth and survival (Shipley & Vu, 2002). The specific leaf area data is presented in Figure 5.2. Average specific leaf area value recorded in this experiment was 9.8 m^2 kg^{-1}. The SLA line followed a decreasing tendency with increase in the number of days after planting, as observed from 40 DAP to 121 DAP. The highest SLA value was

12.5 m^2 kg^{-1} (at 40 DAP) and the lowest value attained was at 121 DAP (6.71 m^2 kg^{-1}). SLA has to be known in order to convert leaf dry matter yield to leaf area and LAI in the SWB model (Jovanovic *et al*., 1999)

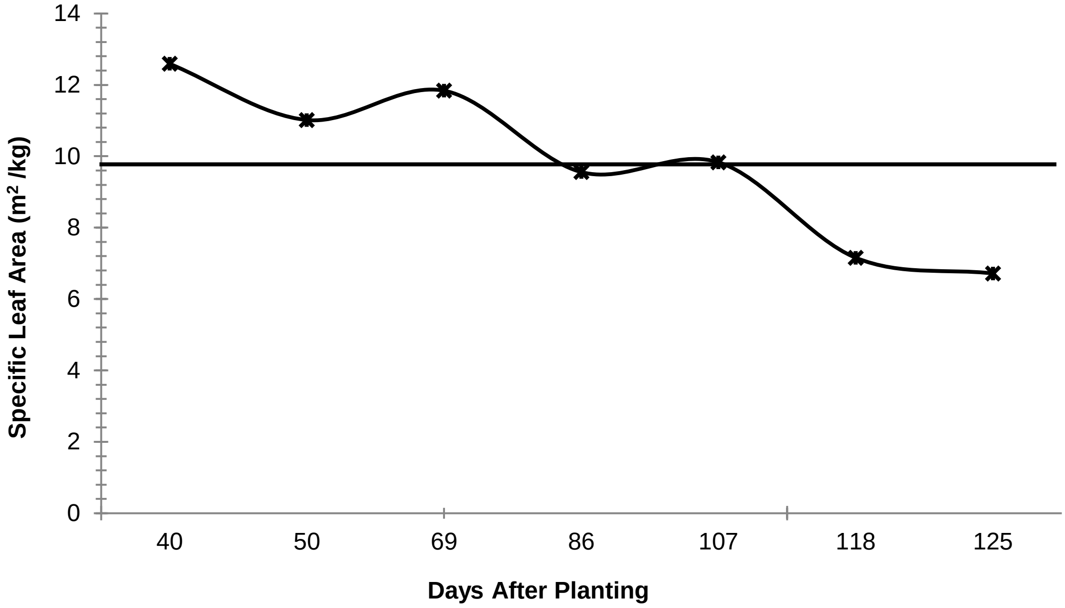

FIGURE 5.2: Measured values of specific leaf area of treatment T_{dryl} during the cropping season of sweet potato.

5.3.2 Model calibration

The Soil Water Balance model was calibrated using values of data measured in the field block that was outside the rainshelter. The field measurements used for the calibration included leaf area index (LAI), harvestable (storage root) and total biomass yield (TDM and HDM), fractional interception of photosynthetically active radiation (FI), crop water use and calculated soil water deficits (SWD).

Figures 5.3 and 5.4 consist of graphical plots extracted from the model results for the calibration data set. This includes a summary of the soil water balance, simulated and measured values of root depth, leaf area index, total and harvestable dry matter yields; and soil water deficits.

Figure 5.3 is comprised of two histograms that represent rainfall (brown) and irrigation (blue) input data of the growing season. The line at the lower extreme of the soil water balance graph (blue and red) is the simulated soil water deficit; and the horizontal line (blue) represents field capacity of the soil. The soil water balance graph also provides a summary of seasonal water balance components, planting date and the type of irrigation system.

The model simulations of LAI, TDM and HDM; and SWD fitted the measured values reasonably well (Figure 5.4). The model, however, underestimated LAI during the maximum leaf development phase. Statistical measures (Table 5.4) were within the acceptable ranges as recommended by De Jager (1994).

The measured values of total dry matter were marginally underestimated and the harvestable dry matter yield was only slightly underestimated at the beginning and at the end of the season. In general, the statistical measures indicated acceptable accuracy (refer to Table 5.4).

Simulations for soil water deficit were predicted in a reasonable manner. From December to January, the model simulated lower soil water deficits. As the season progressed, the simulated soil water deficits followed the tendency of measured values. Around late February/early March, the measured values showed descend in deficits. The simulation showed that the rainfall during that period did not absolutely eliminate the deficit resulting into marginally overestimated simulations. This continued to the end of the season. Another reason of the simulation to overestimate the deficit could be that the measured deficits did not include soil layers deeper than 1.5 meters (the root depth for sweet potato); and the simulation could have included, assuming that the storage roots were growing under dry soil.

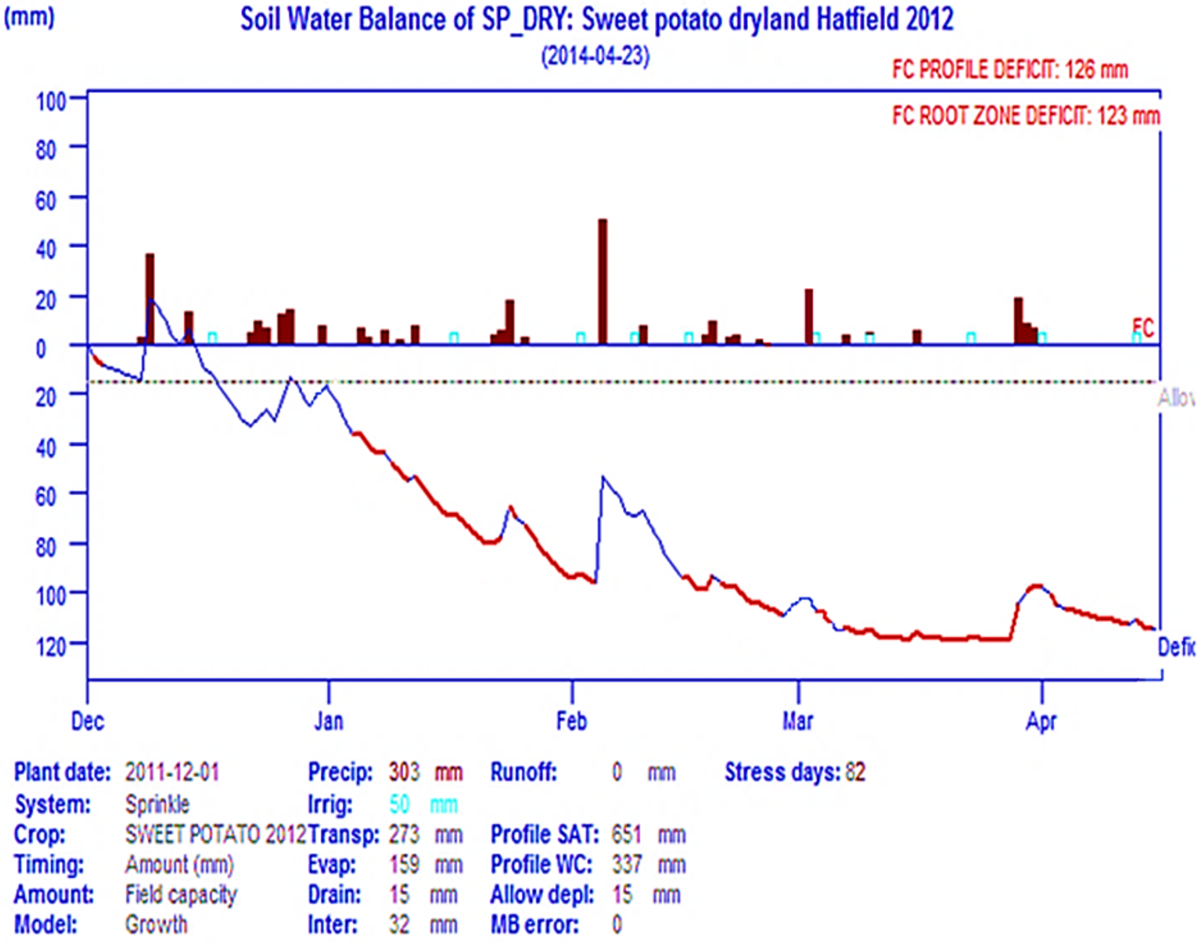

Figure 5.3: Soil water balance summary graph for treatment T_{dryl} (calibration data set)

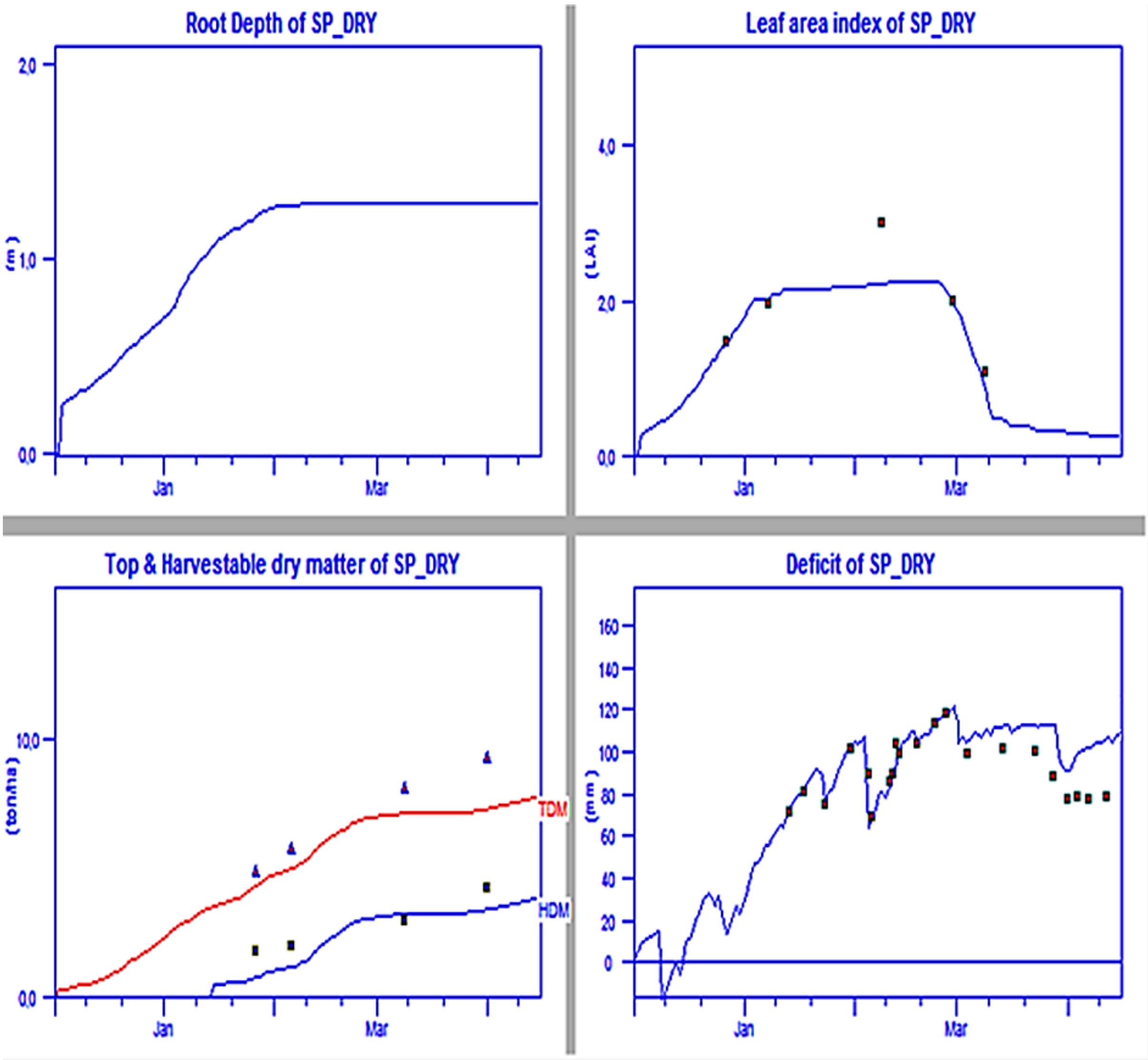

FIG 5.4: Simulated (lines) & Measured (symbols) values of Root Depth, Leaf Area Index, Total and Harvestable Dry Matter & Soil Water Deficit (T_{dryl}) (calibration data set). (*Refer to Table 5.4 for simulated and measured values*)

Table 5.4: Statistical results of the simulated and measured values for treatment T_{dryl}

Statistical norms	LAI	TDM & HDM	Deficit
N	5	4	21
r^2	0.80	0.97	0.87
D	0.90	0.86	0.79

(*N - number of observations, r^2 – coefficient of determination, D- Wilmott's index of agreement)*

5.3.3 Model validation

An independent data set, of the same planting season, was used to validate the calibrated SWB model. The data for validating the model was collected from the treatments of the trial under the rainshelter (T_{tw}, T_{ow} and T_{otw}). The total and harvestable dry matter yields were only determined at final harvest. A summary soil water balance graph, comparison between simulated and measured values of total and harvestable dry matter yields; and soil water deficits for Treatment T_{tw} are shown in Figures 5.5 and Figure 5.6. The total dry matter simulation for T_{tw} was marginally lower than the measured data, while simulations for harvestable dry matter was slightly over estimated relative to the measured values.

Soil water deficits were predicted in a reasonable manner (r^2 = 0.65, d= 0.77). From early-January to early-February, simulations of the water deficit values were overestimated compared to the measured values. Simulations of decreasing water deficits were observed during the rapid bulking phase of storage roots (from late February). During this phase (early March), LAI simulations showed reduction in leaf area.

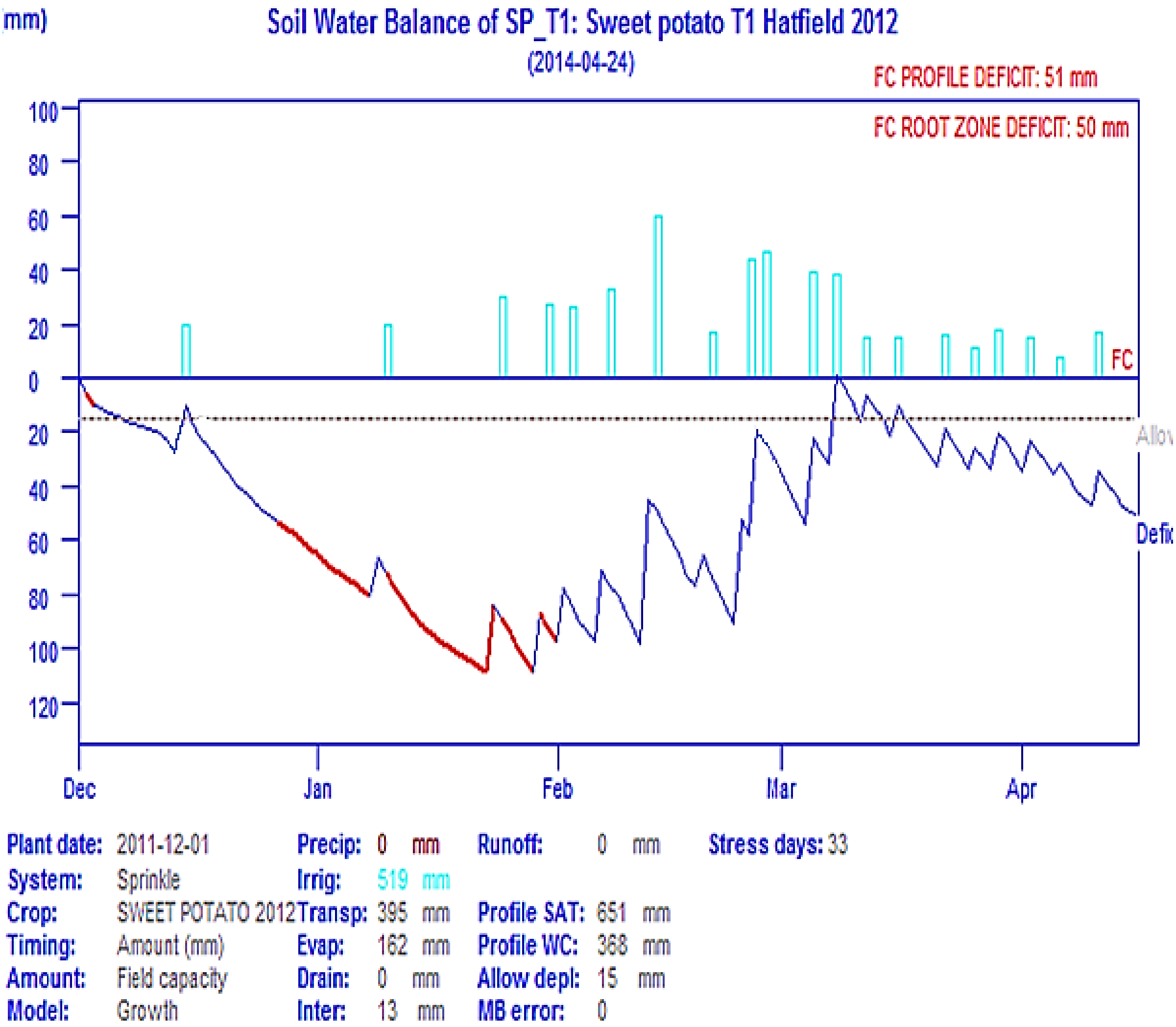

Figure 5.5: Soil water balance summary graph for treatment T_{tw} (validation data set)

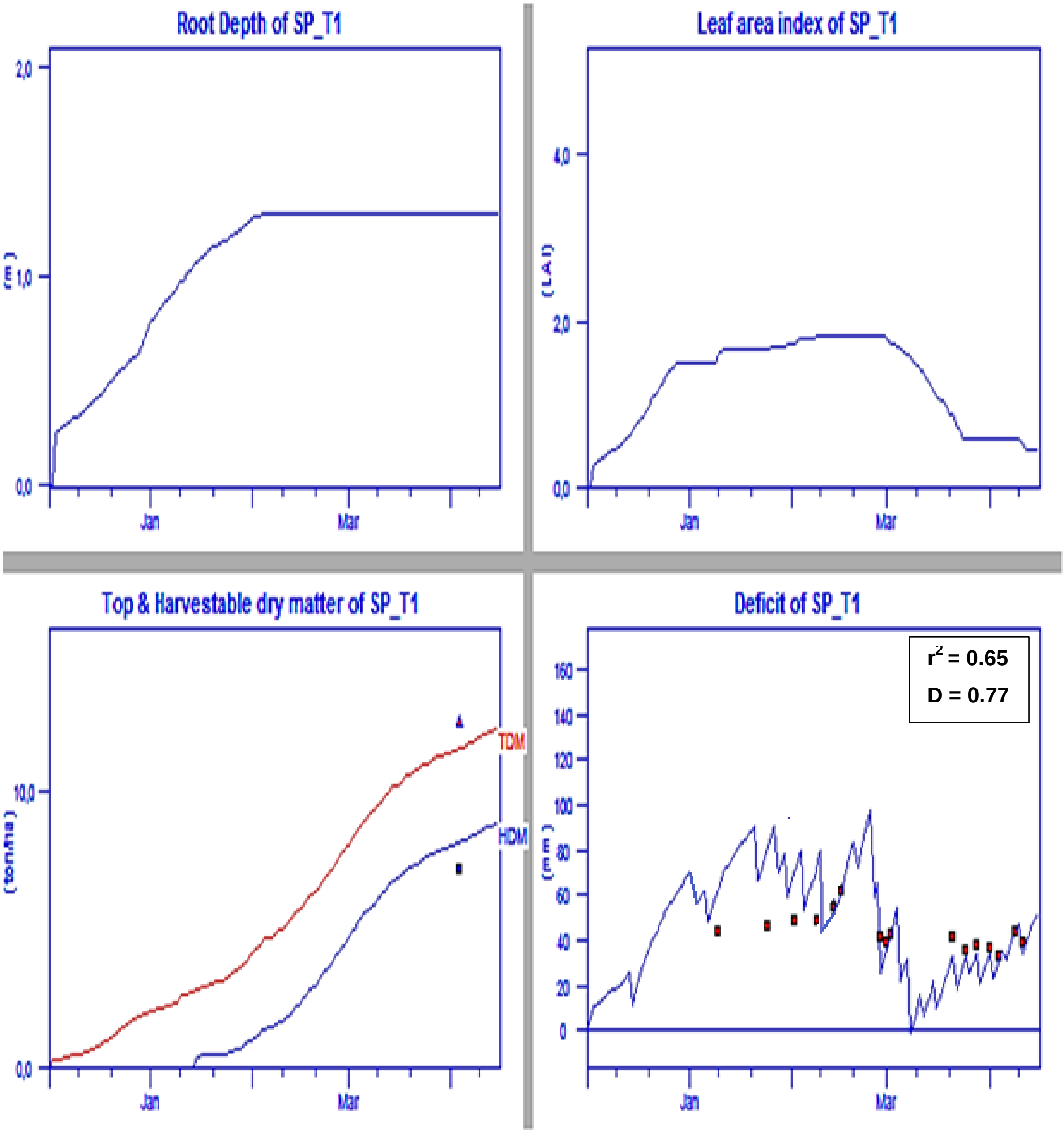

Figure 5.6: Simulated (lines) and measured (symbols) values of Root Depth, Leaf Area Index, Total and Harvestable Dry Matter and Soil Water Deficits (Treatment T_{tw}; validation data set)

5.3.4 Summary and conclusions

This study was conducted to determine crop specific model parameters for OFSP and; to calibrate and validate the SWB model in a reasonable manner. Data obtained from the trial was used to generate crop parameters for OFSP cultivar Resisto, which were then added to the database of crop-specific model parameters in SWB. The soil water deficit to field capacity was predicted with reasonable accuracy and thus the model can essentially be used for future irrigation scheduling and planning.

In this experiment, reasonable predictions (with mostly acceptable statistical accuracy values) of leaf area index, biomass produced, crop water use, calculated soil water deficits and storage root yield were achieved. Most importantly, the Soil Water Balance model was calibrated and validated for the selected cultivar, and crop modellers may in future simulate growth and water use of the crop under different conditions and scenarios from the parameters that were determined. Even though statistical accuracy in some simulations may need improvement, the model can still be a useful tool to assess the yield and water requirements of the sweet potato crop in different environments.

CHAPTER 6

GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

6.1 GENERAL DISCUSSION AND CONCLUSIONS

Results of this experiment show that there were significant differences between the treatments in the water use of orange fleshed sweet potato. Water use was higher when the sweet potato crop was exposed to frequently irrigated treatment (T_{tw}). The crop water use for treatment T_{dryl} was 38% less than T_{tw}. Interestingly, the results showed that the highest storage root yield was obtained by treatment T_{dryl} and T_{tw}. Furthermore, water use efficiency was higher under treatment T_{dryl} compared to the other treatments. This indicate that the response of sweet potato under treatment T_{dryl} performed well, considering the high WUE and high storage root yield compared to the treatments under the rain shelter.

LAI measurements of this study were only collected from the dryland block (T_{dryl}) for the purpose of SWB simulation. Values attained from this study were within values reported within literature (Mukhopadhyay *et al*., 1992; Nair & Nair, 1995). It was observed that, from the 4th week after planting, the canopy had completely covered the ground surface between the plants; the canopy remained active until the onset of frost, whereafter leaf numbers began to decline. LAI measurements from each treatment could have aided the study with good comparison of the crop performance under the different irrigation scenarios.

Harvest index (HI) is a very valuable component of yield as it represents the efficiency of the conversion of photosynthetic products, by the crop, to economically valuable form (Bhagsari & Doyle, 1990). Water supply frequency significantly influenced total dry matter yield (TDM) of the crop. According to Shamsi *et al* (2010) total dry matter (TDM) yield is positively correlated to yield components such as harvest index and storage root yield under water stress conditions. Although TDM yield of T_{ow} was relatively lower (10.3 t ha^{-1}), the treatment (T_{ow}) produced higher harvest index (59.3%) among the treatments. This is indicative that the sweet potato crop under treatment T_{ow} encouraged better harvest index, thus enabling the treatment to efficiently translocate photosynthates to the main sink (storage root yield).

Under soil water deficit conditions, the carotenoid biosynthetic pathway is expected to accumulate more beta carotene (Riggi *et al*., 2008). Although statistical differences amongst the treatments were not significant, beta carotene content of treatment T_{dryl} was 17 % higher than the other treatments. K'Osambo *et al.* (1998) reported that beta carotene content and accumulation could be influenced by a variety of environmental factors and cultural management practices. A similar response was identified on the results of nutritional water productivity where T_{dryl} had high value NWP of 1177 mg m^{-3}. Results of this study demonstrated that the sweet potato crop under T_{dryl} performed relatively better to the other treatments.

Reasonable results on calibration and validation of the Soil-Water Balance (SWB) model for orange fleshed sweet potato (Resisto cultivar) to enable accurate water use estimation, under a range of conditions and different environments was achieved. Crop modellers can consider using the calibrated model as a useful tool to assess yield and water requirements of the crop.

6.2 RECOMMENDATIONS

In a water-limited environment, optimal depth of irrigation water must be maintained in the soil to a level where severe water stress, which could adversely affect the crop yield and quality, is prevented. Secondly; in future experiments, each plot must be allocated a water meter that will quantify the specific amount of irrigation water applied to each plot for ease in irrigation data collection. Thirdly; future studies should consider factors such as trial design, soil type and a different orange fleshed sweet potato cultivar to test and validate the outcomes of water supply levels on the beta carotene content. Lastly, some model parameters of the SWB model for the sweet potato may need to be improved for better accuracy.

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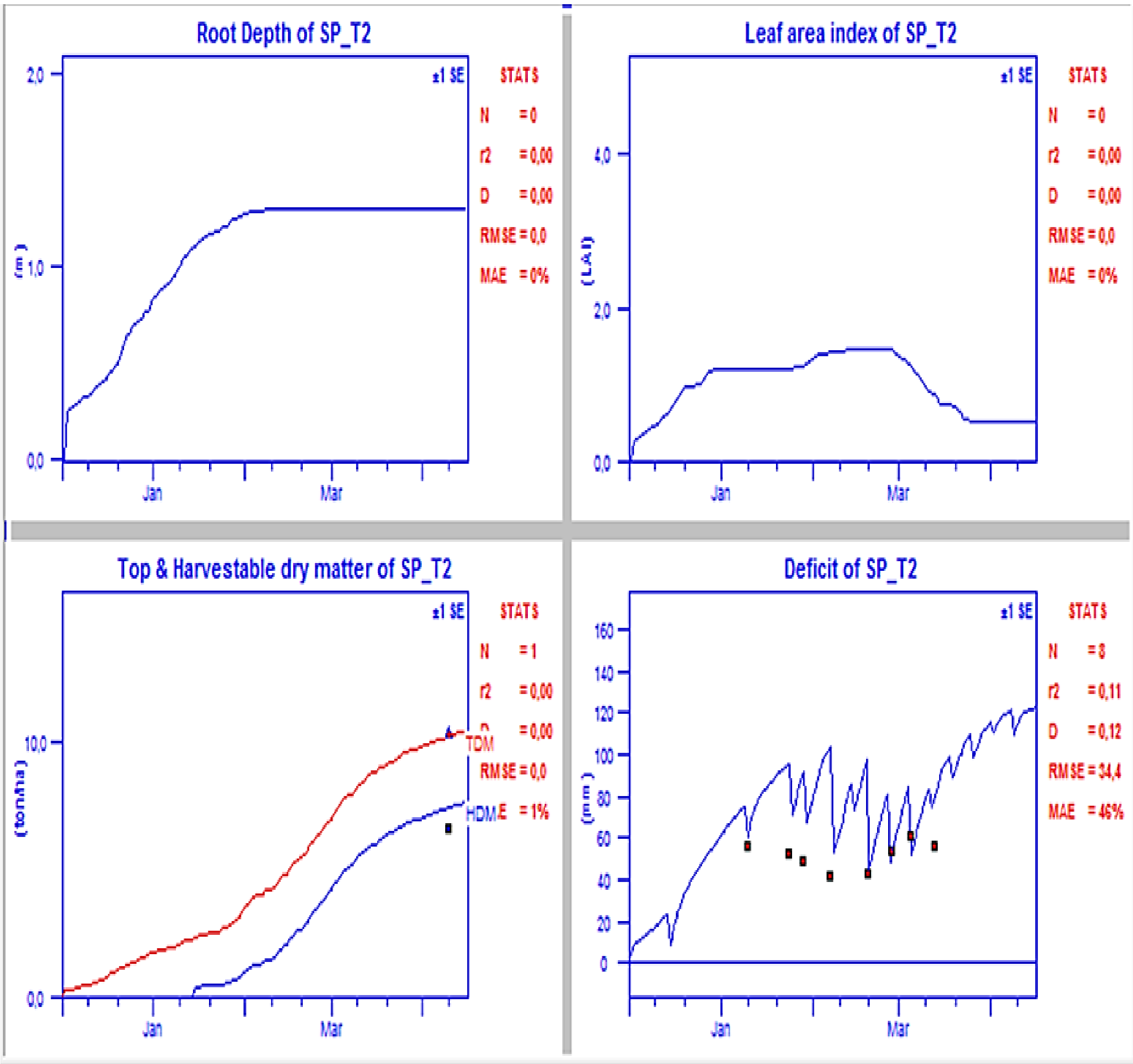
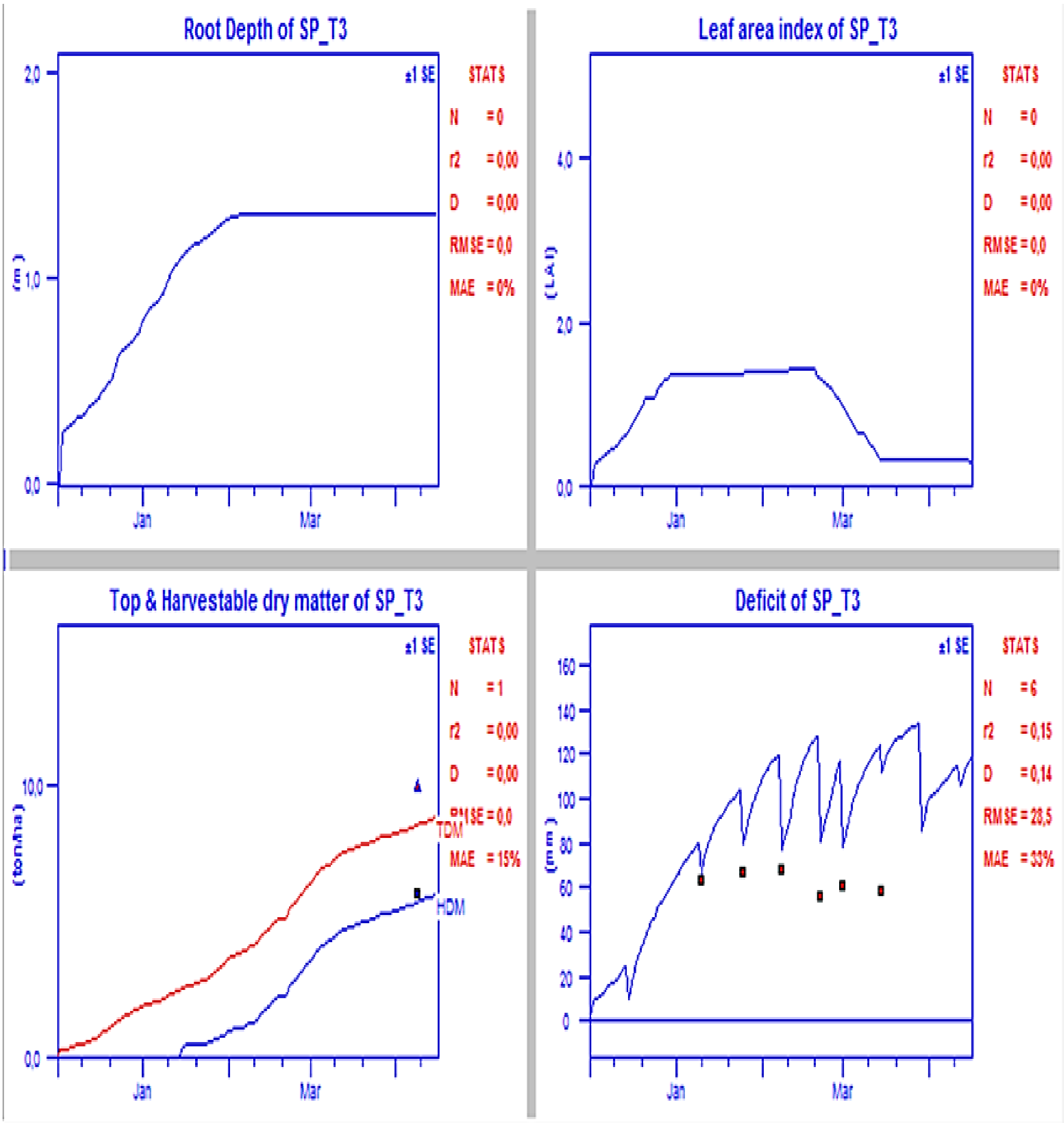
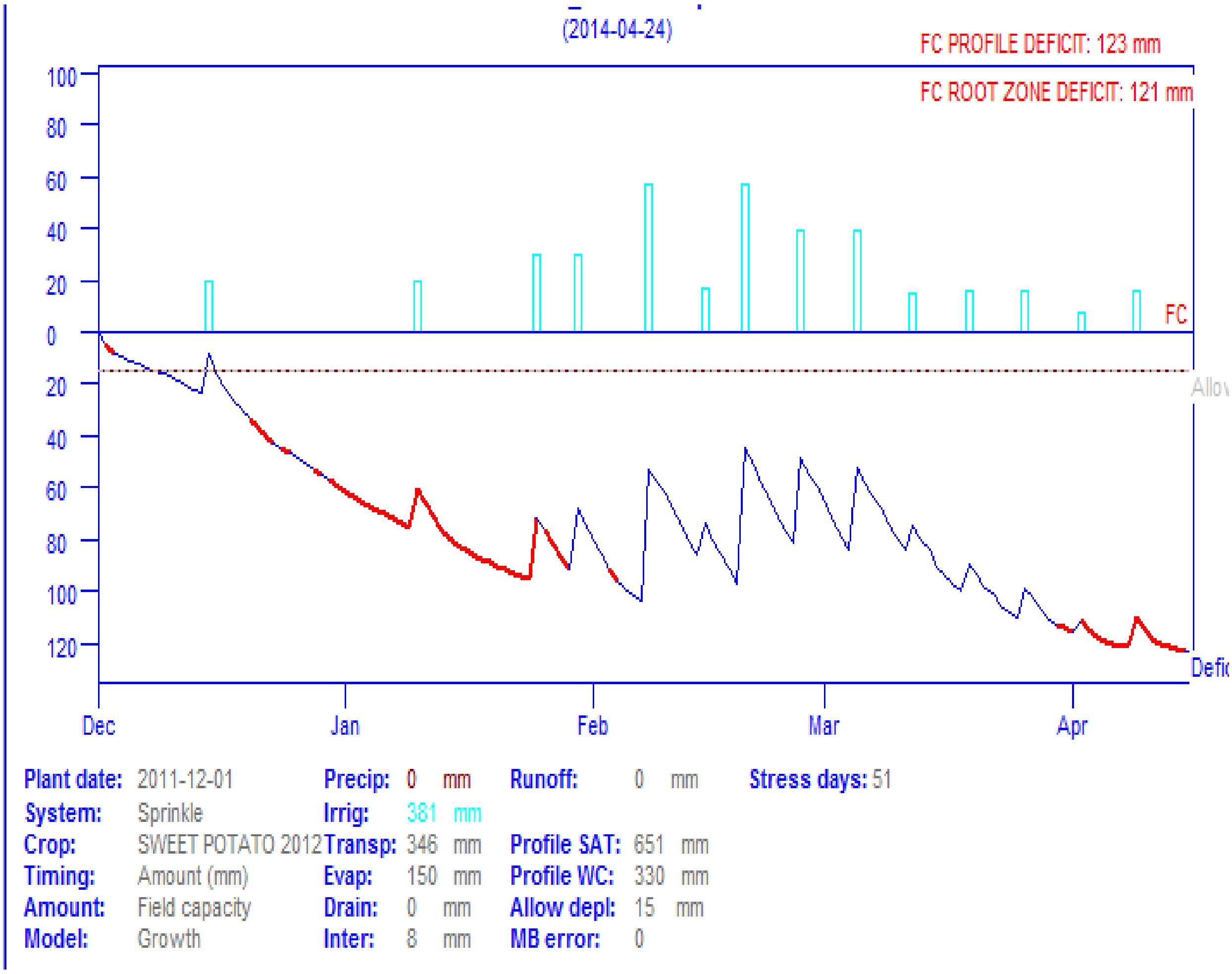
APPENDIX 1: A figure representing simulated (lines) & Measured (symbols) values of Root Depth, Leaf Area Index, Top and Harvestable Dry Matter & Soil Water Deficit (Treatment T_{OW})



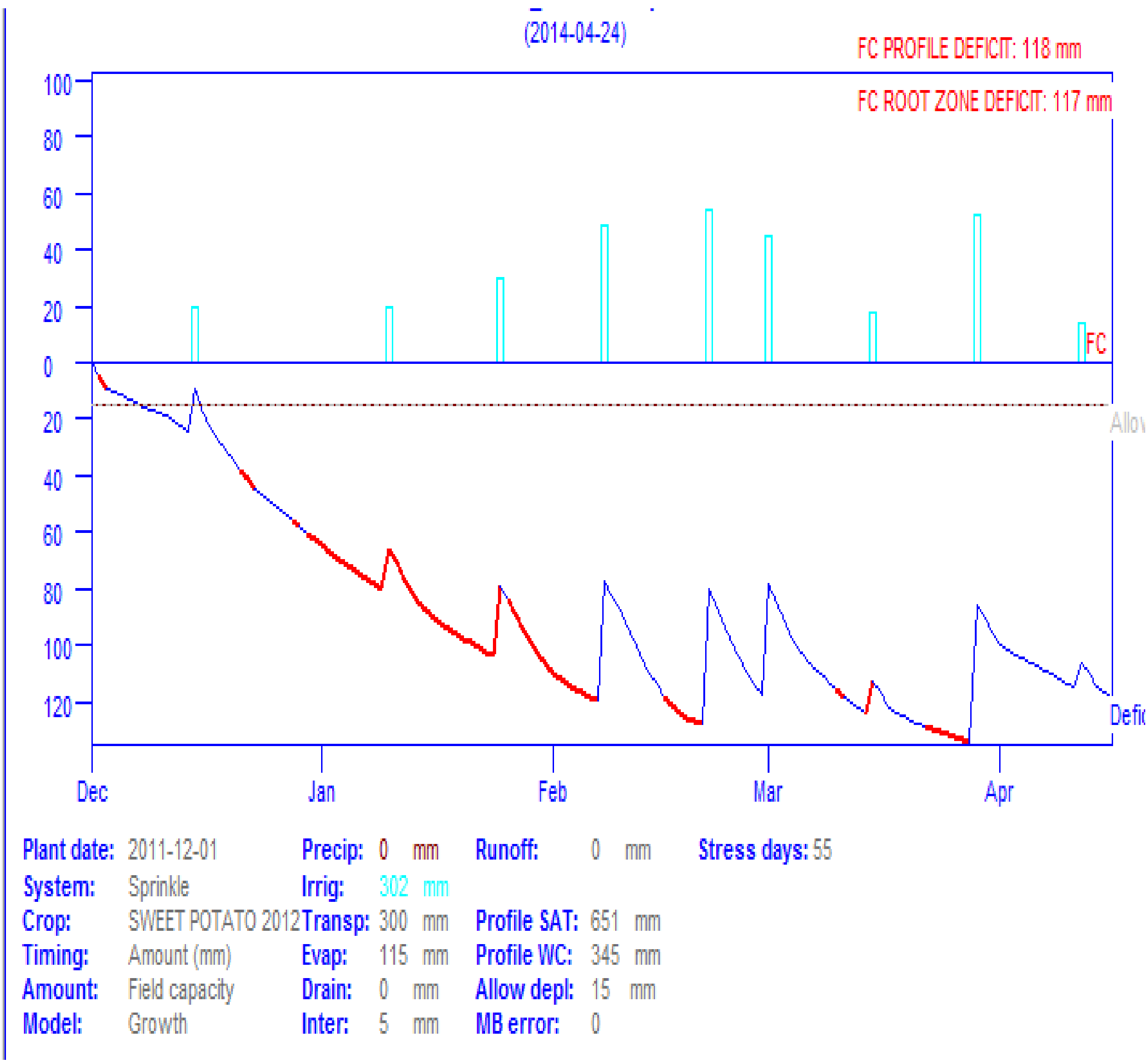
***APPENDIX 2*: ** A figure representing simulated (lines) & Measured (symbols) values of Root Repth, Leaf Area index, Top and Harvestable Dry matter & Soil Water Deficit (Treatment T_{otw})



APPENDIX 3: Soil water balance summary graph for treatment T_{ow}



APPENDIX 4: Soil water balance summary graph for treatment T_{otw}



APPENDIX 5: ANOVA tables

Water use

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	76073.187	25357.7292	1.76	0.2077
Error	12	172656.75	14388.0625		
Total	15	248729.93			
CV	32.81	LSD	184.8		

Water use efficiency

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	2325.42	775.142292	3.73	0.0421
Error	12	2496.75	208.06		
Total	15	4822.18			
CV	18.33	LSD	22.22		

Storage root yield (Fresh)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	94274568.5	31424856.2	5.10	0.0167
Error	12	73979440.7	6164953.4		
Total	15	168254009.3			
CV	8.75	LSD	3825.3		

Storage root yield (Dry)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	2.382	0.894	0.87	0.492
Error	12	9.254	1.028		
Total	15	14.637			
CV	6.8	LSD	1.622		

Harvest index

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	120.79	40.26	3.71	0.0426
Error	12	130.31	10.85		
Total	15	251.11			
CV	5.95	LSD	5.07		

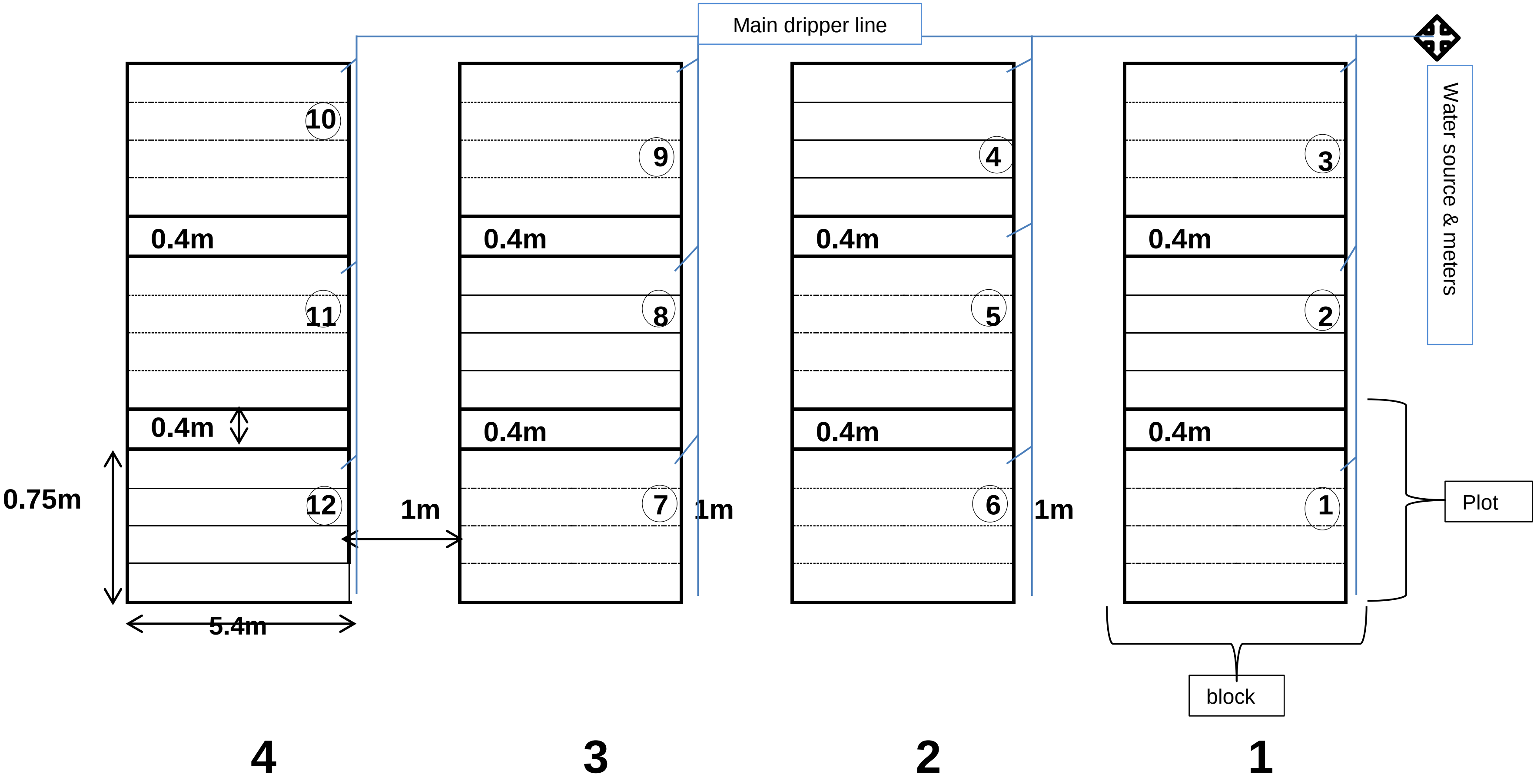
Total dry mass

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	32.62	10.87	22.18	<.0001
Error	12	5.88	0.49		
Total	15	38.50			
CV	5.88	**LSD**	1.07		

Beta carotene content

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	1114.97	371.65	0.97	0.4390
Error	12	4600.33	383.36		
Total	15	5715.30			
CV	18.63	**LSD**	30.16		

APPENDIX 6: Trial plan



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TEST REPORT

SABS

APPENDIX 7: Beta carotene analysis test results

SWEET POTATOES

RESULTS OF ANALYSIS

Date received: 2012-05-22

Date commenced: 2012-05-31

Method used	Test performed	Requirements	Sample No.		
			Plot 1	**Plot 2**	**Plot 3**
AOAC + HPLC	ß-Carotene Content, mg/kg	-	106,7	100,8	111,5
			Plot 4	**Plot 5**	**Plot 6**
	ß-Carotene Content, mg/kg	-	82,8	120,2	84,9
			Plot 7	**Plot 8**	**Plot 9**
	ß-Carotene Content, mg/kg	-	109,8	78,9	86,3
			Plot 10	**Plot 11**	**Plot 12**
	ß-Carotene Content, mg/kg	-	66,5	119,7	135,3
			Row Y, DLB	Row 2, DLB	Row 3, DLB
	ß-Carotene Content, mg/kg	-	121,5	117,0	121,9

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APPENDIX 8: Soil test analysis results

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Jaar / Year	LabNo	VeldNo / FieldNo	pH water	Weerstand / Resistance / Ohm	P Bray I mg/kg	Ammonium Acetaat Oplosbare : / Ammonium Acetate Extractable : Ca mg/kg	K mg/kg	Mg mg/kg	Na mg/kg
2011	1421	R - shelter (11/11/11)	6.0		47.6	708	74	116	18
2011	1422	Outside block (11/11/)	5.6		55.7	452	70	90	0.0