NUTRITIONAL WATER PRODUCTIVITY OF TRADITIONAL VEGETABLE CROPS

Report to the

WATER RESEARCH COMMISSION

by

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EXECUTIVE SUMMARY

Background and rationale

Sub-Saharan African (sSA) countries are facing three interrelated challenges, namely water scarcity, population growth, and food and nutritional insecurity of essential micronutrients (Fe and Zn) and vitamin A. Agricultural production needs to increase and has to be achieved against a backdrop of issues such as climate change (extreme weather, flooding, and droughts), soil fertility depletion, and land degradation. Micronutrient (Fe and Zn) and vitamin A deficiencies affect resource poor households (RPHs) who are located in less favourable areas characterized by poor soil fertility, low yield, as well as lack of capital and agricultural inputs (specifically water and fertilizer). Therefore, Agriculture needs to re-think agro-biodiversity solutions when planning a food based approach in curbing micronutrient deficiency. Traditional vegetable crops (TVCs) are highly nutritious in terms of Fe, Zn, and β-carotene and are drought tolerant (can withstand adverse environmental conditions), when compared to exotic vegetables. However, this assumption has been based on the fact that some TVCs grow naturally in marginal environments that are characterized by poor soil fertility, while depending solely on sporadic rainfall. In 2012, the Water Research Commission of South Africa published a report entitled **Nutritional value and water use of African leafy vegetables for improved livelihoods** (WRC Report No. TT 535/12)**.** Key findings of the project were that these TVCs have the potential of providing more than 50% of the recommended daily allowance for Fe, Zn, and vitamin A. However, these findings were based on plant samples taken from locations where soil fertility and actual evapotranspiration (Eta), or crop water use, were unknown. As such, further research was needed to better understand the link between management practices, water, soil nutrients, biomass, and nutritional content of TVCs. *Beta vulgaris (*Swiss chard) was used as a reference crop because it is a leafy vegetable, highly nutritious (contains Fe, Zn and β-carotene), commercialized in South Africa and mostly utilized by RPHs who eat it as a relish with maize porridge.

Project aim and objectives

The main aim of the project was to understand the effects of water and soil nutrient (N, P, and K) interactions on nutrient content (Fe and Zn) and β-carotene of selected TVCs (*Amaranthus cruentus* (Amaranth), *Cleome gynandra* (Spider flower), and *Ipomoea batatas* var*. Bophelo* (orange fleshed sweet potato, OFSP), and to use modelling techniques to out scale the application of project results.

The specific objectives of the project were:

i. To evaluate water productivity (WP) of selected TVCs.
ii. To evaluate the effects of different levels of N, P, and K on the nutritional value (Fe, Zn, and β-carotene) of TVCs.
iii. To evaluate the interaction effects of different levels of water on nutritional water productivity (NWP).
iv. To predict WP for different regions in South Africa using available crop models.

Methodology

Three experiments were conducted under a rain-shelter and an open field site (Rooiland) during the 2013/14 and 2014/15 seasons at the Agricultural Research Council-Vegetable and

Ornamental Plants (ARC-VOP). For the **rain-shelter**, the experimental design was a randomized complete block design, while the treatment design was a 4 x 3 factorial with two factors/treatments, namely crops and water levels, replicated three times. Four crops (Amaranth*,* Spider flower, OFSP and *Beta vulgaris* subsp. *Vulgaris* (Swiss chard)) and three water levels (Irrigation (I1) that refilled the water extraction depth (WED) of 60 cm to FC when 30% of plant available water (PAW) was depleted; Irrigation (I2) that refilled the WED to FC when 50% of PAW was depleted; and Irrigation (I3) that refilled the WED to FC when 80% of PAW was depleted). Leaf area index (LAI-2000 canopy analyzer, Licor, United States of America), stomatal conductance (SC-1 leaf porometer Decagon Devices, United States of America) were measured on weekly basis to monitor the effect of different irrigation amounts on crop growth during the growing seasons. Leaf samples were harvested and taken for oven drying and dried leaf samples were analyzed for Fe and Zn content, whereas, fresh leaf and storage root samples were analyzed for β-carotene content. The total amount of micronutrients (Fe and Zn) and β-carotene that was harvested during the entire season was regarded as the nutritional yield (NY) that was calculated from raw edible biomass x NC. Water productivity (WP) was calculated as the yield of total dry raw edible biomass per unit of Eta. Nutritional water productivity (NWP) was calculated from WP x nutrient content of the crops. A two-way analysis of variance (ANOVA) was conducted to evaluate the main effects of the individual factors (crops and water levels) and their interactions in terms of biomass, edible biomass, WP, NC NY and NWP of the TVCs.

Experiments 2 and 3 were conducted as open field trials at the **Rooiland site** with the same three TVCs. The experimental design for the OFSP was a randomized complete block design. The treatment design was a 2 x 2 x 2 factorial design with 3 replicates: 2 water levels (Full (W1) and supplemental irrigation (W2)), 2 fertility levels (Full – F1 and no fertilizer – F2) and 2 harvesting methods (No harvesting of OFSP leaves – H1) and harvesting every 4 weeks – H2). Orange fleshed sweet potato leaves were harvested by plucking the first five well developed leaves from each vine at 4, 8, 12, and 16 weeks after planting from the leaf harvesting treatment (H2). Storage root yield was also determined at the end of the season. The supplemental irrigation treatment (W2) was applied only if it did not rain for a period of 4 weeks in order to revive the plants. The experimental design used for Amaranth and Spider flower was the same as for OFSP, but the treatment design was a 2 x 2 x 2 factorial design with 3 replicates: 2 water levels x 2 fertility levels x 2 crops. The same procedures as described for the rain-shelter experiment were used for the determination and calculation of dried leaf samples, WP, Fe, Zn and β-carotene concentrations, NC, NY, and NWP for the three experimental crops.

The AquaCrop model was calibrated with the 2013/14 no water stress treatment data, and validated with the 2014/15 no water stress (30% of PAW depleted) data, from the rain-shelter experiment. Soil characteristics, meteorological, soil water content and plant growth parameters (biomass, storage root yield, length of growing period, length of tap root and harvesting index) data were collected and used to develop the crop, irrigation scheduling, soil, and climate files in AquaCrop. For the purpose of modelling growth and production of Amaranth and Spider flower, OFSP, as well as WP for different scenarios, three irrigation schemes which are representative of different agro-ecological zones of South Africa, where the selected crops can be commercialized, were selected. These were Dingleydale, Dzindi and Tugela Ferry.

Results and discussion

Literature findings suggested that TVCs are highly nutritious compared to exotic vegetables and that they have the potential to meet the daily recommended nutrient intake of all age groups. However, there was lack of information on their production practices. In chapter 2 it is proposed that multi-disciplinary research should be conducted in controlled environments to meet particular objectives of the project. Results of this study indicate that under no water and severe water stress, Swiss shard produced the highest (5.09 t ha^{-1} and 3.96 t ha^{-1}) average raw edible biomass compared to the TVCs because the bulky stems of the latter were regarded as not edible and, therefore, were discarded. Moreover, under the W2F2 treatment combination, dry raw edible biomass and WP of TVCs declined, whereas, under the W1F1 treatment combination, biomass and WP of TVCs increased. Harvesting of OFSP leaves resulted in approximately 43% storage root yield reduction.

The analytical data on Fe, Zn, and β-carotene indicate that TVCs are higher in Fe, Zn, and β-carotene nutrient content (NC) compared to Swiss chard. Under severe water stress conditions, Fe and Zn exhibited consistency, whereas β-carotene decreased significantly. These results suggest that β-carotene NC is more sensitive to water stress compared to Fe and Zn NC. Moreover, low input agricultural practices (supplemental irrigation and no fertiliser application) did not necessarily affect NC of crops negatively. In some instances, they actually led to increases in NC. For example, Fe content of Amaranth increased from 8.2 to 28.1 mg 100 g^{-1}, whereas, for Spider flower it increased from 7.5 to 34.4 mg 100 g^{-1}. From an agronomic perspective, NC of crops cannot be evaluated in isolation with yield or raw edible biomass, because they are intertwined. Nutritional yield (NY= raw edible biomass x NC) is a crucial agronomic parameter which indicate the quantity of nutrients which can be harvested during the entire season. Key findings suggest that water stress has a major effect on NY of crops. As the severity of water stress was increased, NY decreased. The highest average NY for Fe, Zn and β-carotene was obtained from Spider flower (2771 g ha^{-1}), Swiss chard (276 g ha^{-1}), and Amaranth (4897 g ha^{-1}) under no the water stress treatment. These results suggest that more Fe and β-carotene can be harvested from TVCs compared to Swiss chard. An opposite result was found for Zn. In addition, under low input agricultural practices, NY of TVCs decreased with β-carotene NY showing a major decline under the W2F2 treatment combination. Moreover, OFSP leaf harvesting resulted in approximately 50% reduction in NY of Fe, Zn and β-carotene of OFSP storage roots.

Increased water stress improved nutritional water productivity (NWP) of TVCs. Ranking the TVCs from highest to lowest NWP for Fe and Zn and under the severe water stressed treatment: Spider flower, Amaranth, Swiss chard and OFSP leaves ranked 1st, 2nd, 3rd and 4th, respectively. For β-carotene, Amaranth, Spider flower, Swiss chard, and OFSP leaves ranked 1st, 2nd, 3rd and 4th, respectively. Key findings are that: (i) Amaranth and Spider flower can be grown under rainfed agriculture and still produce the required micronutrients (Fe and Zn) and β-carotene, (ii) TVCs (Amaranth and Spider flower) are highly productive compared to Swiss chard, and (iii) under low input production conditions (rainfed and no fertilizer application), NWP for OFSP storage root will decrease for Fe and Zn, whereas, it will increase for β-carotene.

The AquaCrop model was successfully calibrated and validated for selected TVCs for canopy cover, profile soil water content, biomass, storage root yield and ETa. This was proven by higher coefficient of determination, lower root mean square error (RMSE), and RMSE-standard deviation ratio. The model simulation results suggest that OFSP storage root yield varied between the locations: It ranged from 3.2 to 13.1 t ha^{-1} in Dingleydale, 3.0 to 10.5 tha^{-1} in Dzindi, and 2.6 to 7.1 t ha^{-1} in Tugela Ferry. Amaranth biomass ranged from 2.4 to 11.7 t ha^{-1} in Dingleydale, 2.4 to11.4 t ha^{-1} in Dzindi, and 2.4 to 11.8 t ha^{-1} in Tugela Ferry. Spider flower biomass ranged from 4.5 to 11.4 t ha^{-1} in Dingleydale, 5.6 to 11.2 t ha^{-1} in Dzindi, and 3.7 to 11.5 t ha^{-1} in Tugela Ferry. These results suggest that there would be no difference in terms of biomass production for Amaranth and Spider flower when grown in the selected locations.

Summary and conclusions

The findings of this research project indicate that TVCs are not miracle crops as suggested by literature, because they require fertilizer and water if they were to be cultivated for commercial purposes. Their added value is that they are tolerant to water stress when compared to Swiss chard. Moreover, Amaranth and Spider flower are more productive per unit of water used in the production of essential micronutrients (Fe and Zn) and β-carotene. It is concluded that TVCs are resource efficient in terms of water and fertilizer use when compared to Swiss chard. Moreover, OFSP has the potential of being utilized as a leafy vegetable and also as storage root crop. These crops are suitable for RPHs who lack access to major inputs (water and fertilizer) for agricultural production. Therefore, RPHs are encouraged to cultivate them for household consumption and also for commercial purposes. The AquaCrop model was successfully calibrated, validated, and tested for different agro-ecological zones for the selected TVCs. Interested stakeholders are encouraged to use the model for decision making and also for identifying suitable locations where selected TVCs can grow optimally.

Recommendations for further research

Key recommendations are that: (i) further research, assessing the effects of soil fertility and water levels on NC of selected crops, be conducted in various locations having different externally impacting conditions, (ii) further research should also focus on improved varieties and cultivation practices to increase NC and yield of TVCs, (iii) OFSP be utilized as a leafy vegetable and storage root crop, (iv) participatory action research should be conducted with RPHs to avoid using a top down approach, whereby researchers conduct research at a research station and then disseminate results to beneficiaries, (v) TVCs should be commercialized in South Africa by following the model that has been used by Eastern African countries, and (vi) more TVCs be used in food-processing to add value and promote the production of TVCs in South Africa.

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LIST OF ABBREVIATIONS

A	Amaranth
ARC-VOP	Agricultural Research Council – Vegetable and Ornamental Plants
CC	canopy cover
CCi	intercellular CO_2 concentration
CCo	initial canopy cover
CDC	canopy decline coefficient
CGC	canopy growth coefficient
Cr	capillary rise
CVA	Commercial Village Approach
DAT	days after transplanting
Dp	deep percolation
DRNI	daily recommended nutrient intake
Eta	actual evapotranspiration
ET_0	reference evapotranspiration
F	soil fertility
FAO	Food and Agricultural Organization
$Fc_{Decline}$	canopy decline
FCI	Farm Concern International
Fe	iron
FNS	food and nutrition security
GDD	growth degree days
H	leaf harvesting
HI	harvesting index
I	irrigation
IWMI	International Water Management Institute
K_s	saturated hydraulic conductivity
Ks_{CCx}	maximum canopy cover coefficient
Ks_{exp}	canopy expansion coefficient
Ks_{wp}	biomass water productivity coefficient

LAI	leaf area index
LSD	Least Significant Difference
masl	metres above sea level
NC	nutritional content
NFI	nutritional food insecurity
NFS	nutritional food security
NWP	nutritional water productivity
NY	nutritional yield
OFSP	orange fleshed sweet potato
p	statistical probability
Pr	rainfall
PAW	plant available water
R	run-off
R^2	coefficient of determination
RE	retinol equivalents
RMSE	root mean square error
RPHs	resource poor households
RSR	RMSE standard deviation ratio
SA	South Africa
SF	Spider flower
sSA	sub-Saharan Africa
STDVobs	standard deviation observations
SWC	soil water content
Tr	transpiration
TVCs	traditional vegetable crops
VPD	vapour pressure deficit
W	water
WED	water extraction depth
WP	water productivity
WRC	Water Research Commission
Y	yield
Y_{var}	dependent variable

Zn	zinc
ΔSf	change in sub-surface in- and outflow
ΔW	change in SWC

1 GENERAL INTRODUCTION AND BACKGROUND

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1.1 Project background and motivation

By the year 2050, the Earth's population is expected to grow from the current 7 billion to approximately 9.6 billion, of which would be mostly from sub-Saharan Africa (sSA) countries (Dupont, 2015). It is estimated that in the next 40 to 50 years, there would be a need to produce as much food as was necessary for the previous 10 000 years (Dupont, 2015). This requires a dramatic increase in agricultural production, which must be achieved against a backdrop of issues such as climate change (extreme weather, flooding, and droughts), water scarcity, soil fertility depletion, land degradation, and possible yield reduction in key production areas. Higher temperatures in sSA will make it difficult for agriculture to meet the demand of food in the next coming decades (McLachlan and Thorne, 2009). There is a need to intensify production on existing lands rather than relying too heavily on new ones (Dupont, 2015).

Micronutrient (Fe and Zn) and vitamin A deficiencies are also major problems in South Africa affecting resource poor households (RPHs) who are located in rural areas of the country. Resource poor households are vulnerable to food and nutrition security (FNS) because they are economically marginalized and their production occurs on small areas of land which are characterized by low yield, as well as poor quality in terms of nutrition, capital, and agricultural inputs (water and fertilizer) (Frayne et al., 2009; McLachlan and Thorne, 2009; Blignaut et al., 2014; Dupont, 2015). Dupont (2015) indicted that RPHs, or small holder farmers, are key in alleviating food insecurity because approximately 60% of them produce food for home consumption. Their ability to increase production depends solely on improving access to agricultural inputs (water, seeds, and fertilizer), which are typical of the Green Revolution which promoted production of staple crops with no intention to address micronutrient deficiency of essential micronutrients (Fe and Zn) and vitamin A (Dupont, 2015). Agriculture need to re-think agro-biodiversity solutions when planning a food based approach to curb micronutrient deficiencies. Experts, including agronomists, nutritionists, social scientists, and agricultural water resource managers (Faber and van Jaarsveld, 2007; van Rensburg et al., 2007; Uusiku et al., 2010, Hart, 2011; Oelofse and van Averbeke, 2012; Wenhold et al., 2012; Mavengahama et al., 2013; Chivenge et al., 2015) suggested that traditional vegetable crops (TVCs) are highly nutritious, drought tolerant (can withstand adverse environmental conditions), and are highly productive compared to exotic vegetables. However, this was based on the assumption that TVCs grow naturally in marginal environments that are characterized by poor soil fertility and depending solely on sporadic rainfall.

Key findings of a study conducted by Oelofse and van Averbeke (2012) showed that TVCs have the potential of providing more than 50% of the recommended daily allowance for Fe, Zn, and vitamin A. However, these findings were based on plant samples taken from locations where soil fertility and evapotranspiration (Eta), or water use, was unknown. As such, further research was needed to better understand the link between water, soil nutrients, management practices, biomass and nutritional content (NC) of TVCs. This research gap has been acknowledged by a scoping study on nutritional water productivity (NWP) of food crops in SA (Annandale et al., 2012).

1.2 Project scope and extent

The duration of the project was from May 2012 to May 2016. The proposed project focused on NWP of selected TVCs, using *Beta vulgaris* subsp. *vulgaris* as a reference crop because it is a leafy vegetable, highly nutritious (contains Fe, Zn, and β-carotene), commercialized in South Africa and mostly utilized by RPHs who eat it as a relish with maize porridge (Mavengahama et al., 2013). Three TVCs were selected based on their popularity, nutritional value, and potential of being commercialized in South Africa (van Rensburg, 2007). These were:

- *Amaranth cruentus* (Amaranth)
- *Cleome gynandra* (Spider flower)
- *Ipomoea batatas* (orange fleshed sweet potato *var. Bophelo*, OFSP)

This project focused on water use, soil fertility, and nutritional content (NC) of selected TVCs conducted at the same location. The project was conducted in two experimental units: (i) the rain-shelter trial, and (ii) open field trials conducted at a site called Rooiland. The trials were selected to emulate production characteristics of RPHs.

1.3 Project aim and objectives

The main aim of the project was to understand the effects of water and soil nutrient (N, P and K) interactions on nutrient content (Fe and Zn) and β-carotene of selected TVCs (Amaranth, Spider flower and OFSP) and to use modelling techniques to out scale the application of project results.

Specific objectives of the project were:

i. To evaluate water productivity (WP) of selected TVCs.
ii. To evaluate the effects of different levels of N, P and K on the nutritional value (Fe, Zn and β-carotene) of TVCs.
iii. To evaluate the interaction effects of different levels of water on nutritional water productivity (NWP).
iv. To predict WP for different regions in South Africa using available crop models.

1.4 Contribution of individual chapters to the objectives of the project

This section presents the content of different chapters which are briefly described and the contribution of each chapter to the achievement of the main aim and the project objectives.

1.4.1 Chapter 2

This chapter reviews the literature of TVCs on NC, water use, soil fertility, and propose a new unity of purpose approach which should be conducted at a research station and up scaled to RPHs through participatory action research. Moreover, it poses two research questions which need to be addressed by the new unity of purpose research, namely (i) whether TVCs are resource efficient in terms of water use compared to exotic vegetables, and (ii) why are nutritional values of traditional vegetable crops variable? Literature suggests that TVCs are highly nutritious compared to exotic vegetables such as Swiss chard and cabbage, and proposes that sweet potato can be utilized as a leafy vegetable and also as storage root crop. Chapter 2 provides a basis of what elements should be addressed by the entire research fraternity and it addresses the main aim of the project.

1.4.2 Chapter 3

Chapter 3 presents research findings on WP of TVCs from two experimental sites; (i) the rain-shelter trial and (ii) the open field trials. It further elaborates on WP and proposes a definition of WP which is used throughout the report, as follows:

$$\text{WP} = (\text{Dry raw edible biomass})/\text{ETa}$$

The standard units of WP are kg m^{-3}. The key findings are that WP of TVCs are comparable with that of Swiss chard. Moreover, WP from the rain shelter experiment is higher compared to the open field experiment, which might have been caused by different soil and management practices. This chapter addresses objective 1.

1.4.3 Chapter 4

Chapter 4 reports on NC, nutritional yield (NY), and nutritional water productivity (NWP) of TVCs. The results are presented on fresh and dry raw edible biomass. This indicates the nature of the disciplines involved in the project, including agronomists, agricultural water resource managers, and nutritionists. The key findings of this chapter are that under optimum conditions, TVCs are lower in terms of nutrients that can be harvested per unit area (NY) when compared with Swiss chard. Chapter 4 addresses objectives 2 and 3.

1.4.4 Chapter 5

Chapter 5 reports on modelling crop WP for selected TVCs. The calibrated model was used to estimate WP of three selected irrigation schemes (Dingleydale, Dzindi, and Tugela). The key findings of this chapter are that the AquaCrop model was successfully calibrated and evaluated for canopy cover, biomass, profile soil water content, and actual evapotranspiration. This was proven by a higher coefficient of determination (R^2), lower root mean square error (RMSE), and RMSE-ratio. A notable finding was that under low input agriculture (no irrigation and fertilizer application), WP of selected crops will decline. Chapter 5 addresses objective 4.

1.4.5 Chapter 6

This is a concluding chapter that discusses all the key findings of the research project and makes recommendations on how to improve NWP of TVCs. Moreover, it recommends that research should be conducted in the farmers' fields using a participatory approach.

1.5 Glossary of core terminology

Term	Definition or description from literature
Agro-biodiversity	The variety and variability of plants that are used directly or indirectly for food and agriculture. It comprises the diversity of genetic resources (varieties, breeds) and species used for food, fodder, fibre, fuel and pharmaceuticals. It also includes the diversity of non-harvested species that support production (soil micro-organisms, predators, pollinators), and those in the wider environment that support agro-ecosystems (agricultural, pastoral, forest and aquatic) as well as the diversity of the agro-ecosystems (Brookfield and Stocking, 1999).
Bio-fortification	Is the process of generating genetically improved food crops that are rich in bioavailable micronutrients, either through conventional breeding or genetic modification (Johns and Eyzaguirre, 2007).
C3 photosynthesis	A mode of photosynthesis where CO_2 is first incorporated into a 3-carbon compound and the Rubisco enzyme plays a major role in the uptake of $CO_{2.}$ C3 plants have lower water use efficiency than C4 plants because they keep their internal CO2 concentration relatively high and therefore stomata need to remain wide open and more water is lost through the process of transpiration. Example of a C3 plant is sweet potato (Annandale et al., 2012).
C4 photosynthesis	A mode of photosynthesis where CO_2 is first incorporated into a 4-carbon compound and the PEP carboxylase enzyme plays a major role in the uptake of $CO_{2.}$ C4 plants have a high water use efficiency than C3 plants because they keep their internal CO2 concentration relatively low and therefore stomata is not open at all times, thus losing less water compared to C3 plants. Examples of C4 plants are Amaranth and Spider flower (Annandale et al., 2012).
Evapotranspiration (ETa)	Is a combination of two processes- evaporation and transpiration, which occurs simultaneously. Evaporation refers to the physical process of water vapourisation into gaseous phase from the soil surface, whereas, transpiration is a biophysical process where water is transported from the plant root zone through its cells and stomata into the atmosphere (Annandale et al., 2012; Wegerich & Warner, 2010).
Food and nutrition security (FNS)	Is a combination of two terms- food security and nutrition security. The Food and Agricultural Organisation (2009) had defined food security as a condition when all people, at all times, have physical, social, and economic assess to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for a healthy life. Nutrition security refers to access to and control over the physical, social, and economic means to ensure sufficient, safe, and nutritious food at all times, in order to meet the dietary requirements for a healthy life (DAFF, 2013).
Hidden hunger	Is a form of undernutrition that occurs when intake or absorption of vitamins and minerals is too low to sustain good health and development in children and normal physical and mental function in adults. Causes include poor diet, disease, or increased micronutrient needs not met during pregnancy and lactation (Von Grebmer et al., 2014).
Micronutrients	Micronutrients are those nutrients required by human beings in relatively small quantities. They are vitamins and minerals, and are required in milligram and microgram amounts. Examples of essential micronutrients are Fe, Zn and iodine.
Nutritional content (NC)	The concentration of micro-nutrients (β-carotene, Fe, and Zn) in raw edible yield.
Nutritional yield (NY)	A function of raw edible yield and nutrient content of crops (Bumgarner *et al.*, 2012).
Raw edible biomass or yield	The portion of plant material on a fresh mass basis which is suitable for human consumption.

Term	**Definition or description from literature**
Resource poor households (RPHs)	In South Africa, the term ‘resource poor households’ (RPHs) refers to households or farmers with minimal access to major livelihood resources. In rural areas this entails limited access to land, water, capital and sources of income. Most rural RPHs are vulnerable to nutritional food insecurity because they are located in less productive areas that are characterised by infertile soils, semi-arid conditions (e.g., low rainfall, high temperatures and water scarcity), poor road infrastructure, poor market access and overpopulation (Aliber and Hart, 2009; Mavengahama et al., 2013; Pereira et al., 2014).
Traditional vegetable crops (TVCs)	Can be *indigenous* – meaning they evolved naturally in an area and have been part of the traditional production system – or, *indigenised*, which refers to vegetables that were introduced in an area a long time ago and through breeding have been adapted to local conditions and become part of the local culture. In literature these vegetables are referred to under various connotations as *indigenous, underutilised, African leafy, dark green vegetables,* or even crops for the future; with as of yet no standard and agreed upon definition (Dweba and Mearns 2011; Faber et al*.,* 2010; van Rensburg et al., 2007).
Unity of purpose	Is used here as a concept and notion for framing and setting of new objectives for agronomic research for food and nutrition security, which *has* been directed towards understanding and optimisation of agronomic inputs (water, nutrients, disease and pest control) and genetic varieties (higher yielding varieties) for yield maximisation, which has led to the known effects and critique of the Green Revolution. The new focus on nutritional food insecurity, resource poor households, and TLVs, requires a clear new agenda with a different focus (Sumberg et al., 2013).
Value chain	The value chain links the steps a product takes from the farmer to the consumer. It includes research and development, input suppliers, production, processing, marketing and finance (The National Agricultural Marketing and Development Corporation, 2016).
Vitamin A	Preformed vitamin A occurs either as retinol, retinal or retinoic acids. All three compounds have vitamin A activity and are known as preformed vitamin A. Preformed vitamin A is only found in animal products, while plant foods such as vegetables and fruit do not contain preformed vitamin A. However, carotenoids, a group of compounds found in plants, can be metabolised in the human body to retinoids, and thus vitamin A. There are several hundred types of carotenoids in food, but only some have vitamin A activity, the most active being β-carotene. The amount of vitamin A (retinol) formed from the carotenoids depends on how well the carotenoids are absorbed, and how efficiently it is converted to vitamin A in the body (UNICEF, 1998).
Water productivity (WP)	In a broad sense, productivity of water refers to the benefits derived from use of water. The concept is scale-dependent and can be expressed, *inter alia*, at a crop, field, farm or basin scale. The expression is most often given in terms of mass or produce, or monetary value, per unit of water consumed. Crop water productivity is defined in either physical or monetary terms as the ratio of the product (usually measured in kg) over the amount of water consumed (usually crop evapotranspiration (ETa), measured in m^3). Crop water productivity can either be expressed as either fresh or dry plant mass per unit of ETa (Kijne et al., 2003; Molden et al., 2003; Oweis and Hachum, 2003). Water productivity can also be defined more broadly to assess nutritional water productivity, number of calories or of protein calories, for instance, per unit of water consumed (HLPE, 2015). In literature (Kijne et al., 2003; Ong and Swallow 2003; Oweis and Hachum, 2003), the term water productivity is used interchangeably with water use efficiency. However, in this study the term water productivity will be used, meaning physical crop water productivity, expressed as dry plant mass per unit of ETa.

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2 THE POTENTIAL ROLE OF TRADITIONAL VEGETABLE CROPS IN ACHIEVING FOOD AND NUTRITIONAL SECURITY OF RESOURCE POOR HOUSEHOLDS

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2.1 Introduction

Food and nutrition security (FNS) is one of the most pressing issues, particularly in sub-Saharan Africa (sSA), as there is yet no country able to meet the minimum recommended consumption of 200 kg^{-1} $person^{-1}$ $year^{-1}$ of fruits and vegetables. Approximately 239 million people are still suffering from micronutrient deficiency as a form of "*hidden hunger*" (Mhanji et al., 2011; Afari-Sefa et al., 2012; Greaf et al., 2014; Njume et al., 2014). Hidden hunger is a chronic lack of micronutrients (Fe and Zn) and vitamins whose effects may not be immediately apparent but may have severe consequences in the long term by inducing stunted growth (Brouwer, 2014). Since the early 1970s, the Green Revolution has significantly contributed in alleviating protein-energy malnutrition, but has had minimal impact in addressing micronutrients (Fe and Zn) and vitamin A deficiency (Welch and Graham, 2004). Various food-base approaches – e.g. plant breeding, food supplementation, food fortification, bio-fortification, and dietary diversification – are being piloted as strategies to combat micronutrient deficiency in SSA (Faber et al., 2010; Njume et al., 2014). However, plant breeding and bio-fortification strategies may have been successful in developing varieties of crops that have a higher disease resistance and higher productivity, but their contribution towards achieving human nutritional requirements has been less straightforward. For example, to meet the daily recommended intake of pro-vitamin A, an individual would be required to consume at least 16.3 kg of cabbage (Afari-Sefa et al., 2012; Lin et al., 2009; Saltzman et al., 2013).

Traditional vegetable crops (TVCs) are abundant in the wild, fallow fields or alongside field crops (maize, sorghum, cotton), cultivated landraces, and consumed frequently by resource poor households (RPHs). Research has shown that TVCs are highly nutritious in micronutrients and vitamins (particularly A and C), which has brought them to attention as alternative crops for combating malnutrition (van Rensburg et al., 2007; Oelofse and van Averbeke, 2012). Although seemingly very promising in their high nutritional content (NC), their widespread uptake and consumption is presently hampered and highly variable across regions by a variety of factors such as negative cultural connotations of the "poor man's crops", lack of technical knowledge and information, lack of (quality) seeds, poor marketing, and poor policy frameworks. From agronomic and nutritional perspectives, TVCs still represent an "unknown" "wild" and "traditional" food source that is difficult to support and uphold in agronomic and nutritional research, policy, and outreach. The government of South Africa has recently shown commitment in addressing core issues of FNS by introducing the National Development Plan (2011) and the food-nutrition security policy of 2013 (DAFF, 2013). These new policies have incited agronomic research to define a new unity of purpose that is multidisciplinary and holistic in its approach (Greaf et al., 2014). Unity of purpose is used here as a concept and notion (Sumberg et al., 2013) for the framing and setting of new objectives for agronomic research for FNS among RPHs. In the classical agronomy, the unity of purpose has been directed towards the understanding and optimization of the agronomic inputs (water, nutrients, disease and pest control) and genetic varieties (high yielding varieties) for yield maximization, with the known effects and successes of the Green Revolution. A new focus on FNS and RPHs requires a clear new agenda on TVCs with a different focus. This new unity of purpose for agronomic research on TVCs needs to encompass three distinctive elements: (i) how to capture and merge these "wild" crops with mainstream agronomic knowledge on resources utilization and productivity;(ii) how to adapt the agronomic cultivation strategies to the specific production constraints of RPHs; and (iii) how to fulfill the specific consumption requirements and constraints of RPHs while meeting nutritional requirements. This chapter reviews existing knowledge and emerging questions on the development of TVCs for increased agricultural usage and their uptake by RPHs as an effective means to improve household food and nutritional security in South Africa and SSA. In targeting FNS of RPHs, the paper defines a new unity of purpose for agronomic research of TVCs by focusing on agronomic production, household consumption, and marketing aspects of TVCs as highly nutritious crops that need to be assessed in a broad holistic setting. The chapter comprises of the following sections; (i) food and nutritional security in South Africa; (ii) contribution of TVCs to human nutrition; (iii) production and marketing of TVCs; and the (iv) new unity of purpose for agronomic research on TVCs. This last section makes special references to questions of agricultural research design to increase understanding of both physiological and production performance of TVCs.

2.2 Food and nutrition security in South Africa

In South Africa, three major surveys have highlighted the severity of malnutrition; (i) the South African Vitamin A Consultative Group (SAVACG) survey of 1994 (SAVACG, 1996), (ii) the National Food Consumption Survey Fortification Baseline (NFCS-FB-I) of 2005 (Labadarios et al., 2000; Labadarios et al., 2007), and (iii) the South African National Health and Nutrition Examination Survey (SANHANES-1) of 2012 (Shisana et al., 2014). Results from the latter survey indicate that 1 in 4 children was stunted and 1 in 10 was underweight, while 1 in 2 households was at risk of, or were, experiencing hunger. The latter survey also showed that 45.6% of households were food secure, 28.3% at risk of hunger, and 26% were experiencing hunger. While these surveys also show that between 1994 and 2012, there was some reduction in food insecurity, however, South Africa (SA) still faces high rates of food insecurity at the household level, particularly in rural areas, affecting RPHs. In SA, RPHs refers to "households" as farmers, located in the rural areas of the country, with minimal access to major resources such as land, water, and a source of income. Most RPHs are vulnerable to FNS because they are located in the former homelands of the country, characterized by infertile soils, semi-arid conditions (low rainfall; high temperatures, water scarcity, poor road infrastructure, overpopulation, and low agricultural productivity (Aliber and Hart 2009; Mavengahama et al., 2013; Pereira et al., 2014).The high prevalence of FNS in SSA and SA has prompted a new focus on research and policy development with the goal of alleviating micronutrient deficiencies of RPHs in SSA. Achieving these goals requires a comprehensive integration of agriculture, health, nutrition, rural development, and livelihoods. Different initiatives and developments are being undertaken that target FNS at different segments of the production-market-consumer chain (Figure 2.1). The Harvest Plus project (HarvestPlus, 2015) is an example of a global initiative trying to bridge the gap between plant breeding and human nutrition. It aims to meet the nutritional requirements of essential micronutrients (Fe and Zn) and vitamin A of the poor by means of bio-fortification of the major staple crops (maize, cassava, wheat, rice and sweet potato). Where from a *consumer perspective* these developments in bio-fortified high nutritious staple foods may be very welcome and attractive, especially when explicitly targeted and affordable for the urban poor, they may be less suitable and constraining when targeting poverty alleviation, as well as NFS of the rural poor. This latter requires a *producer's* and household consumption perspective, for which this bio-fortified crops exhibit a number of constraints such as high external input requirements (water, fertilizer, agrochemicals and hybrid seeds), long maturity duration of staple crops, and considerable plot size for cultivation – elements that are typical limiting production factors of RPHs. The production of TVCs is seen as a potential alternative FNS strategy that can explicitly meet the production and consumption constraints of RPHs. Their widespread and traditional use "from the wild" and consumption as green relish in customary diets across sSA form hereby the basis for valuation and targeting of TVCs in achieving FNS among the rural poor. This does require an explicit recognition of the role of TVCs in the wider framework of agricultural production in relation to the other components of the food system as the natural resources base, socio-economic factor, public health, and policy (Figure 2.1). This means that the potential role of TVCs needs to be assessed in terms of their production capacity under low external input capacity of RPHs and their capacity to provide adequate nutritional value at household level.

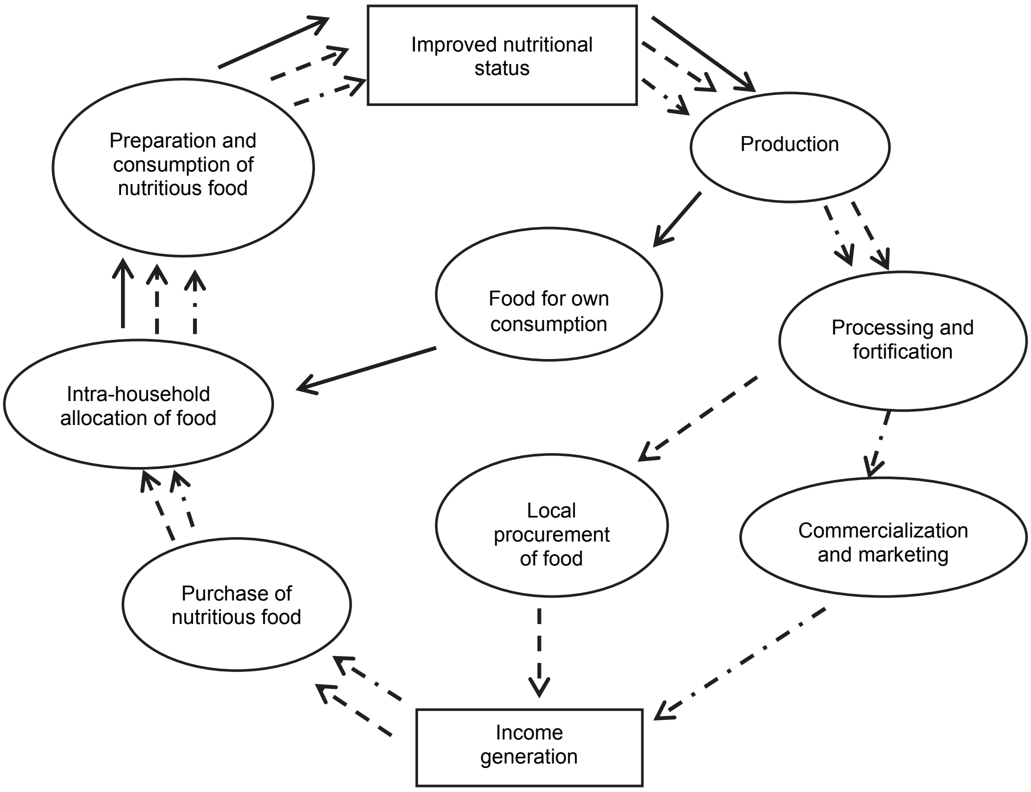

Figure 2.1: Components of the REACH smallholder value chain model (Adapted from WUR-CDI, 2011). NOTE: circles indicate smallholder value chain components and the boxes indicate impact to small holders

2.3 Contribution of traditional vegetable crops to human nutrition

Sub-Sahara Africa is home to 45000 plant species classified as vegetables, of which approximately one thousand can be consumed as leafy vegetables. In SA more than 100 species of this kind have been identified (Wehmeyer and Rose, 1983). In this chapter, the focus will be on 12 of these genera, based on their popularity, nutritional value, and potential for future commercialization (Table 2.1). In literature these vegetables are referred to under various connotations as *indigenous, underutilized, African leafy, dark green vegetables,* or even crops for the future; with as of yet no standard and agreed upon definition (van Rensburg et al., 2007; Faber et al., 2010; Dweba and Mearns, 2011). Traditional vegetable crops can be *indigenous* – meaning they evolved naturally in an area and have been part of the traditional production system – or, *indigenized*, which refers to vegetables that were introduced in an area a long time ago and through breeding have been adapted to local conditions and become part of the local culture. In this chapter, the term TVCs refers to both indigenous and indigenized vegetables (van Rensburg et al., 2007; Dweba and Mearns, 2011; Oelofse and Averbeke, 2012). Swiss chard was used as a reference crop because of it is a leafy vegetable, high in nutritional value (Fe, Zn and β-carotene), easy to grow by RPHs, disease resistant, and commercialized in South Africa (Mavengahama et al., 2013).

Table 2.1: Selected traditional leafy vegetables which are widely used in South Africa (Adapted from: Uusiku et al., 2010; Mavengehama et al., 2013; van Rensburg et al., 2014)

Scientific name	English name	Selected vernacular names	Seasonality
Amaranthus cruentus	Amaranth	Imbuya / Vowa / Thebe	Summer
Amaranthus graecizens	Amaranth	Imbuya / Vowa / Thebe	Summer
Amaranthus hybridus	Amaranth	Imbuya / Vowa / Thebe	All year
Amaranthus spinosus	Amaranth	Imbuya / Vowa / Thebe	Summer
Amaranthus tricolor	Amaranth	Imbuya / Vowa / Thebe	Summer
Bidens pilosa	Black jack	Amalenjane / Uqadolo / Mushidzhi	All year
Brassica rapa	Chinese cabbage	Mutshaina / Dabadaba	Winter
Corchorus olitorius	Jute mallow	Ligusha / Delele	Summer / autumn
Corchorus trilocularis	Jute mallow	Ligusha / Delele	Summer / autumn
Citrillus lanatus	Bitter water melon	Tsamma	Summer
Cleome gynandra	Spider flower	Murudi	Summer
Cleome monophylla	Spider flower	Isiwisa	Summer
Cucumis melo	Pumpkin leaves	Litsanga / Ithanga/ Fhuri	Summer
Cucurbita pepo	Pumpkin leaves	Litsanga / Ithanga/ Fhuri	Summer
Ipomoea batatas	Sweet potato leaves	Bhatata	Summer
Momordica balsamina	African cucumber	Inkaka / Umkaka	All year
Solanum nigrum	Black nightshade	Umsobo / Momoli / Muxe	Winter / summer
Vigna unguiculata	Cow pea leaves	Dinawa / Indumba / Munawa	Summer

2.3.1 Nutritional value of traditional vegetable crops

The nutritional deficiency of most prevalent, and with severest malnourishment, effects in SSA and SA concern the micronutrients (Fe and Zn) and vitamin A (Wenhold et al., 2007). The nutritional value of 12 TVCs and two exotic vegetables (*Beta vulgaris* and *Brassica oralecea*) sourced mostly from South African databases, are presented in Table 2.2. Iron and Zn values are given in mg per 100 g of fresh edible leaf mass, and for vitamin A in the nutritional standard of retinol equivalents (RE) of β-carotene (1 RE equaling 6 mg of β-carotene), which is the compound that is converted to vitamin A after consumption (Uusiku et al., 2010). It should be noted that the bioconversion of β-carotene to vitamin A was not as efficient as expected and, as a result, the Food and Nutrition Board recently revised the estimated efficiency factor for the conversion of dietary β-carotene to vitamin A from 6:1 by weight to the new value of 12:1 by weight (Tang, 2010). The data presented in Table 2.2 indicate that TVCs, especially Spider flower and Amaranth, are rich in β-carotene, Fe, and Zn compared to *Beta vulgaris* and *Brassica oralecea*. The reported nutritional values, however, show a large variability that could be attributed to variations in the plant variety, environment (soil type and properties), the method of harvesting, climatic conditions, and water availability (Uusiku et al., 2010).

Table 2.2: Micronutrient content of selected leafy vegetables per 100 g edible fresh mass

	Micronutrients		
	Vitamin A	Iron	Zinc
Scientific name	µg RE 100 g^{-1}	mg 100 g^{-1}	mg 100 g^{-1}
Amaranthus spp.	59-327^{a,b}	0.3-16.2^{a,b,c}	**0.02-8.4^{a,b,c}**
Bidens pilosa	nd	2-6^{1}	0.9-2.6^{a}
Brassica rapa	nd	1.44^{c}	0.3^{d}
Corchorus spp.	717^{c}	2-6^{a,b,c}	0.05-0.8^{a,b,c}
Citrillus lanatus	nd	6.4^{3}	0.74^{c}
Cleome spp.	**1200^{a}**	**2-29^{a,b,c}**	0.6-1^{a,b,c}
Cucubita pepo	194^{1}	4-16^{b,c,e}	0.6-0.9^{b,c,d}
Ipomoea batatas	103-980^{a}	0.6-1^{a}	0.03-3.1^{a}
Momordica balsamina	nd	3.5^{a}	1.8^{a}
Solanum nigrum	1070^{a}	7-13^{a,c}	0.6-3.5^{a,c}
Vigna unguiculata	99^{1}	0.3-4.7^{a,b,c}	0.2-0.5^{a,b,c}
Beta vulgaris	669^{a}	2.7^{1}	0.5^{a}
Brassica oleracea	75^{c}	0.3-0.5^{a,d}	0.2-0.5^{a}

Adapted from: ^{a}Uusiku et al. (2010), ^{b}Schonfeldt and Pretorius (2011), ^{c}van Jaarsveld et al. (2013), ^{d}Annandale et al. (2012). Note: nd means no data. The highlighted values indicate highest content. Recommended daily nutrient intakes: Vitamin A = 400 µg RE (1-3 years) to 600 µg RE (19-65 years); Iron (Fe) = 5.8 mg (1-3 years) to 32.7 mg (10-14 years); Zinc (Zn) = 8.3 mg (1-3 years) to 17.1 mg (10 to 14 years).

2.3.2 Agronomy of traditional vegetable crops

Traditional vegetable crops are well suited for RPHs because they occupy smaller areas (home grown gardens), take a shorter period of time to mature (thus readily available), requiring low-external agricultural production practices (grow naturally in the "wild" or fallow fields, without addition of fertilizer and irrigation – which make them cheaper, accessible to RPHs), easy to harvest on daily basis and without a need for storage. However, they can still supplement the essential micronutrients, and can ensure continued supply to the market (Faber and van Jaarsveld, 2007; Baiphethi and Jacobs, 2009; Gjeci, undated; Matshe et al., 2010; Mhanji et al., 2011; Pereira et al., 2014). To promote their uptake and consumption by RPHs as a viable alternative cultivation and consumption strategy for alleviating FNS, there is a need to assess their agronomical characteristics and quality (nutritional content). This requires a new unity of purpose for agronomic research and valuation: i) in terms of capturing the performance and agronomic knowledge of TVCs within the mainstream agronomic knowledge framework (water productivity, response to fertility, crop physiology, yield and nutritional response), and ii) in terms of defining and valuing agronomic cultivation strategies that fit the production and consumption constraints of RPHs with regard to their limitation on resources utilization of water, fertility, yield, and management/marketing. Resource poor households are located in less favourable areas where rainfall is sporadic, therefore resource scarcity (water and land) is a significant constraint for them to produce food. There is a need to close the gap between water availability and demand, by adopting the practice of "more crop per drop", which calls for improvement in water productivity of crops (yield per unit of water used) (Renault and Wallender, 2000). The concept of NWP is explained in Chapter 4 of this report. Amaranth and Spider flower are C4 crops-meaning they have lower intercellular CO_2 concentration (C_{ci}), thus they produce more dry matter per unit water which improves their water use efficiency. These TVCs fit well within this new unity of purpose towards alleviating the hidden hunger of RPHs, because they are known to withstand harsh environmental conditions such as water scarcity, higher temperatures, and infertile soils. Their drought tolerance and higher nutritional value make them ideal crops for a water constrained country such as SA (Luginaah et al., 2009; Afari-Sefa et al., 2012; Oelofse and Averbeke, 2012).

To implement the new unity of purpose, the framework by the Wageningen University Centre for Development Innovation (WUR-CDI, 2011) was followed, which suggests three pathways that link agriculture with food consumption and nutrition: (i) production of food for household consumption; (ii) generate income which can be used to purchase highly nutritious food; and (iii) local procurement of TVCs from RPHs is used (Figure 2.1). The first two pathways which fit in well with the two types of farming systems that are practised by RPHs are followed; (i) low external input agriculture, which encourages the use of on-farm inputs (kraal manure, chicken manure, green manure, composting and cover crops) and minimizes the purchase of off-farm inputs (fertilizer and pesticides), and (ii) high input agriculture- which promotes the use of modern machinery and intensive use of off-farm resources such as pesticides, fertilizer, and genetically modified crops (Daberkow and Katherine, 1988). Low external input agriculture links well with production for household consumption, because production costs are very low, whilst high input agriculture connects well with production to generate income because production costs are higher, requires larger land area (> 1 ha), and higher yields to compensate for higher inputs costs. Traditional vegetable crops can fit in well with both farming systems, however, information on their agronomic practices is lacking. A case study conducted by Aliber and Hart (2009) on the incidence of FNS in the Molati village, Limpopo province, which is semi-arid, found that RPHs survive on TVCs for a period of 6 months – during summer they harvest and conserve them by drying. Because of water scarcity, they cannot grow exotic vegetables. All these conditions seem to suggest that TVCs are extremely suitable to meet the production and consumption constraints of RPHs. However, much of these claims are based on anecdotal evidence with minimal data available to support these claims, while reported nutritional values are highly variable because of plant variety, the environment (soil type and properties), the method of harvesting and climatic conditions. The new unity of purpose research should answer the following questions:

2.3.2.1 *Are TVCs resource efficient in terms of water and soil fertility compared to exotic vegetables?*

Traditional vegetable crops had been reported by world experts (Oelofse and van Averbeke, 2012; Mavengahama et al., 2013) to be growing naturally in the wild, on fallow field, or as weeds without addition of fertilizer and irrigation (Aliber and Hart, 2009, Afari-Sefa et al., 2012; Oelofse and Averbeke, 2012; Chivenge et al., 2015). Experts from different fields of study (policy makers, researchers, nutritionists, and environmentalists) suggested that TVCs should be commercialized in SSA. However, little is known on what yield to expect under different water and fertility conditions. Therefore, there is a need to bring TVCs into the realm of agronomic knowledge as has been done for maize, staples, and exotic vegetables by understanding their yield response to water and fertilizer (Figure 2.2). In the figure W_a is under rainfed conditions, W_b is supplemental irrigation, and W_c is full irrigation. The relationship between water use and yield is directly proportional, where Yd is yield under W_a, Y_e is yield under W_b and Y_e is yield under W_c. However, the interaction effect of water x fertility for micronutrient content (Fe and Zn) and β-carotene is unknown but may change the slope of N_h, causing it to move to N_g, or to move to N_i; where N is the micronutrient content of crops.

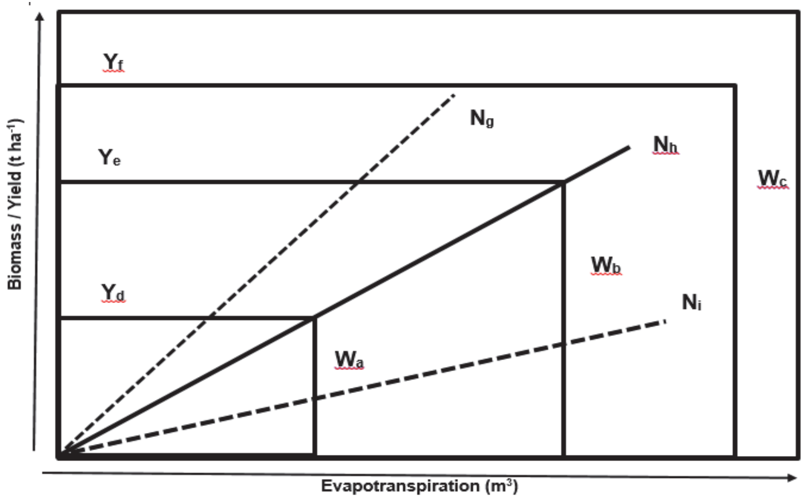

Figure 2.2: Hypothetical relationship between water use and biomass or yield within different spectra of water (W) levels (Adapted from Tittonell et al., 2012).

2.3.2.2 Why are nutritional values of traditional vegetable crops variable?

Variation in nutrient content of TVCs is caused by plant variety, environment (soil type and properties), harvesting method, climatic conditions, different seasons and water availability (Chapin, 1980; Uusiku et al., 2010). Moreover, Chapin (1980) explained that wild plants from fertile environments grow more rapidly compared with those from less fertile environments. However, in the process of altering yield due to the difference in fertility stress levels, it is uncertain of what happens to the NC of crops – do nutrients increase or decrease (Figure 2.2)? As for now, this question cannot be answered – new research should focus on the effect of different fertility stresses on NC of TVCs.

2.3.3 Agronomic re-assessment of sweet potato

Sweet potato (*Ipomoea batatas* (L.) Lam.) is a major crop in sSA and approximately 12.6 million tonnes are produced per annum, mostly by RPHs for subsistence use (Low et al., 2009; Motsa et al., 2015). Orange fleshed sweet potato (OFSP) is widely used for alleviating vitamin A deficiency in developing countries because of its high β-carotene content, reliable yields under low input agriculture, and wide ecological adaptability (Laurie et al., 2012a, Laurie et al., 2012b; Motsa et al., 2015). However, sweet potato leaves have been underutilized, except for feeding livestock. This crop can be consumed as a dark green leafy vegetable and storage root, which could significantly increase food availability in SSA (Islam 2006). The leaves can be harvested several times for a maximum period of 6 months and are rich in Fe, Zn, Ca and β-carotene (Islam, 2006). However, three agronomic challenges need to be addressed if OFSP is to be consumed as a leafy vegetable, namely: (i) what will happen to storage root yield – will the yield increase, decrease or remain the same? and (ii) the quality of micronutrients (Fe, Zn and β-carotene) – will they, over time, increase, decrease or remain the same? All these challenges can be addressed by conducting controlled experiments with leaf harvesting as a treatment.

2.4 Production and marketing of TVCs

In sSA, TVCs grow naturally in the ''wild'' or on fallow field with field crops such as maize, sorghum and cotton, and some are cultivated landraces (sweet potato). However, they are likely to become extinct because under commercial farming systems they are regarded as weeds. If seen, they are sprayed with chemicals, whereas, under small scale farming systems, the women who usually conduct weeding leave them undisturbed and harvest them by plucking the leaves which are then cooked and eaten as a relish, thus serving as easily available sources of Fe, Zn, and β-carotene (Taleni et al., 2012; Mavengahama et al., 2013). Traditional vegetable crops are not yet commercialised in South Africa because they are not produced under well-defined agronomic practices (growing naturally in the wild), thus they lack a market value chain. To be commercialised TVCs need to meet the demand and supply elements of economics. Another salient issue is the location of RPHs living in remote areas where road infrastructure is very poor and transportation of goods is a major problem. To resolve micronutrient deficiency in SSA, especially in rural areas, markets need to be established where RPHs can market their produce, and those not producing at home can purchase TVCs from the market (Mhanji et al., 2011; Afari-Sefa et al., 2012). Cheleng'a et al. (2013) found that there is a market potential for TVCs in Kenyan supermarkets and open air markets and they be sold profitably. Traditional vegetable crops can be sold more profitably in supermarkets (34 Kshs/bunch, 1 Kshs = 0.011 USD dollar) than open air markets (18.8 Kshs/bunch) (Cheleng'a et al., 2013). A model for commercializing TVCs can be adopted from Eastern African countries. One success story is the project initiated by Farm Concern International (FCI) in Kenya and Tanzania, in collaboration with the AVRDC-World Vegetable Centre. The major aim of the project was to enhance market access for TVCs and women's empowerment through participatory action research by following the Commercial Village Approach (CVA). Farmers were given high quality seeds, access to finance, training on agricultural production practices, and organized into marketing support units so that they can meet the demand and supply of TVCs. Farm Concern International partnered with Uchumi supermarkets as a vehicle for promotion and consumer awareness of TVCs. Awareness campaigns were furthered through local radio stations, TV stations, trade fairs, exhibitions, in-store promotions, outdoor promotions, nutritional walks, and product sampling (Mwangi and Kimathi, 2006). The demand for TLV's increased from 31 to 600 tonnes per month with an average profit margin of USD1539.2 acre^{-1} (0.405 ha^{-1}), which were double those of exotic vegetables (Mwangi and Kimathi, 2006). Another study conducted by Muhanji et al. (2011) indicated higher annual profit margins for TVCs (USD2426-USD4571) when compared to exotic vegetables (USD960-USD1760), because of lower production costs. In SA, TVCs are not yet commercialized, except in extreme cases like the Polokwane Spar supermarket, which sell Amaranth on their vegetable shelves. The vegetable value chain is still dominated by exotic vegetables such as Swiss chard, cabbage, carrots, beetroot, cauliflower, and tomatoes (DAFF, 2013). Markets are divided into informal markets (farm gate), fresh produce markets (council markets in each of the 9 provinces, with Tshwane and Johannesburg markets being the biggest in the country), and supermarkets (Baiphethi and Jacobs, 2009). Consumers can be classified as low and high income earners, which determine the affordability to purchase fresh produce by them. Decisions made by consumers to purchase a product are based on availability, accessibility, affordability, cultural beliefs, and quality (nutritional value). Since 1994, the Agricultural Research Council has conducted case studies that showed that there is a great potential for TVCs to be commercialized in SSA, as long as there is a proper marketing value chain, technical support, capacity building of RPHs, availability of quality seeds and finance are in place. To commercialize TVCs, Southern African countries need to follow the same model as in the Eastern African countries.

2.5 The new unity of purpose research

Food and nutrition security (FNS) of RPHs can never be understood in isolation from development, because the food system is complex, requiring a trans-disciplinary approach to look beyond production, by understanding the role which can be played by natural sciences, technology, social sciences, economics, food sciences and policy (Drimie and McLachlan, 2014; Pereira et al., 2014). The authors of this chapter are aware that TVCs cannot solve all the problems of FNS, but they can be part of the solution through dietary diversification. Mavengahama et al. (2013) suggested that more controlled experiments need to be conducted to understand the effect of soil type, fertiliser amount, and leaf harvesting on the nutritional composition of TVCs. A new unity of purpose research is proposed and it should be multi-disciplinary and follow the marketing value chain approach, which evaluates major components of the food system (Graef et al., 2014):

- A multi-disciplinary team should visit RPHs to conduct a detailed analysis of the constraints hampering their FNS by assessing major components of the food system including natural resources, food production, processing, marketing, and consumption. These teams should not focus on whose knowledge counts, but investigating and understanding the complexity of the local problems and use local knowledge and resources in solving those problems (Scoones et al., 2005).
- Henke (2000) developed the concept of 'place' as a way to explore the land, water, and crops of a site, together with differences in users, thus differentiating research sites between the controlled 'place' of a research station from the 'cooperative space' of trials in farmers' fields. Field experiments can be conducted on a research station under controlled conditions by investigating the yield response of TVCs to various water and fertility stresses. This research should assess the NWP of TVCs, which quantifies nutrition per volume of water used (Renault and Wallender, 2000). To determine NWP, raw edible biomass, NC, and actual evapotranspiration are measured (Table 2.3). NWP is calculated as Y_a/Eta x NC, where Y_a is actual harvested yield (kg ha^{-1}), ETa is actual evapotranspiration (m^3 ha^{-1}), and NC is nutritional content per kg product (nutritional unit kg^{-1}). Controlled trials should be carried out under a rain-shelter and in an open field which represents the poor soils of the region, with soil water conditions managed under drip irrigation systems. The experimental plot layout should be developed with an understanding of the specific characteristics of soil and landscape variability of the research location that do shape the choice of experimental plot layout. The design of the trials has to take into account the requirements of valid testing with these variable site characteristics.
- We propose that results from the research station should be scaled up to RPHs using the participatory action research approach which was suggested by Chambers and

Jiggins (1987). Smallholder farmers can be selected by purposeful selection from a site which is truly representative of RPHs in South Africa. Two sets of experiments need to be conducted on a farmer's field: (a) production for household consumption (using local resources such as kraal manure), and (b) production for commercial purposes (well-managed agronomic practices). Their fields could be monitored throughout the growing period through field visits. The results can be used to understand the technical, institutional, behavioural and capacity building innovations for RPHs.

- However, the food system is complex, and to understand this complexity, experiments need to be conducted throughout the country, which can be very expensive and cumbersome, demanding focused approaches are (Conroy and Sutherland, 2004). This study adopts the approach of ''system thinking'', to help in understanding a food system, based on different socio-environmental conditions. Thus, alongside field trials with selected farmers, local results can be studied further through crop models (AquaCrop, soil water balance, WOFOST, and DSSAT) which simulate yield response to different environmental conditions (Paola et al., 2015). Data collected could be used to calibrate and validate the selected crop model (s) and be used to upscale results by simulating different environmental and socio-economic conditions for fragile regions in SA and their potential for alleviating food insecurity. Calibrated models can be used as decision support tools for policy makers to address NFIS in South Africa.

Table 2.3: Parameters relating to nutritional value to be assessed under the new unity of purpose research on TLVs

Parameter	Definition	Justification
1. Raw edible yield or biomass	The portion of plant material on a fresh mass basis which is suitable for human consumption.	Biomass can be high at harvest but the edible portion which can be consumed by humans can be lower due to yellow leaves and stems.
2. Nutritional content (NC)	The concentration of micro-nutrients (β-carotene, Fe, and Zn) in raw edible yield.	The amount of micro-nutrients available in plant material is very important because it relates to the possibility of the crop to meet human dietary needs.
3. Bio-availability of nutrients	The proportion of nutrient intake that is capable of being absorbed by the body of humans.	The nutrient content of crops can be high on fresh mass basis but not available for human nutrition because of compounds that block their availability.
4. Nutritional yield (NY)	A function of raw edible yield and nutrient content of crops (Bumgarner et al., 2012).	NY is one of the important agronomic parameters which indicate nutrient mass that can be harvested from a certain crop during the entire season.
5. Nutritional water productivity (NWP)	The ratio of nutrient content per volume of water used (Renault and Wallender 2000).	NWP is a novel concept that quantifies the amount of water needed to produce a certain micro-nutrient yield, thus relate to water resource use.

2.6 Summary and conclusions

The potential of TVCs to combat micronutrient deficiencies and hidden hunger is starting to be recognized, but more needs to be done. The SANHANES-1 survey of 2012 suggests that since 1994 there has been a reduction in food insecurity overall in South Africa. However, the country still faces high rates of micronutrient deficiency, affecting RPHs. To alleviate FNS, the time to act is now. Available research efforts are until now poorly collated and lacks scientific vigour, environmental and social context that enables data to be exchanged and used for research and policy development. This chapter attempts a compilation of existing data for the role of TVCs in FNS, to which it is hoped other authors will contribute in future. As a focus also of social and agricultural policy, research on production of TVCs by and for RPHs needs a design that can bring transformational innovation in resources and policy approaches, where research interacts with and informs policy development in new ways, also with support from multi-disciplinary teams. This chapter should serve as an example, and it is hoped more authors will write about research design for new agricultural production approaches. This work needs to build not only on the conventional approaches from within agronomy, such as food based approaches like plant breeding, food supplementation, food fortification, bio-fortification, and dietary diversification, but also link with a new understanding of food and market chains. This chapter has focused on the potential of TVCs to be part of possibilities for change through dietary diversification, but the ARC-VOP research programme will also look at wider impacts of growing TVCs by RPHs. The authors of this chapter aware that TVCs are not miracle crops, but can supplement essential nutrients for RPHs in SSA. Controlled experiments need to be conducted on a research stations, but also on the farmer fields in a participatory way, to understand the environmental and sociological factors that influence the production, utilization, and marketing channels for TVCs in SSA, including SA. Traditional vegetable crops can contribute to the alleviation of FNS by production for home consumption, and also for selling to make profit. South Africa can learn from Eastern African countries, like Kenya and Tanzania, where TVCs have already been commercialized through diverse strategies of support in production and marketing in its pursuit of NFS.

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3 WATER PRODUCTIVITY OF TRADITIONAL VEGETABLE CROPS

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3.1 Introduction

The millennium development goal of eradicating extreme poverty and hunger had not been realized in sub-Saharan Africa (sSA) because a third of the population still faces acute hunger and it is exposed by prolonged famines (Haile, 2005). Moreover, the population is expected to increase which is a threat to food and nutrition security (FNS) of resource poor households (RPHs) who solely rely on rainfed agriculture (World Bank Group, 2016). Rainfed agriculture plays a major role in determining agricultural production thus ensuring economic development of RPHs (Haile, 2005), however, rainfall in SSA is sporadic and influenced by El Nino events, resulting in frequent occurrence of droughts which reduce crop yield dramatically. Recently, South Africa had experienced extremely hot weather conditions during the rainy season (usually from October to March) which resulted in higher evaporation rates in water bodies such as dams, lakes, and rivers. Some crops could not be grown and production decreased significantly because of limited water for irrigation. Water was rationed in major cities such as Cape Town, Johannesburg, Pretoria, and Durban, whilst irrigated agriculture is blamed to be using more water (60%) compared to the other industries. The impact of recent El Nino is still being experienced by consumers through increased food prices (Teagle, 2016). Resource poor households need to find coping strategies which could be:

- Management of limited resources more efficiently.
- Re-thinking agro-biodiversity solutions.

Traditional vegetable crops (TVCs) are known to be growing naturally in the “wild”, fallow fields, and cultivated landraces without irrigation and fertilizer inputs, which had prompted researchers and policy makers to suggest that these crops are drought tolerant and can be ideal for cropping systems in water scarce areas such as sSA (Faber and van Jaarsveld, 2007; Juroszek et al., 2008; Hart, 2011). These crops presents more advantages over exotic vegetables because they:(i) tolerate less favourable conditions by being resilient to local conditions of higher temperatures, require minimal inputs (water and fertilizer), less prone to pests and diseases, as well as a short growth period, ranging from 2-4 weeks, (ii) include some C4 crops (*Amaranth spp.* and Cleome *spp.*) which are well-known for higher water use efficiency, and (iii) have potential to generate income in some parts of SSA where they had been commercialized. However, TVCs poses some weaknesses such as: (i) unreliable yield because of growing under marginal environments, (ii) having a low status because they are linked to RPHs who consume them when there are no other means of acquiring food, and (iii) the threat of being extinct – they are collected in the wild and there exist negative connotations towards their consumption by younger generations (Jacobsen et al., 2015; Chivenge et al., 2015). Despite these weaknesses, TVCs demonstrate significant potential to reduce micronutrient deficiency because of high nutritional value and can be cultivated for income generation. Several studies (Afari-Sefa et al., 2012; Oelofse and van Averbeke, 2012; Mavengahama et al*.,* 2013; Bodner et al., 2015; Chivenge et al., 2015) had indicated that research on yield and water use of TVCs should be conducted. However, these studies had evaluated water productivity (WP) of TVCs using yield and water use from different locations, which vary due to climatic conditions, soil fertility, and water availability. The objective of this study was therefore to assess the WP of *Amaranthus cruentus* (Amaranth), *Cleome gynandra* (Spider flower), and *Ipomoea batatas* var*. Bophelo* (orange fleshed sweet potato, OFSP) under different water availability and soil fertility conditions, using soil, water, and meteorological data sets from the same location. *Beta vulgaris* subsp. *vulgaris* (Swiss chard) was used as a reference crop to compare the TVCs' yield response with a popular commercial crop in South Africa. The reasons for including Swiss chard as a reference crop are that it is a leafy vegetable, highly nutritious (contains Fe, Zn, and β-carotene), commercialized in South Africa and mostly utilized by RPHs who eat it as a relish with maize porridge (Mavengahama et al., 2013). Orange fleshed sweet potato is a dual purpose crop depending on the farming system considered. Under commercial production, the storage roots are mostly harvested, whilst in small scale farming systems, leaves, and storage roots are harvested for human consumption. Therefore, OFSP is considered as a leafy vegetable and a storage root crop in this study.

3.2 Water productivity

In a broad sense, the productivity of water refers to the benefits derived from water use. Crop water productivity is defined in either physical or economic terms as the ratio of the product (usually measured in kg) over the amount of water depleted (usually crop evapotranspiration) (Molden et al., 2003). In this study the term water productivity will be used, meaning physical crop water productivity. In the next 40 years, water scarcity will become a reality and agriculture will need to produce more food with less water. Worldwide researchers (Renault and Wallander, 2000; Zoebl, 2006; Rockstrom and Barron, 2007; Ali and Talukder, 2008) are in agreement that WP of crops needs to increase in order to meet the increasing demand. Water productivity (WP) was calculated as suggested by Renault and Wallander (2000):

$$[\text{Biomass (B) or Yield (Y)}] \,/\, [\text{actual evapotranspiration (ETa)}] \text{ ………. (1)}$$

The units of WP are kg m^{-3} or kg ha^{-1} mm^{-1}; the numerator is in kg ha^{-1} and the denominator is in m^{-3} ha^{-1}. In literature (Kijne et al., 2003; Ong and Swallow 2003; Oweis and Hachum, 2003), the term WP is used interchangeably with water use efficiency. In the present study, the term WP will be used, meaning dry total biomass per ETa. There are several opportunities to improve WP of crops including deficit irrigation, water harvesting, soil fertility management, mulching, installation of drip irrigation, and selection of proper crops (Renault and Wallender, 2000; Ali and Talukder, 2008; Vincent and van Halsema, 2012). There is no study which has assessed WP of TVCs using soil, water, and meteorological data sets from the same location. This is the first attempt to benchmark WP of Amaranth, Spider flower and OFSP in South Africa.

3.3 Materials and methods

3.3.1 Rain-shelter experiments

3.3.1.1 Site description

Experiments were conducted under a rain-shelter at the Agricultural Research Council-Vegetable and Ornamental Plants (ARC-VOP), Roodeplaat, Pretoria (25^0 60’ S; 28^O 35’ E; 1168 masl), Gauteng Province during the 2013/14 and 2014/15 summer seasons which are from November to May. The soils under the rain-shelter were classified as sandy loam using the USDA taxonomic system (Mabhaudhi et al., 2013), containing an average of 78.3% sand, 5.7% silt, and 16% clay with soil pH (H_2O) of 6.87. The field capacity (FC) of the soil is 18.5 % (by volume) and permanent wilting point (PWP) is 11.7 % (by volume). The saturated hydraulic conductivity (K_s) is 839.3 mm day^{-1} and the average bulk density of the soil is 1.51 g cm^{-3} (Tables 3.1 and 3.2). The climate of the region is one of summer rainfall (October-March), with an average of approximately 650 mm per year, and highly variable. January is the month with the highest average maximum temperature (30°C), whilst July is the month with the lowest average minimum temperature (1.5°C). Frequent occurrence of frost is experienced during the winter months.

Table 3.1: Chemical soil properties for the rain-shelter

Depth (cm)	**Chemical properties**							
	Fe	**Zn**	**Org. C**	**N-NO$_3$**	**N-NH$_4$**	**pH (H_2O)**	**P (Bray 1)**	**K**
	mg kg^{-1}	mg kg^{-1}	%	mg kg^{-1}	mg kg^{-1}		mg kg^{-1}	mg kg^{-1}
2013/14								
0-30	19.8	10.7	0.9	15.5	7.9	7.3	77.7	190.1
30-60	52.3	4.3	11.6	3.3	4.7	7.3	16.2	86.3
2014/15								
0-30	13.7	5.09	2.5	26.5	3.5	6.02	76	156.0

Table 3.2: Physical soil properties for the rain-shelter

Depth	**Sand**	**Silt**	**Clay**	**Textural class**	**FC^a**	**PWP^b**	**K$_s$^{c}**	**BD^d**
cm	**%**	**%**	**%**		Vol %		mm day^{-1}	g cm^{-3}
0-20	78	4	18	Sandy loam	19.5	12.6	678	1.52
20-30	76	6	20	Sandy loam	21.1	13.8	535	1.53
30-40	76	8	16	Sandy loam	18.8	11.5	813	1.50
40-60	76	6	18	Sandy loam	19.9	12.6	664	1.52
60-80	82	4	14	Sandy loam	16.5	10.3	1062	1.50
80-100	82	6	12	Loamy sand	15.3	9.1	1284	1.49

[a]Field capacity; [b]permanent wilting point; [c]saturated hydraulic conductivity; [d]bulk density

3.3.1.2 Experimental setup

The experimental design was a randomized complete block design, while the treatment design was a 4 x 3 factorial with two factors/treatments, namely crops and water levels, replicated three times. Four crops (Amaranth, Spider flower, OFSP and Swiss chard) and three water levels (Irrigation (I_1) that refilled a water extraction depth (WED) of 60 cm to FC when 30% of plant available water (PAW) was depleted; Irrigation (I_2) that refilled the WED to FC when 50% of PAW was depleted; and Irrigation (I_3) that refilled the WED to FC when 80% of PAW was depleted). *Beta vulgaris* subsp. *Vulgaris* was used as a reference crop because it is a leafy vegetable, highly nutritious (contains Fe, Zn and β-carotene), commercialized in South Africa, and mostly utilized by RPHs who eat it as a relish with maize porridge (Mavengahama et al., 2013)

3.3.1.3 Water regime management

The rain-shelter was divided into 36 small plots of 3 x 3 m to accommodate the treatments and replications. Compensating non-leaking (CNL) Urinam drip lines of 2.3 L h^{-1} were designed to irrigate each plot separately. The CNL drip operates similar to a pressure compensated drip, but has the advantage of having a non-leakage device that prevents water from draining out of the drip emitter once the system has shut-off and the pressure within the drip system drop down below 2 m (20 kPa). Other necessary existing components of the irrigation system included a pump, filters, solenoid valves, water meters, control box, online drippers, 2000 litre JOJO tank, mainline, sub-main, and laterals. Irrigation was scheduled based on the PAW required to refill soil water content (SWC) back to FC when 30% (no stress), 50% (moderate stress), and 80% (severe stress) of PAW is depleted, which was calculated as the difference between SWC at FC and PWP. The plots were irrigated with the same amount of water for the first 14 days. Thereafter, the irrigation treatments were implemented.

3.3.1.4 Crop management

Orange flesh sweet potato cuttings, Amaranth, Spider flower and Swiss chard seedlings were obtained from the ARC-VOP Plant Breeding Division. Orange flesh sweet potato cuttings were planted on ridges (30 cm high and 20 cm wide) at a spacing of 0.8 m between ridges and 0.3 m within cuttings (22 plants per plot (5.2 m^2)), whereas, Amaranth, Spider flower and Swiss chard seedlings were planted on a flat surface at an inter- and intra-spacing of 0.3 m x 0.3 m. Because the residual soil P and K values were very high (Table 3.1), it was decided to only apply limestone ammonium nitrate (LAN, 28% N) fertilizer at a recommended rate of 120 kg N ha^{-1} for OFSP and 150 kg ha^{-1} for Amaranth, Spider flower, and Swiss chard. The crop management practices were similar to the 2013/14 and 2014/15 seasons.

3.3.1.5 Data collection

Neutron water meter access tubes were installed in the middle of each plot to a depth of 1 m. Soil water content was measured twice a week, before irrigation, at fixed depth increments of 0.2 m using a neutron water meter (NWM) (CPN, 503 DR Hydroprobe, USA) calibrated for the site with measurements at the wet and dry spot, respectively. The wet spot was established by ponding water on the soil until the complete profile was saturated and left to drain for 48 hours to reach field capacity (FC). The dry spot was established by leaving the soil for a period of approximately six months to dry out. The gravimetric method was used to determine SWC from the wet and dry spots a number of times, simultaneously taking counts at 0.2 m intervals of a 1 m soil profile with the Hydroprobe. Volumetric SWC was calculated by multiplying gravimetric SWC with soil bulk density, which was calculated as follows:

$$\text{Bulk density} = [Ms] / [Vsoil] \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where Ms is the mass of dry soil and Vsoil is the volume of the dry soil. A linear relationship was established between counts and volumetric SWC. The soil water balance equation below was used to calculate crop water use (ETa):

$$ETa = I + Pr + \Delta W + Cr - Dp - \Delta Sf - R \ldots\ldots\ldots (3)$$

Where ETa (mm) is the actual evapotranspiration, I is the irrigation amount, Pr is the rainfall amount, ΔW is the change in soil water in mm of the WED (The WED for Amaranth, Spider flower, and Swiss chard was 0.60 m, whereas, for OFSP it was 1 m), Cr is the capillary rise in mm (assumed to be negligible), Dp is the deep percolation (assumed to be negligible), ΔSf is the change in sub-surface in- and out-flow (assumed to be negligible), and R is the runoff amount (assumed to be negligible). In the case of the rain-shelter experiment, rainfall equals zero. Leaf harvesting for Amaranth, Swiss chard, Spider flower and OFSP was conducted on all plant rows per plot, but to avoid border effects, only data from the middle rows were utilized. At every harvest, destructive samples were removed from two plants per plot for determination of above ground plant growth (LAI, stem length, stem diameter) and below ground root growth (length and mass of tap root). The destructive samples data were used in the calibration and validation of AquaCrop model (see chapter 5). At every harvest, the fresh mass was also determined by weighing fresh harvested above ground growth biomass (leaves and stems) and raw edible leaves of the TVCs. Thereafter, samples were taken for oven drying for 3-4 days in an oven at 75°C. Leaf area index (LAI-2000) and stomatal conductance (SC-1 leaf porometer Decagon Devices) were measured on a weekly basis to monitor the effect of different irrigation amounts on crop growth during the growing seasons. Water productivity (WP) was determined as follows (Renault and Wallander, 2000):

$$WP = [\text{Biomass}] / [\text{actual evapotranspiration}] \ \ldots\ldots\ldots\ldots (4)$$

However, meteorological conditions were not similar for the 2013/14 and 2014/15 growing seasons. Therefore, WP was normalized using a method which was suggested by van Halsema (2003):

$$WP = [\text{Biomass}] / [\sum (ETa/ET_0)] \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Where ETa represents actual evapotranspiration and ET_0 reference evapotranspiration. Nutritional water productivity (NWP) was calculated as WP x NC (Renault and Wallender, 2000; Vincent and van Halsema, 2012).

3.3.1.6 Statistical analysis

Two-way analysis of variance (ANOVA) was conducted to evaluate the main effects of the individual factors (crops and water levels) and their interactions in terms of biomass, edible biomass and WP of the TVCs. The GenStat version 14, VSN, UK was used to calculate the least significant difference at 5% confidence interval. *Post hoc* analysis was conducted using the Tukey HSD test (VSN International, 2012).

3.3.2 Open field (Rooiland) field experiments

3.3.2.1 Site description

The main aim of the open field trial at a site called Rooiland was to evaluate during the 2013/14 and 2014/15 summer seasons the effect of different combination rates of N, P and K fertilizer application on biomass development and, hence, NC of selected TVCs under irrigated and rainfed conditions. This experiment was conducted on a marginal soil that was low in macro and micro nutrients. Soil samples were taken before planting and were analyzed for certain soil properties (Table 3.3). The experimental soil was classified (Soil Classification Working Group, 1991) as a yellow-brown Oakleaf form, Buchuberg family (Oa 1120), with a soil depth of 0.65-0.85 m and a clay content of 20% in the 0-0.3 m layer.

3.3.2.2 Experimental setup

A 35 m x 40 m field was laid out at Rooiland field to accommodate 48 plots of 3 m x 3 m. The experimental design for the OFSP was a randomized complete block design. The treatment design was a 2 x 2 x 2 factorial design with 3 replicates: 2 water levels (Full (W1) and supplemental irrigation (W2)), 2 fertility levels (Full: F1 and no fertilizer: F2) and 2 harvesting methods (No harvesting of OFSP leaves (H1)) and harvesting every 4 weeks (H2) = 24 plots. The experimental design used for Amaranth and Spider flower was the same as for OFSP, but the treatment design was a 2 x 2 x 2 factorial design with 3 replicates: 2 water levels x 2 fertility levels x 2 crops = 24 plots.

3.3.2.3 Water regime management

The Rooiland field experiment was divided into two experiments: Experiment 1 was planted to OFSP and experiment 2 planted to Amaranth and Spider flower. Each experiment comprised of 24 plots and compensating non-leaking (CNL) Urinam drip lines of 2.3 L h^{-1} were used to irrigate each plot separately. Irrigation was scheduled based on the PAW required to refill SWC back to FC when 30% (W1) of PAW was depleted. The latter was calculated as the difference between SWC at FC and PWP. The supplemental irrigation treatment (W2) was irrigated to 50% of PAW, only if it did not rain for a period of 4 weeks in order to revive the plants. The irrigation system included a pump, filters, water meters, control box, online drippers, 2000 litre JOJO tank, mainline, sub-main, and laterals.

Table 3.3: Pre-trial properties of the experimental soil at the Rooiland trial site

Nutrient	Units	Range per 30 cm depth	Fertility status
Total N	mg kg^{-1}	380-850	
P	mg kg^{-1}	3.2-3.6	Low
K	mg kg^{-1}	44-64	Low
Ca	mg kg^{-1}	120-436	Low-Medium
Mg	mg kg^{-1}	49-363	Low-High
Na	mg kg^{-1}	4.2-175	Low-Medium
Clay	%	16-28	
pH (H_2O)	-	6.08-7.98	Medium-High

3.3.2.4 Crop management

Amaranth (*Amaranthus cruentus*), Spider flower (*Cleome gynandra*), and OFSP (*Ipomoea batatas var. Bophelo*) were selected based on their popularity, nutritional value and future commercialization potential in South Africa (van Rensburg et al., 2007). Amaranth and Spider flower are C4 plants and OFSP is a C3 plant. C4 plants (tropical grasses) have lower intercellular CO_2 concentration (C_{ci}) compared to C3 plants, therefore they produce more dry matter per unit of water than C3 plants. Seeds of Amaranth and Spider flower for these experiments were obtained from the ARC-VOP Plant Breeding seed bank. Orange fleshed sweet potato, cultivar *Bophelo*, cuttings were also obtained from the ARC-VOP Plant Breeding Division, OFSP nursery. For the 2013/14 and 2014/15 seasons, straight fertilizers (LAN 28% N), Calsiphos (12% P and 14% Ca), KCl (50% K) and $Ca(NO_3)_2$ (15.5% N)) were applied as sources of N, P, and K based on the soil analysis and target yields as recommended by ARC-VOP (F1) of 150 kg ha^{-1} N, 74 kg ha^{-1} P, 200 kg ha^{-1} K and 160 kg ha^{-1} Ca, whereas, no fertilizer was applied for the control treatment (F2). Orange fleshed sweet potato were planted on the 6th of December 2013 a planted on ridges (30 cm high and 20 cm wide) at a spacing of 0.8 m between ridges and 0.3 m within cuttings (37 plants per plot (9 m^2). When planting the cuttings, 3 nodes above and below ground were maintained to allow the cuttings to develop roots from the nodes. Fertiliser used for Amaranth and Spider flower was similar to the ones used for OFSP trial – the only difference was the fertilizer application rates (125 kg ha^{-1} N, 60 kg ha^{-1} P, 150 kg ha^{-1} K and 224 kg ha^{-1} Ca). The rainfed trial was set up in a similar layout to the irrigated one and was supplemented with irrigation if it did not rain for a period of one month. Seedlings were prepared during October of each season (which is from November to May) so that they were ready after about 6 weeks to be transplanted.

3.3.2.5 Data collection

For all the crops, leaf harvesting was conducted on all plant rows per plot, but to avoid border effects, only data from the middle rows were utilized. Harvesting of Amaranth and Spider flower leaves were done every three weeks after they were transplanted. However, OFSP leaves were harvested by plucking the first five well developed leaves from each vine at 4, 8, 12, and 16 weeks after planting from the leaf harvesting treatment (H2). Storage root yield was also determined at the end of the season. Fresh mass was determined by weighing freshly harvested leaves of sweet potato, Spider flower and Amaranth. Fresh mass samples were then oven-dried for four days at 75°C to determine dry matter content. Aluminium access tubes were installed in the middle of each plot up to a depth of 1.2 m. Soil water content was measured weekly using a neutron water meter (CPN, 503 DR Hydroprobe, USA) that was calibrated for the site as mentioned in section 3.3.1.5. Plant available water was calculated as the difference between the water content at FC and PWP. Irrigation scheduling was determined as the amount of water required to refill the WED back to FC. This amount, which is the difference between FC and the measured soil water level, was taken as the soil water deficit (D) and was calculated on a weekly basis. Water productivity (WP) was determined as the yield of total dry raw edible biomass per unit of water used for each plot: WP = Y/ET_a, where Y is the aboveground biomass or yield (kg m^{-2}) and ET_a (irrigation plus change in SWC is crop water use during the growing period (mm) (Renault and Wallender, 2000; Vincent and van Halsema, 2012).Leaf area index (LAI-2000) and chlorophyll content index (CCI) (CCM-200 plus) were measured on a weekly basis to monitor the effect of different irrigation amounts on crop growth during the growing seasons.

3.3.2.6 Data analysis

The data of the different trials were tested for homogeneity of variances using Levene's test (Shapiro and Wilk, 1965). In cases were the variability in the observations of the different trials were of comparable magnitude an analysis of the different trials' observations together could be validly carried out. In cases where there was strong evidence against homogeneity a weighted analysis of different trials' observations together were carried out using the inverse of the pooled variances of each trial as weight (John and Quenouille, 1977). The Shapiro-Wilk test was performed to test for normality (Shapiro and Wilk, 1965). Student's t-Least Significant Difference (LSD) values were calculated at the 5% level to compare treatment means. All the analyses were done using SAS v9.2 statistical software (SAS, 1999).

3.4 Results and discussion

3.4.1 Rain-shelter experiments

3.4.1.1 Meteorological conditions

Figure 3.1 indicates reference evapotranspiration (ET_0), vapour pressure deficit (VPD), and temperature (minimum and maximum) which were predominant during the 2013/14 and 2014/15 seasons which were from November to May. Reference evapotranspiration for the two seasons were almost similar, except the variation at the initial and final stages of plant growth. For the 2013/14 season (Fig 3.1), ET_0 ranged between 0.88 mm day^{-1} to 7.3 mm day^{-1} for 2013/14 season, whereas for the 2014/15 season it ranged between 1.4 mm day^{-1} to 6.9 mm day^{-1}. Vapour pressure deficit indicated some variation between the two seasons- for season 1 VPD was higher when compared to the second season. Values ranged from 0.22 kPa to 2.39 kPa for the 2013/14 season and from 0.32 kPa to 1.91 kPa. Little variation in temperature was observed during both seasons. The maximum and minimum temperatures for the 2013/14 season were 35°C and 9°C, respectively. For the 2014/15 season, the maximum and minimum temperatures were 34°C and 9°C, respectively (Figure 3.1). The base temperature for Amaranth and Spider flower is 8°C whereas for OFSP it is 10°C. Growth ceases at temperatures above 35°C for traditional crops. Mabhaudhi et al. (2013) reported similar meteorological weather parameters for the Roodeplaat location.

3.4.1.2 Soil water content

Soil water content for the 2013/14 (Figure 3.2) and 2014/15 (Figure 3.3) growing seasons for Amaranth, Spider flower, Swiss chard, and OFSP are presented. The results indicate that water stress treatments were monitored very well for both seasons. The no stress (30%) treatment showed the highest SWC, while the moderate stress (50%) indicated reasonable water stress, and the severe water stress (80%) treatment revealed much lower SWC for both seasons. In the 2014/15 season, the levels of SWC could be clearly identified and corresponded to the various water stress treatments because of good irrigation scheduling.

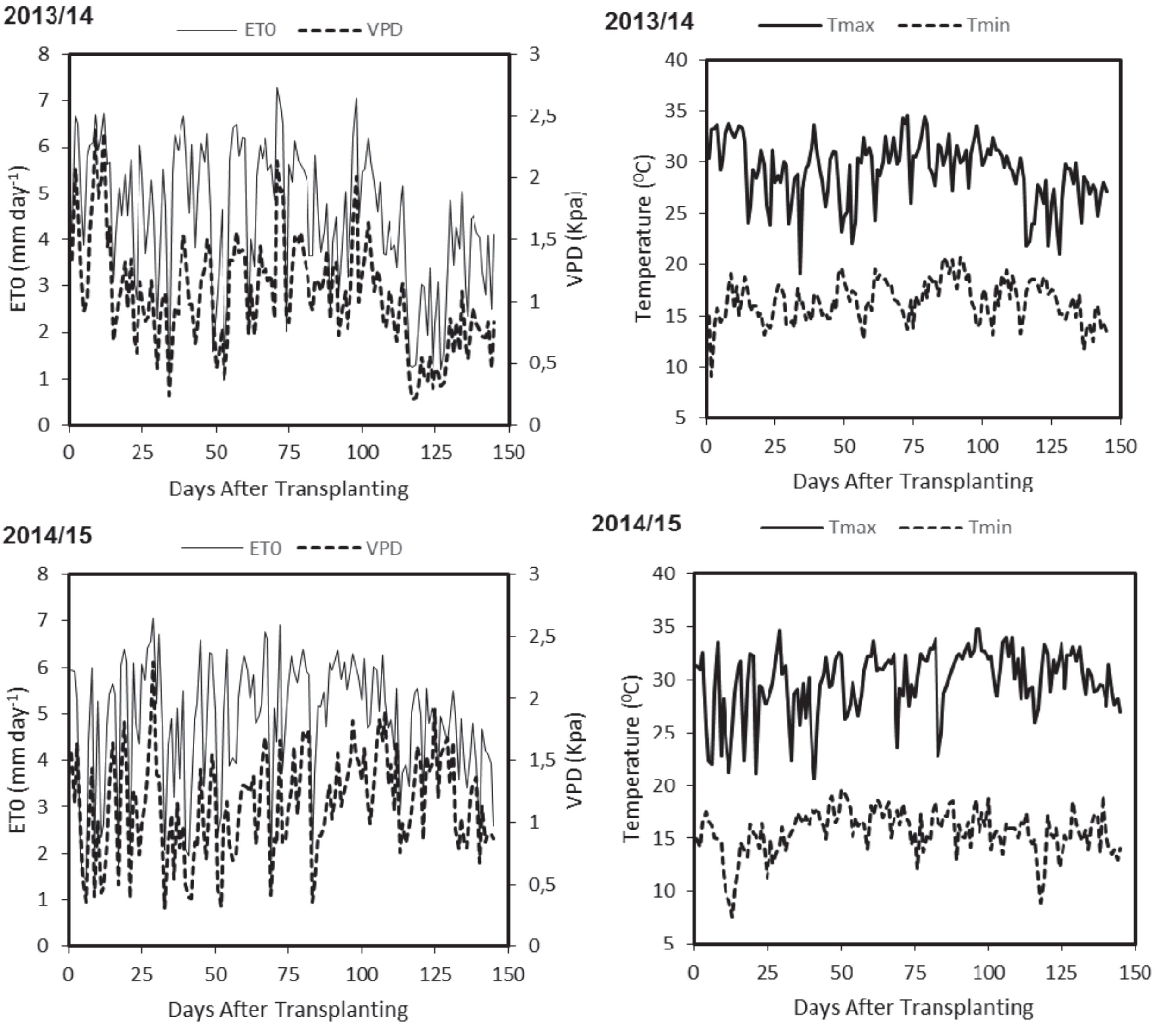

Figure 3.1: Reference evapotranspiration, vapour pressure deficit, maximum and minimum temperature for 2013/14 and 2014/15 seasons

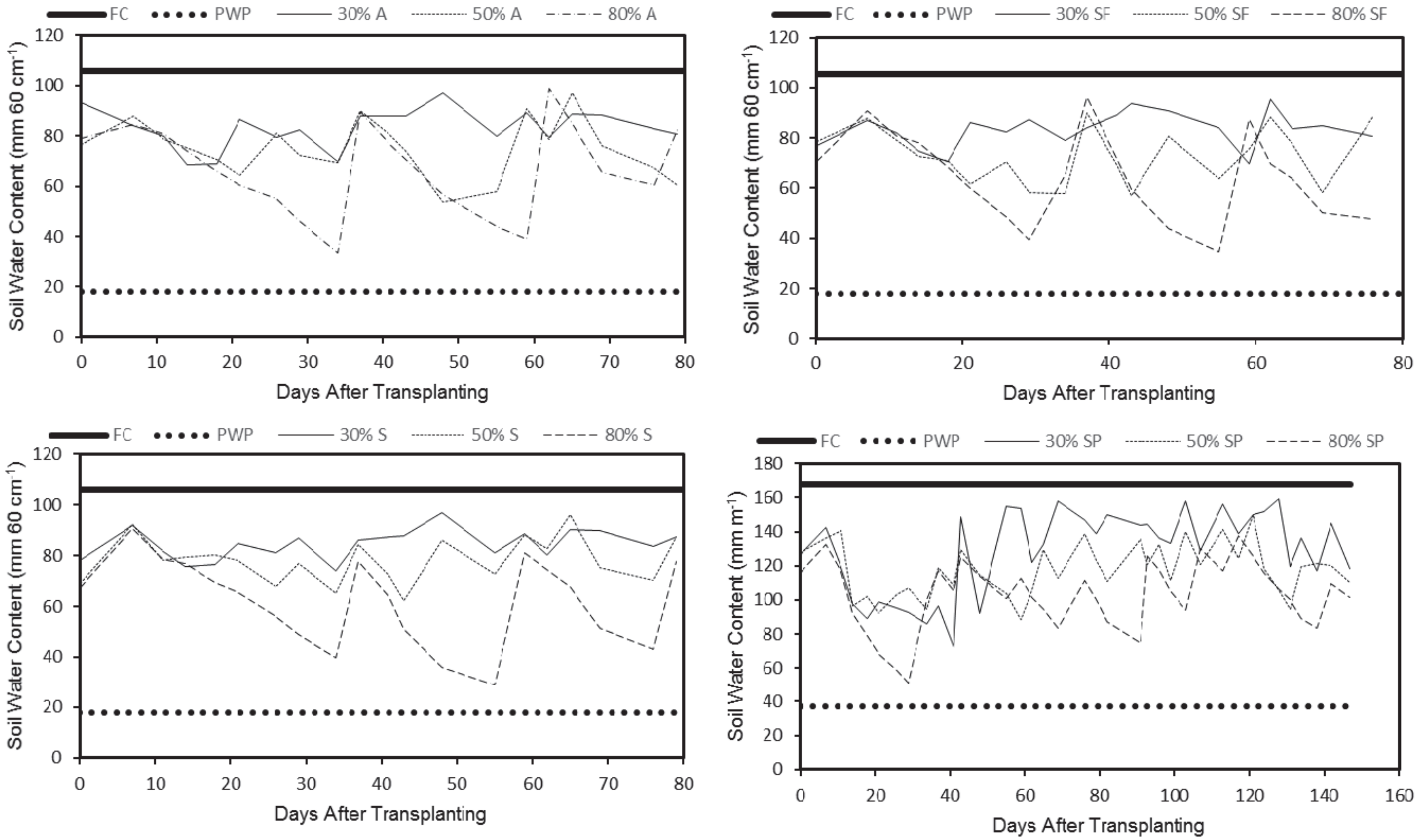

Figure 3.2: Soil water content for different water stress levels for Amaranth (A), Spider Flower (SF), Swiss chard (S), and Orange fleshed Sweet potato (SP) for 2013/14 growing season.

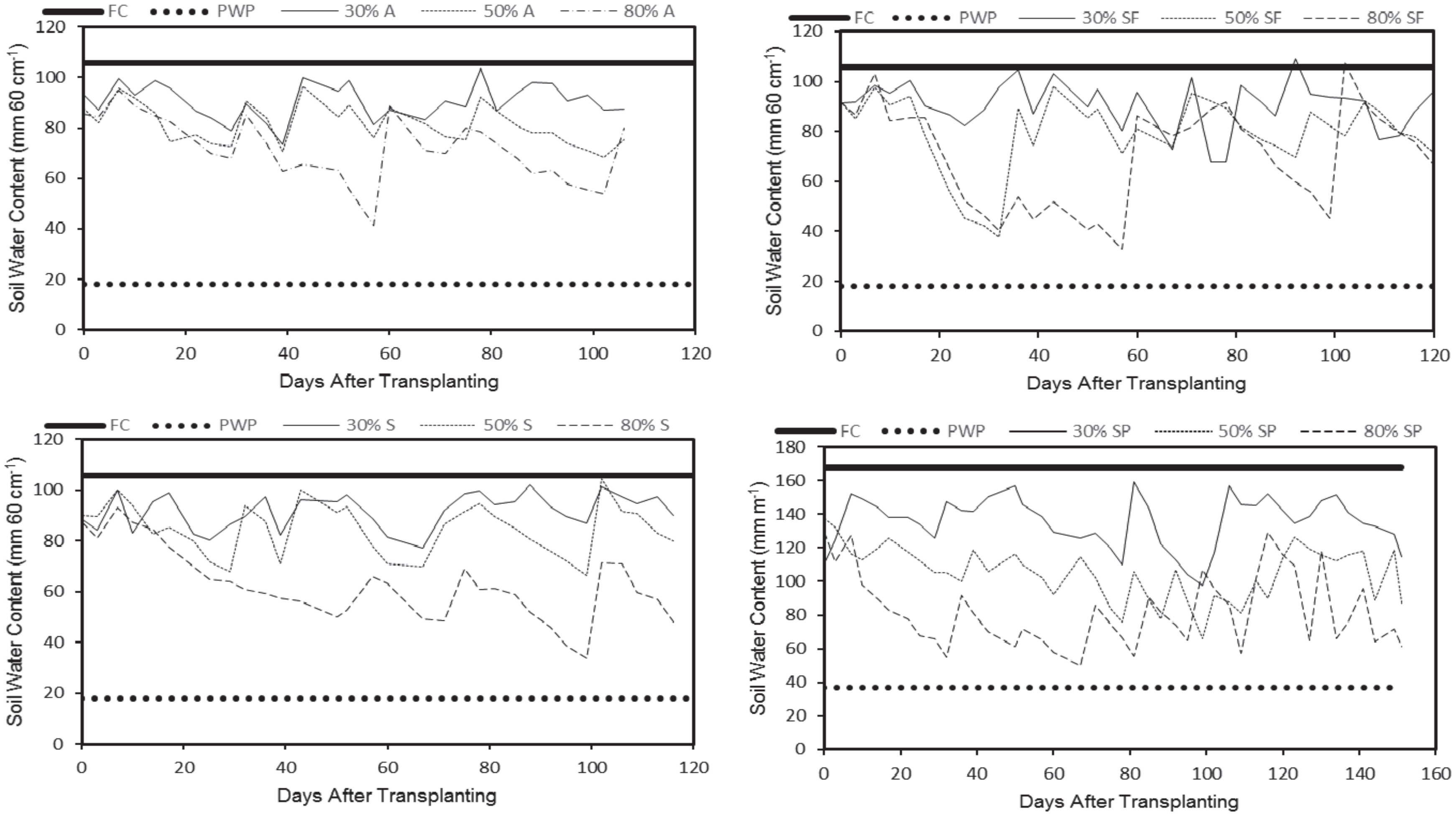

Figure 3.3: Soil water content for different water stress levels for Amaranth (A), Spider Flower (SF), Swiss chard (S), and Orange fleshed Sweet potato (SP) for 2014/15 growing season

3.4.1.3 Leaf area index

Leaf area index (m^2 m^{-2}) is the amount of one-sided leaf area per unit area of ground. (Chen and Black, 1996). During the process of photosynthesis, when plants are exposed to water stress, their stomata close, whereas, when plants are not water stressed, their stomata remain open. Therefore, an increase in LAI increases light interception and the source/sink strength for heat, water and CO_2 exchange (Farshbaf-jafari et al., 2014). Leaf area index was monitored throughout the growing period for Amaranth, Spider flower, Swiss chard, and OFSP for both seasons (2013/14 and 2014/15). The results of the study indicate that water stress had a significant effect ($p \leq 0.05$) on canopy growth of traditional crops (Amaranth, Spider flower, and OFSP) (Table 3.4). These results further indicate that under each water stress treatment, LAI increased from planting and reached the maximum just before every harvesting period. The trend which was observed was that LAI remained lower under water stressed treatments and higher under the no stress treatment (Figures 3.4 & 3.5). Mabhaudhi et al. (2013) reported similar findings on LAI for taro whereby water stress had reduced the LAI. Moreover, the results indicate that TVCs had performed very well in the 2013/14 season, compared to the 2014/15 season, because of the difference in ET_0, which could be attributed to different weather conditions which were prevailing during the two seasons.

Table 3.4: Analysis of variance for LAI for TCVs

	Crops (C)		**Water (W)**		**C x W**	
DAT[a]	**F_{value}**	**P_{value}**	**F_{value}**	**P_{value}**	**F_{value}**	**P_{value}**
2013/14						
14	69.59	<.001	1.42	0.263	2.73	0.039
21	12.8	<.001	46.52	<.001	1.56	0.206
28	154.19	<.001	73.29	<.001	2.94	0.029
35	42.56	<.001	35.7	<.001	1.26	0.316
43	45.13	<.001	42.96	<.001	3.52	0.014
60	221.24	<.001	25.88	<.001	3.5	0.014
67	70.04	<.001	35.96	<.001	5.56	0.001
75	148.25	<.001	30.03	<.001	3.19	0.021
84	121.75	<.001	71.19	<.001	4.27	0.005
2014/15						
10	3.51	0.032	1.74	0.199	2.13	0.091
31	58.94	<.001	43.73	<.001	3.07	0.025
60	227.81	<.001	38.92	<.001	2.28	0.073
73	2.33	0.102	20.59	<.001	4.7	0.003
89	10.77	<.001	51.47	<.001	2.53	0.051
94	38.12	<.001	12.07	<.001	1.6	0.193
101	50.19	<.001	18.28	<.001	3.88	0.009
108	431.15	<.001	49.13	<.001	4.66	0.003
118	59.45	<.001	53.63	<.001	2.52	0.052

[a]DAT – Days After Transplanting

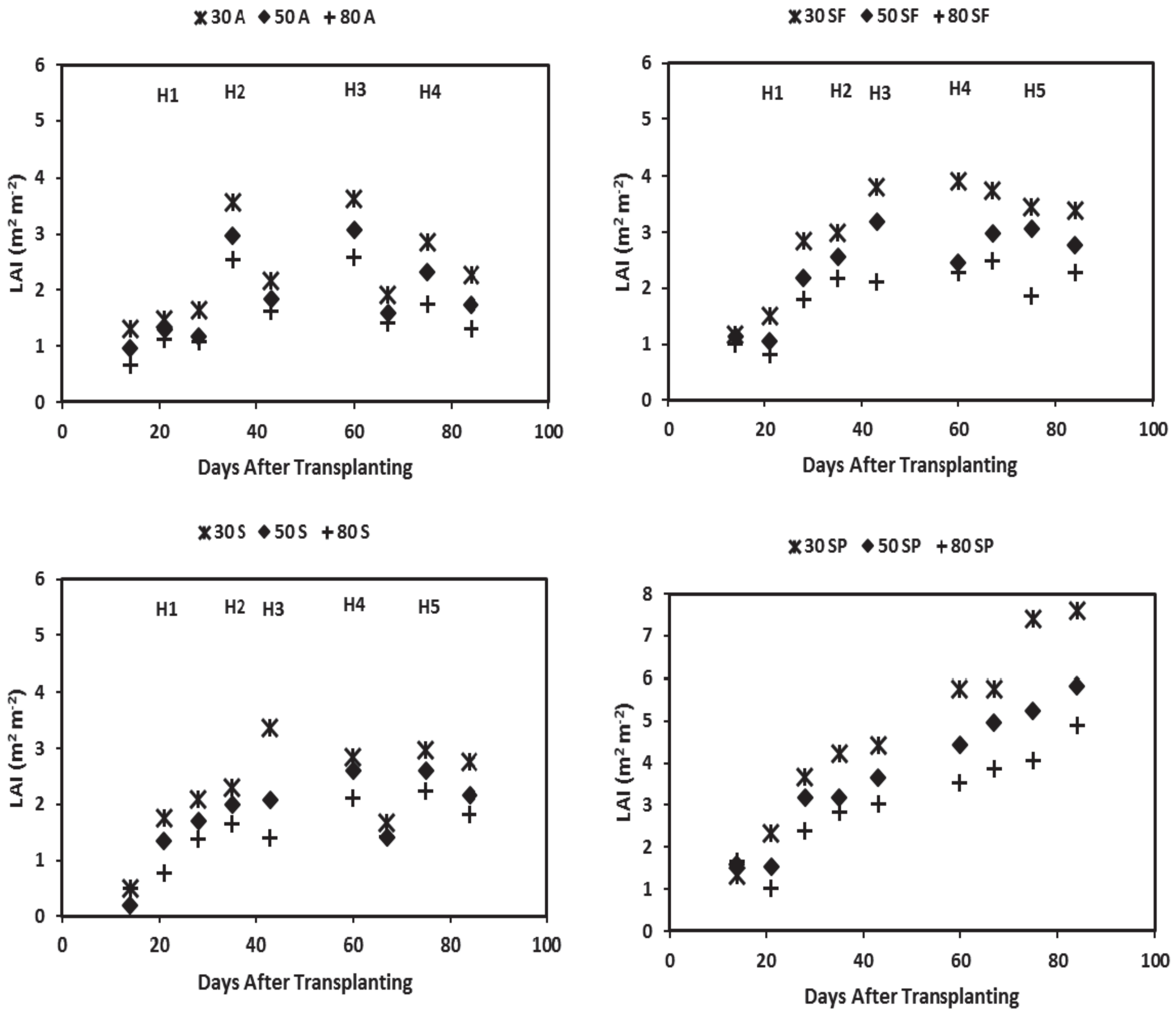

Figure 3.4: Leaf area index for TVCs for Amaranth (A), Spider Flower (SF), Swiss chard (S), and Orange fleshed Sweet potato (SP) for 2013/14 growing season (H1...H_n means harvests during different periods of the growing season).

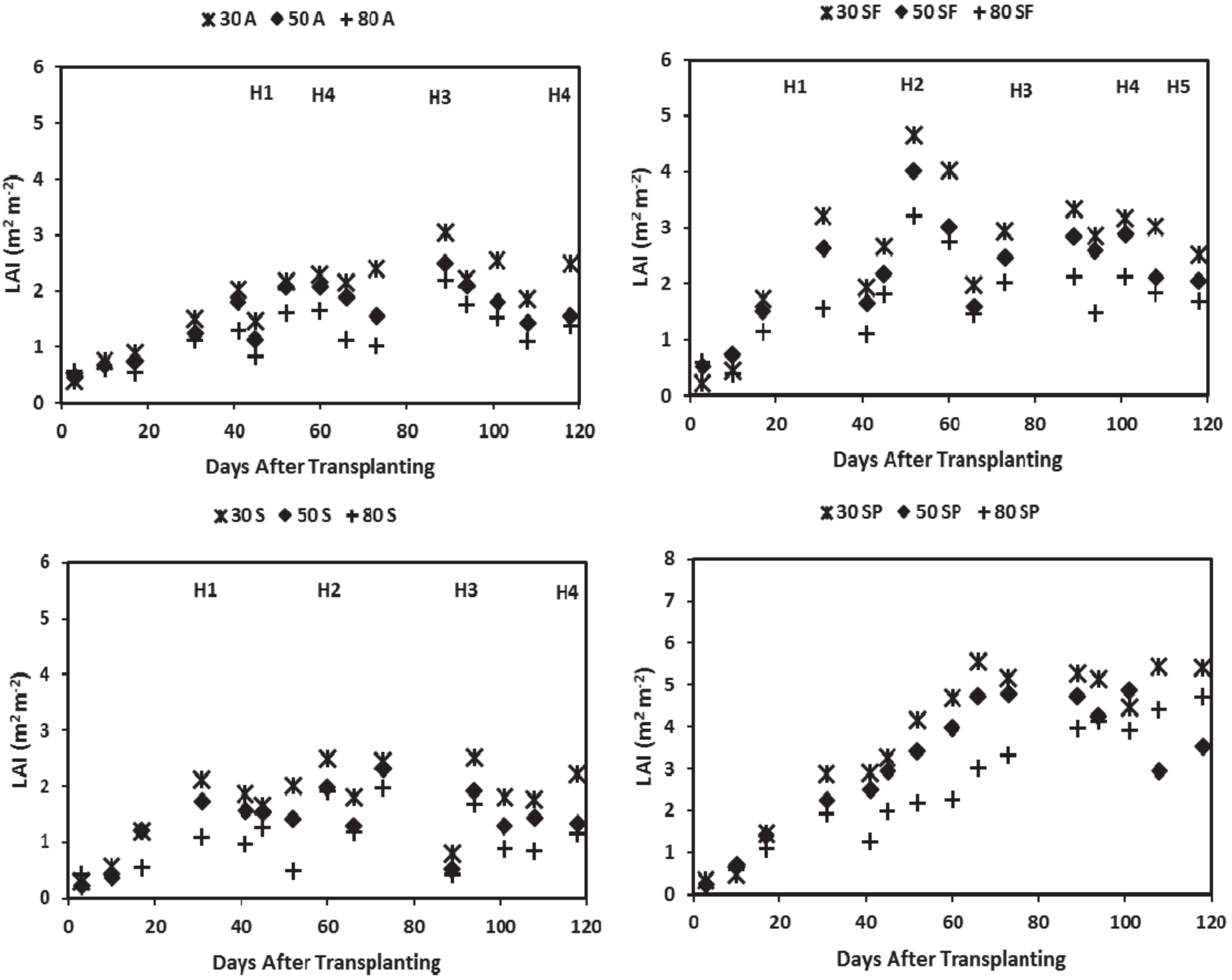

Figure 3.5: Leaf area index for TVCs for Amaranth (A), Spider Flower (SF), Swiss chard (S), and Orange fleshed Sweet potato (SP) for 2014/15 growing season (H1…H_n means harvests during different periods of the growing season)

3.4.1.4 Stomatal conductance

Figure 3.6 presents stomatal conductance for the experimental crops. When plants are water stressed, they tend to partially close their stomata in trying to minimize water loss through the process of transpiration, which would result in the reduction of biomass production. The ability to withstand water stress depends on the crop type (C3 and C4). C4 plants (tropical grasses) have lower intercellular CO_2 concentration (C_{ci}) compared to C3 plants, thus they produce more dry matter per unit water than C3 plants. Stomatal conductance was monitored during the growing period for the 2013/14 growing season. Stomatal conductance was significantly ($p \leq 0.05$) affected by different water stress levels (Table 3.5). The no stress water treatment depicted higher stomatal conductance and as the severity of water stress was increased, stomatal conductance decreased. Moreover, the results indicate that crop species play a major role in conductance. Amaranth (180 mmol $m^{-2}.s^{-1}$) and Spider flower (200 mmol $m^{-2}.s^{-1}$) indicated lower conductance values when compared to OFSP (260 mmol m^{-2}.s^{-1}) and Swiss chard (270mmol m^{-2}.s^{-1}). This can be attributed to the crop type (C3 or C4). Amaranth and Spider flower are C4 plants, and under water limiting conditions; they close their stomata to reduce water loss and in turn produce more dry matter compared to Swiss chard and OFSP which are C3 plants (Vincent and van Halsema, 2012). These results are comparable with findings of Mabhaudhi et al. (2013) on the stomatal conductance of taro.

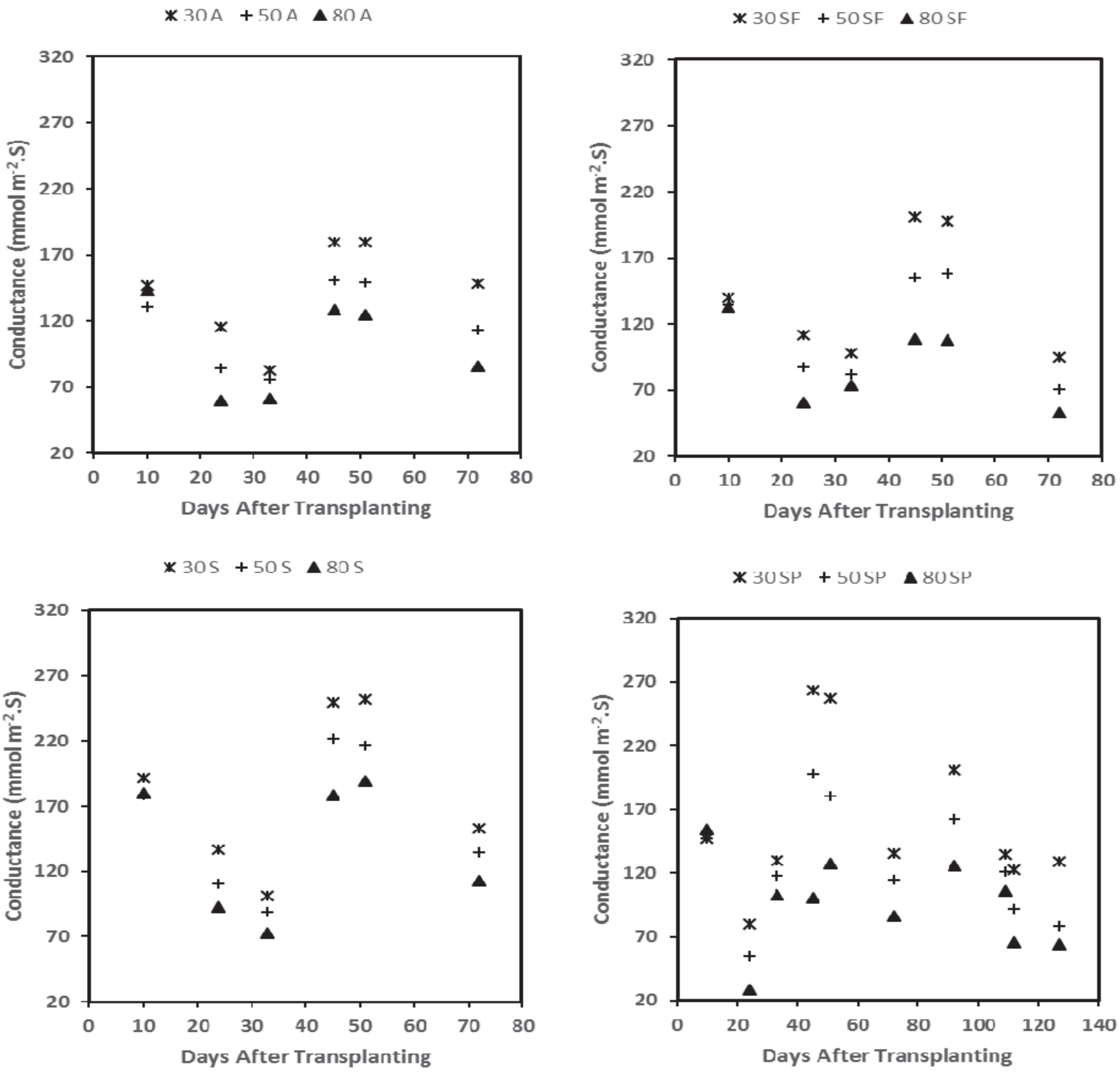

Figure 3.6: Stomatal conductance for Amaranthus (A), Spider flower (SF), Swiss chard (S), and orange fleshed sweet potato (SP) for 2013/14 growing season

3.4.1.5 Biomass and crop evapotranspiration

The following plant growth parameters were measured: Fresh and dry biomass, fresh and dry raw edible leaves, and ETa for selected traditional vegetable crops (Amaranth, Spider flower, OFSP and Swiss chard. Results indicate that water stress had a significant (*p*<0.001) effect on the growth of TVCs and Swiss chard (Table 3.6). Total biomass was reduced because of decreasing SWC (water stress), I_2-50% (moderate water stress), and I_3-80% (severe water stress)). The highest dry biomass (6.89 t ha^{-1}) for the 2013/14 season was obtained from the combination of Spider flower with the no water stress (30%) treatment and the lowest dry biomass (1.96 t ha^{-1}) observed for OFSP leaves, under the severe water stress (80%) treatment (Table 3.7). A similar trend was observed for the 2014/15 season (Table 3.7) whereby highest biomass (9.79 t ha^{-1}) was obtained from the combination of Spider flower under no water stress (30%) and the lowest biomass (3.43 t ha^{-1}) from OFSP leaves under the severe water stress (80%) treatment. The biomass of TVCs such as Spider flower and Amaranth consists of bulky stems which are not suitable for human consumption. Therefore, it is important to consider the proportion which can be used for human consumption. There was a high significant (*p*<0.001) difference between the two seasons for the different crops, as well as water stress (Table 3.6). For the 2013/14 season, the highest dry edible leaves were observed for Swiss chard (4.16 t ha^{-1}) under no water stress (30%) treatment and the lowest for Amaranth (1.58 t ha^{-1}) under the severe water stress (80%) treatment (Table 3.7). For the 2014/15 season, the highest dry mass edible leaves were obtained for Swiss chard (6.02 t ha^{-1}) under the no water stress (30%) treatment, and the lowest for OFSP leaves (1.67 t ha^{-1}) under the severe water stress (80%) treatment (Table 3.7). These values are higher than those reported by Oelofse and van Averbeke (2012) who found that total dry biomass for Amaranth ranged from 1.2 to 2.8 t ha^{-1} and for Spider flower from 0.6 to 1.1 t ha^{-1}. Table 3.8 presents total biomass and raw edible biomass for the experimental crops on a fresh mass basis.

Crop ETa indicates a highly significant difference (*p*<0.001) for seasons 1 and 2, respectively (Table 3.6). Table 3.7 shows that for all crops, ETa remained lower under the severe water stress (80%), and higher under the no water stress (30%) treatments, respectively. Another important observation between the two seasons is that crop ETa values were higher in season 2 compared to season 1, which might had been caused by variation in weather conditions (temperature, vapour pressure deficit, and ET_0). The results indicate that different plant species utilized different amounts of water based on ETa. Water use of the different crops can be ranked as follows from highest to lowest for the no water stress (30%) treatment: (i) OFSP leaves, (ii) Amaranth, (iii) Spider flower, and (iv) Swiss chard. However, when water stress was implemented, *i.e.* severe water stress (80) treatment, the crops can be ranked as follows; (i) OFSP leaves (ii) Spider flower, (iii) Swiss chard, and (iv) Amaranth. Annandale et al. (2012) reported water use values of Amaranth (96-448 mm), Spider flower (50-443 mm), sweet potato (182-1200 mm), and Swiss chard (425-625 mm). The results of this study are within the ranges reported by Annandale et al. (2012).

Table 3.5: Analysis of variance for stomatal conductance (2013/14 season)

	Crop (C)		**Water (W)**		**C x W**		**C X W**	**CV**
DAT[a]	**F_{value}**	**P_{value}**	**F_{value}**	**P_{value}**	**F_{value}**	**P_{value}**	**LSD (%)**	**(%)**
10	6.1	0.004	0.22	0.81	0.11	0.99	41	15.8
24	76	< 0.001	113	< 0.001	0.33	0.92	14	9.7
33	178	< 0.001	107	< 0.001	1.06	0.41	7.1	4.6
45	42	< 0.001	135	< 0.001	9.34	< 0.001	24	7.9
51	24	< 0.001	56	< 0.001	2.39	0.063	33	11
72	81.22	< 0.001	97.64	< 0.001	1.26	0.317	14.4	7.9

[a]DAT – Days After Transplanting

Table 3.6: Analysis of variance for different plant growth parameters (2013/14 and 2014/15 seasons)

	Crops (C)		**Water (W)**		**C x W**	
Parameters	**F_{value}**	**P_{value}**	**F_{value}**	**P_{value}**	**F_{value}**	**P_{value}**
2013/14						
Biomass Fresh	8.37	0.002	35.45	<.001	0.33	0.916
Biomass Dry	10.9	<.001	6.04	0.008	0.23	0.964
Leaves Fresh	14.02	<.001	197.69	<.001	0.47	0.822
Leaves Dry	18.2	<.001	23.06	<.001	2.93	0.03
ETa	1614.8	<.001	519.23	<.001	26.86	<.001
WP	52.66	<.001	4.17	0.029	1.71	0.166
2014/15						
Biomass Fresh	21.27	<.001	9.93	<.001	0.27	0.946
Biomass Dry	15.15	<.001	24.61	<.001	1.13	0.377
Leaves Fresh	12.88	<.001	232.48	<.001	2.73	0.039
Leaves Dry	139.68	<.001	53.34	<.001	1.23	0.33
ETa	59.38	<.001	278.61	<.001	2.57	0.048
WP	33.69	<.001	4.1	0.031	1.75	0.157

Table 3.7: Dry biomass, raw edible biomass, and ETa of TCVs (2013/14 and 2014/15 seasons)

		2013/14				2014/15			
Crop	**Water**	**Biomass**	**Leaves**	**ETa**	**WP**	**Biomass**	**Leaves**	**ETa**	**WP**
		t ha^{-1}	t ha^{-1}	mm	kg m^{-3}	t ha^{-1}	t ha^{-1}	mm	kg m^{-3}
Amaranth	30	6.34^{ab}	2.97^{abcd}	289.4	2^{d}	7.29^{abc}	3.874^{bc}	391.4^{b}	1.86^{cd}
Amaranth	50	4.45^{cde}	2.68^{bcde}	189.4^{b}	2.53^{bcd}	6.29^{bc}	3.38^{cd}	282.6^{d}	2.23^{bc}
Amaranth	80	3.27^{efg}	**1.58^{e}**	108.5^{e}	3.33^{a}	5.25^{bcd}	2.84^{def}	210.7^{e}	2.53^{ab}
Spider flower	30	**6.89^{a}**	2.72^{bcde}	240^{a}	2.85^{abc}	**9.79^{a}**	3.25^{cd}	375.4^{b}	2.59^{ab}
Spider flower	50	5.77^{abc}	2.49^{bcde}	170.2^{bc}	**3.41^{a}**	7.43^{ab}	2.71^{def}	255.8^{de}	**2.91^{a}**
Spider flower	80	4.88^{bcd}	2.28^{cde}	151.9^{cd}	3.21^{ab}	5.90^{bcd}	2.08^{fg}	212.1^{e}	2.78^{ab}
Sweet potato leaves	30	4.49^{cde}	4.16^{a}	**504.2**	0.76^{e}	6.86^{bc}	3.14^{cde}	**536.5^{a}**	1.30^{e}
Sweet potato leaves	50	2.39^{efg}	2.61^{bcde}	416.5	0.70^{e}	5.03^{bcd}	2.28^{efg}	358.7^{b}	1.41^{de}
Sweet potato leaves	80	**1.96^{g}**	2.08^{de}	359.1	**0.64^{e}**	**3.43^{d}**	**1.67^{g}**	302.6^{cd}	**1.13^{e}**
Swiss chard	30	4.16d^{e}	**4.16^{a}**	216.9^{a}	1.92^{d}	6.03^{bcd}	**6.02^{a}**	352.7^{bc}	1.45^{de}
Swiss chard	50	3.65^{def}	3.65^{ab}	170.6^{bc}	2.15^{cd}	4.72^{bcd}	4.72^{b}	287.5^{d}	1.65^{de}
Swiss chard	80	3.38^{defg}	3.38^{abc}	**142.4^{d}**	2.37^{cd}	4.53^{cd}	4.53^{b}	**203.1^{e}**	2.25^{bc}

Table 3.8: Fresh biomass, raw edible biomass TVCs (2013/14 and 2014/15 seasons)

		Season 1		Season 2	
Crop	**Water**	**Biomass**	**Leaves**	**Biomass**	**Leaves**
		t ha^{-1}	t ha^{-1}	t ha^{-1}	t ha^{-1}
Amaranth	30	**66^{a}**	21^{c}	47^{abc}	19^{c}
Amaranth	50	55^{a}	17^{c}	39^{bcd}	14^{c}
Amaranth	80	45^{abc}	13^{c}	33^{bcd}	13^{c}
Spider flower	30	61^{a}	18^{c}	42^{abcd}	11^{c}
Spider flower	50	55^{a}	15^{c}	37^{bcd}	11^{c}
Spider flower	80	45^{abc}	**11^{c}**	**26^{d}**	**8^{c}**
Sweet potato leaves	30	24^{bcd}	22^{c}	47^{abc}	13^{c}
Sweet potato leaves	50	21^{cd}	19^{c}	44^{abcd}	10^{c}
Sweet potato leaves	80	**16^{d}**	14^{c}	32^{cd}	9^{c}
Swiss chard	30	62^{a}	**62^{a}**	**59^{a}**	**59^{a}**
Swiss chard	50	54^{a}	54^{ab}	49^{ab}	49^{ab}
Swiss chard	80	49^{ab}	49^{c}	41^{bcd}	41^{b}

NOTE: For tables 3.7 and 3.8 Column values followed by the same symbol are not statistically different at *p*≤0.05. The bold and underlined values indicate highest treatment means, whereas, the bold values indicate the lowest treatment means.

3.4.1.6 Crop water productivity

Crop water productivity for the experimental TVCs, OFSP and Swiss chard for 2013/14 and 2014/15 seasons is shown in Figure 3.7. The relationship between different water stress levels and biomass for were plotted using linear regression for both seasons and the slope of the line is WP of Amaranth, Spider flower, OFSP and Swiss chard. The trends which were observed for both seasons were that water the stressed treatments retained lower biomass whereas non-stressed treatments indicated higher biomass. Water productivity for TVCs ranged from 0.64 kg m^{-3} (OFSP leaves, 80%) – 3.41 kg m^{-3} (Spider flower, 50%) for the 2013/14 season. For the 2014/15 season, WP ranged from 1.13 kg m^{-3} (OFSP leaves, 80%) – 2.91 kg m^{-3} (Spider flower, 50%) (Table 3.7). The coefficient of determination (R^2) indicates the proportion of the variance in the dependent variable that is predictable from the independent variable and ranges from 0 to 1, with higher values indicating less error variance, and values >0.5 regarded as acceptable The R^2 values for season 1 and season 2 were as follows: Amaranth- 0.754 and 0.751, Spider flower- 0.918 and 0.941, Swiss chard- 0.893 and 0.748, and OFSP- 0.737 and 0.951, therefore, the R^2 values ranged for 0.75 to 0.94 which suggest that there was a strong relationship between water use and biomass development (Figure 7). However, these results need to be treated with caution because the edible portion suitable for human consumption is higher in Swiss chard compared to TCVs. Annandale et al. (2012) reported WP for Amaranth ranging from 1.2-2.5 kg m^{-3}, Spider flower from 0.2-6 kg m^{-3}, OFSP from 4.3-13 kg m^{-3}, and Swiss chard from 1.2-9 kg m^{-3}. These values are higher compared to the results of the present study.

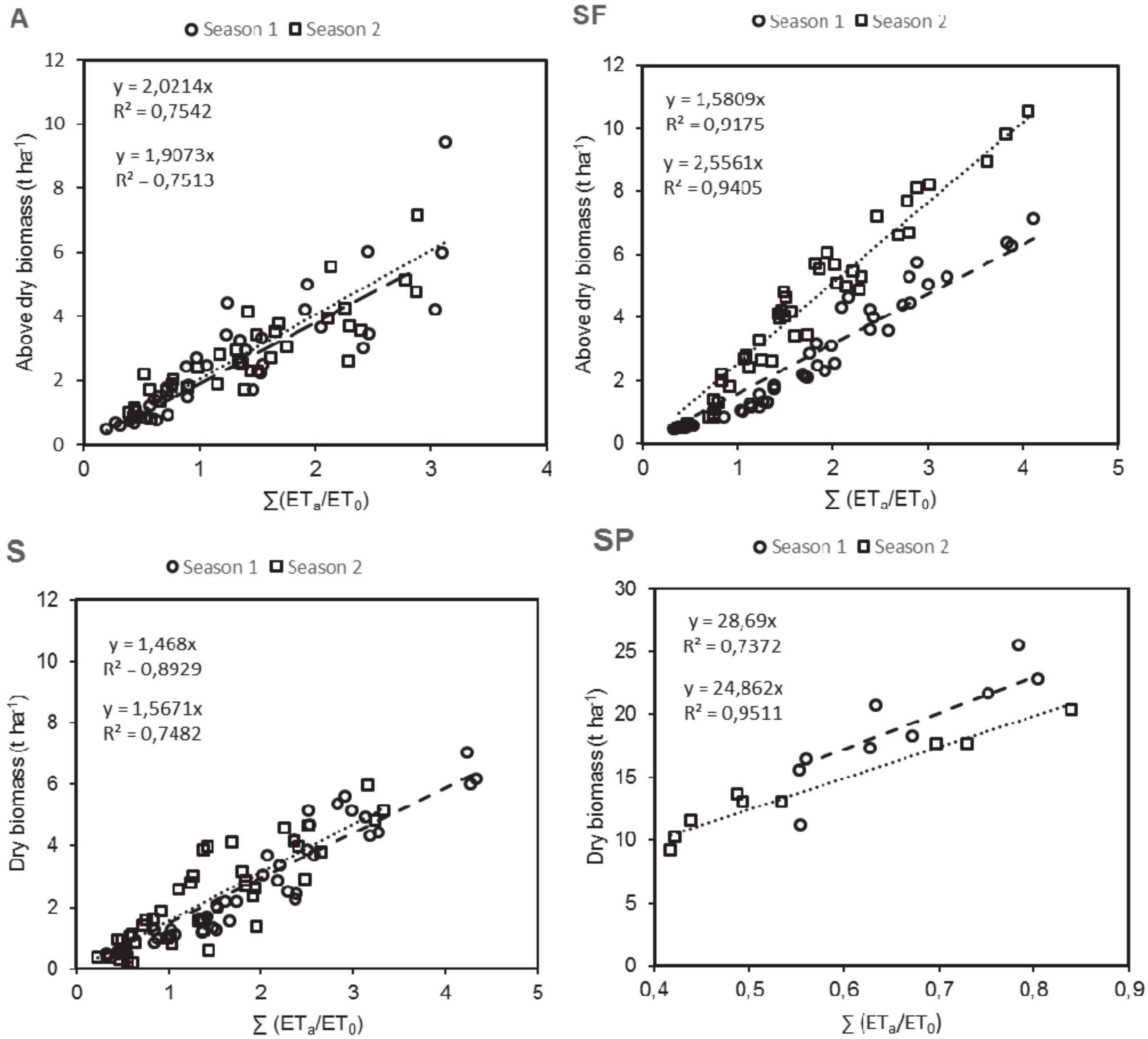

Figure 3.7: Normalized water productivity for Amaranth (A), Spider flower (SF), Swiss chard (S), and orange fleshed sweet potato (SP) for 2013/14 (represented by the broken line) and 2014/15 season (represented by the dotted line)

3.4.2 Rooiland field experiments

3.4.2.1 Orange fleshed sweet potato var. Bophelo

- **Leaf area index**

Leaf area index (LAI, m^2 m^{-2}) is the amount of one-sided leaf area per unit area of the soil surface (Chen and Black, 1996). Leaf area index was monitored throughout the growing period for OFSP for both seasons (2013/14 and 2014/15). Results indicate that water, fertility, and leaf harvesting had a significant effect ($p \leq 0.05$) on canopy growth for OFSP for both seasons (Table

3.9). The observed trend was that LAI remained lower under water and fertility stressed treatments and higher under the unstressed water and fertility treatments (Figure 3.8). Similar findings were reported by Mabhaudhi et al. (2013) on LAI for taro.

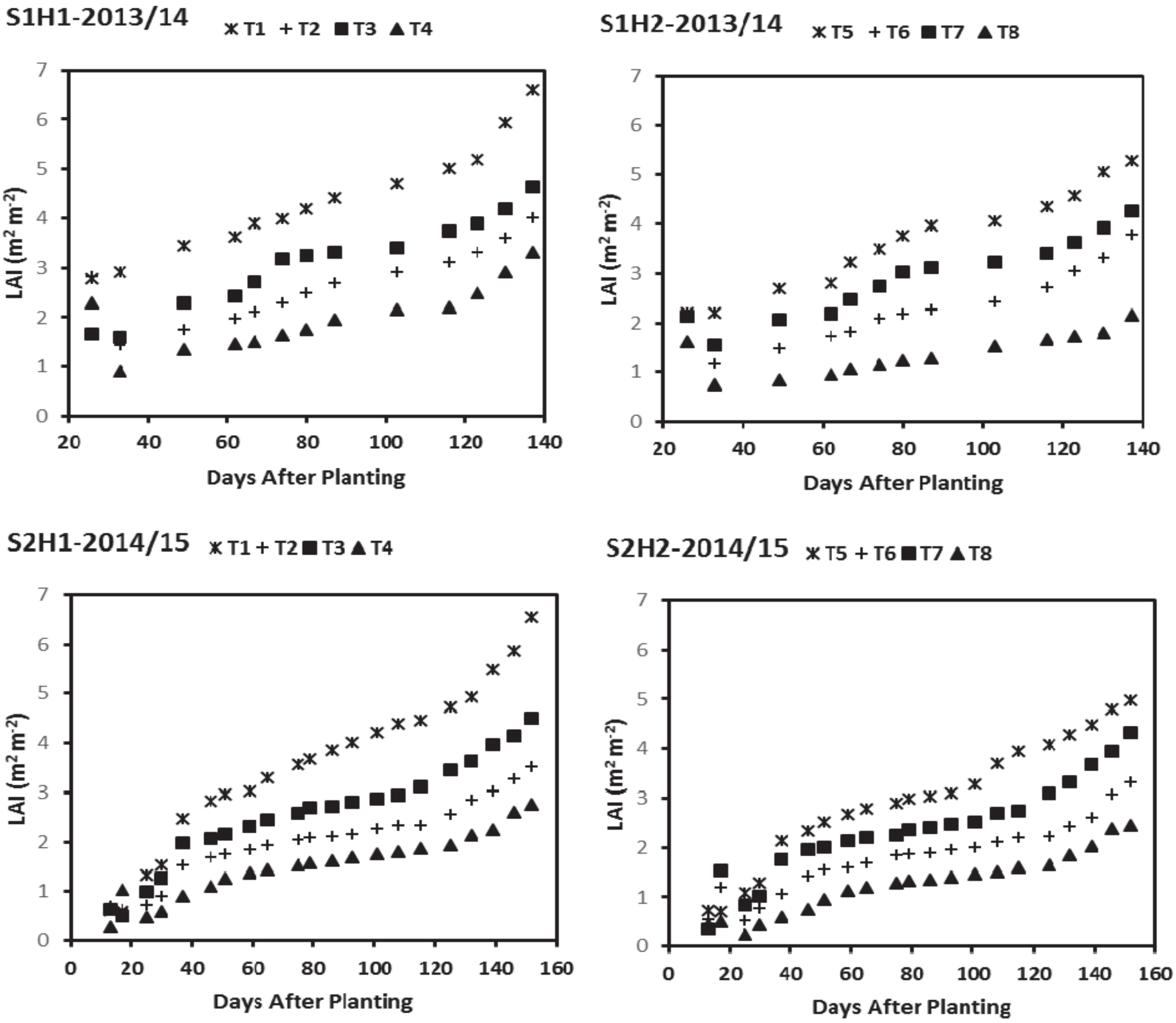

Figure 3.8: Leaf area index (LAI) for orange fleshed sweet potato (S) for 2013/14 and 2014/15 seasons. T1= W1F1H1; T2= W2F1H1; T3= W1F2H1; T4= W2F2H1; T5=W1F1H2; T6=W2F1H1; T7=W1F2H1; T8=W2F2H1 (W1 (full irrigation amount); F1 (full NPK fertiliser application); H1 (no leaf harvesting of OFSP); W2 (supplemental irrigation); F2 (no NPK fertiliser application); H2 (leaf harvesting of OFSP))

- **Chlorophyll content**

Chlorophyll content of OFSP was measured during different periods for the 2013/14 and 2014/15 growing seasons. Results indicate that there was an interaction effect ($p \leq 0.05$) for water, fertility, and leaf harvesting, except for the first two measurement periods in 2013/14 season (Table 3.10). The observed trend was that CCI remained lower under water and fertility stresses and higher under the non-stressed water and fertility treatments (Figure 3.9). Moreover, there was no variation of CCI between the two seasons.

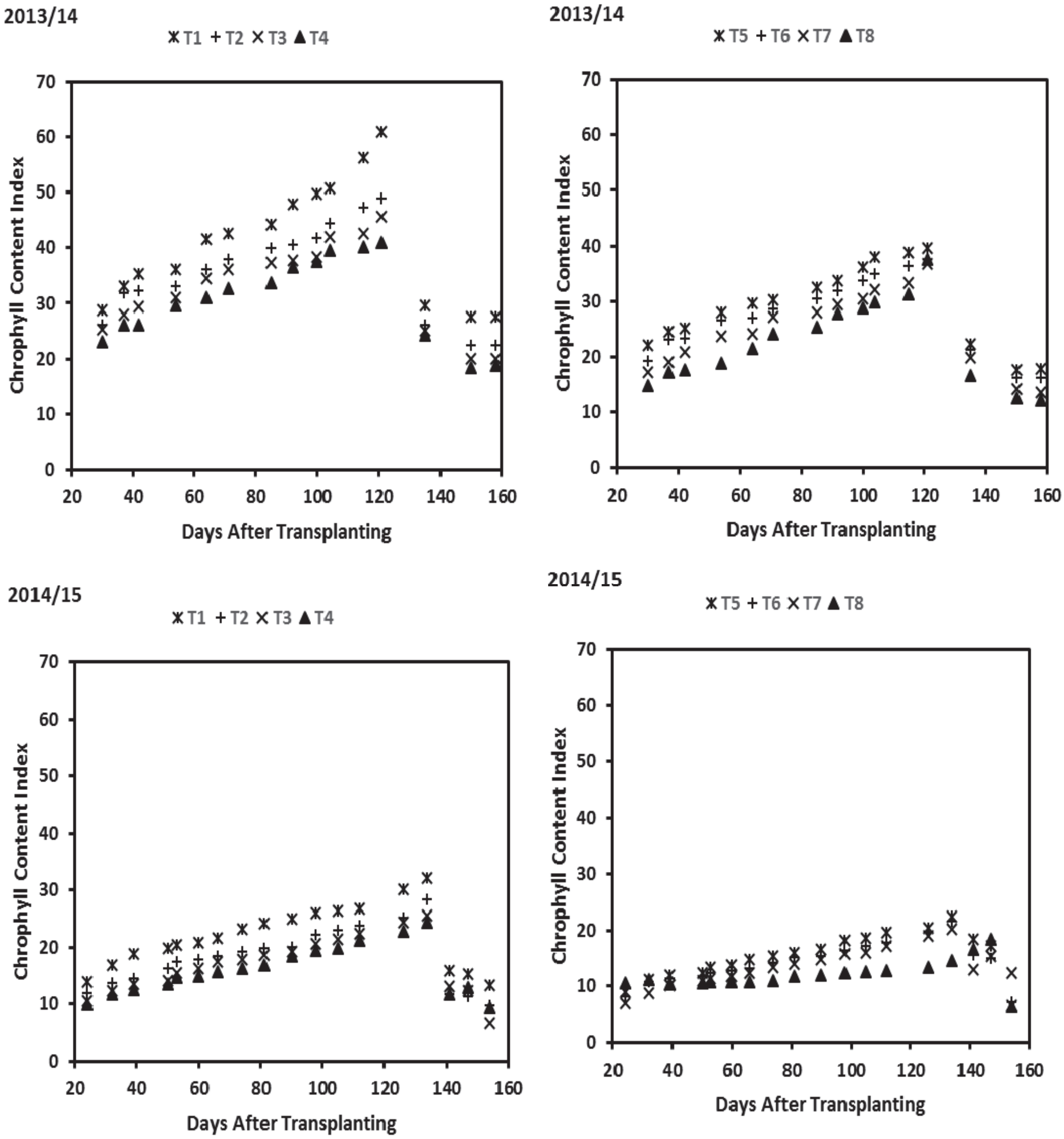

Figure 3.9: Chlorophyll content index for OFSP (S), 2013/14 and 2014/15 season. T1= W1F1H1; T2= W2F1H1; T3= W1F2H1; T4= W2F2H1; T5=W1F1H2; T6=W2F1H1; T7=W1F2H1; T8=W2F2H1 (W1 (full irrigation amount); F1 (full NPK fertiliser application); H1 (no leaf harvesting of OFSP); W2 (Supplemental irrigation); F2 (no NPK fertiliser application); H2 (leaf harvesting of OFSP))

Table 3.9: Leaf area index analysis of variance for OFSP, measured at different periods during the 2013/14 and 2014/15 growing seasons

	Water (W)		**Fertility (F)**		**Harvesting (H)**		**W x F**		**W x H**		**F x H**		**W x F X H**	
DAT[a]	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}
2013/14														
30	206.70	<0.001	69.20	<0.001	16.14	0.00	0.03	0.86	0.22	0.65	1.90	0.19	0.15	0.70
37	233.45	<0.001	93.49	<0.001	26.54	<0.001	2.40	0.14	0.49	0.50	0.63	0.44	5.34	0.04
42	142.03	<0.001	46.13	<0.001	17.33	<0.001	0.20	0.67	0.95	0.35	0.41	0.53	0.33	0.58
81	232.64	<0.001	72.08	<0.001	20.31	<0.001	4.97	0.04	3.86	0.07	6.18	0.03	5.13	0.04
85	154.89	<0.001	74.43	<0.001	16.97	0.00	2.59	0.13	2.47	0.14	6.70	0.02	3.77	0.07
92	307.63	<0.001	108.05	<0.001	34.33	<0.001	1.70	0.21	2.03	0.18	3.80	0.07	1.68	0.22
104	43.72	<0.001	14.80	0.00	6.93	0.02	8.91	0.01	5.02	0.04	2.21	0.16	0.42	0.53
150	148.75	<0.001	67.78	<0.001	20.10	<0.001	3.42	0.09	2.74	0.12	2.03	0.18	2.52	0.14
2014/15														
24	7.72	0.015	1.47	0.245	0	0.999	1.98	0.181	1.53	0.236	1.89	0.19	0.57	0.464
74	258.01	<0.001	92.72	<0.001	39.14	<0.001	3.89	0.069	1.73	0.209	0.62	0.445	6.61	0.022
81	397.15	<0.001	150.9	<0.001	69.3	<0.001	7.79	0.014	7.36	0.017	1.14	0.304	15.17	0.002
90	268.36	<0.001	77.76	<0.001	46.54	<0.001	2.55	0.133	1.4	0.256	2.5	0.136	18.41	<0.001
98	194.51	<0.001	67.17	<0.001	32.69	<0.001	0.86	0.371	0.03	0.87	0.2	0.665	5.54	0.034
126	86.03	<0.001	24.25	<0.001	16.43	0.001	0.04	0.85	0.00	0.989	0.19	0.668	6.52	0.023
154	6.66	0.022	0.49	0.496	5.44	0.035	19.61	<.001	2.71	0.122	0.01	0.929	22.91	<0.001

[a] DAT – Days After Transplanting

Table 3.10: Chlorophyll content index analysis of variance for OFSP, measured at different periods during the 2013/14 and 2014/15 growing seasons

	Water (W)		**Fertility (F)**		**Harvesting (H)**		**W x F**		**W x H**		**F x H**		**W x F X H**	
DAT[a]	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}
2013/14														
20	0	0.79	2.51	0.14	1.09	0.31	0.28	0.6	1.3	0.27	7.62	0.015	0.9	0.36
26	0.01	0.91	3.36	0.088	1.32	0.27	0.01	0.93	0.93	0.35	0.67	0.43	0.78	0.39
33	408	< 0.001	218	< 0.001	35.5	< 0.001	25.2	< 0.001	3.37	0.088	14.08	0.002	8.83	0.01
49	380.21	<0.001	118.66	<0.001	47.04	<0.001	8.65	0.011	0.69	0.42	1.34	0.267	9.41	0.008
62	220.77	<0.001	90.1	<0.001	29.79	<0.001	2.52	0.135	0.71	0.414	0.95	0.346	6.74	0.021
103	692.57	<0.001	242.47	<0.001	66.1	<0.001	3.47	0.083	1.37	0.261	2.16	0.164	6.2	0.026
123	286.19	<0.001	121.62	<0.001	22.44	<0.001	0.04	0.845	0.06	0.804	0.11	0.746	4.62	0.05
130	224.15	<0.001	105	<0.001	25.77	<0.001	1.79	0.203	0.36	0.557	0.19	0.666	8.78	0.01
137	67.16	<0.001	33.61	<0.001	11.04	0.005	0.49	0.496	0.13	0.721	0.00	1	4.24	0.059
2014/15														
13	0.53	0.479	3.63	0.077	0.14	0.718	0.13	0.722	0.11	0.74	0.03	0.865	2.4	0.144
17	0.01	0.922	0.26	0.619	1.68	0.215	1.14	0.304	1.43	0.251	0.02	0.877	4.52	0.052
46	425.44	<0.001	134.26	<0.001	35	<0.001	0.22	0.644	0.02	0.894	2.09	0.17	5.14	0.04
51	385.34	<0.001	135.87	<0.001	28.82	<0.001	1.32	0.27	0.24	0.635	0.94	0.349	4.44	0.054
65	879.8	<0.001	256.65	<0.001	67.1	<0.001	10.56	0.006	3.95	0.067	3.81	0.071	3.25	0.093
86	496.5	<0.001	154.21	<0.001	52.58	<0.001	10.33	0.006	8.47	0.011	4.29	0.057	5.64	0.032
93	429.83	<0.001	127.89	<0.001	47.47	<0.001	10.16	0.007	8.8	0.01	3.83	0.071	6.79	0.021
152	144.52	<0.001	39.47	<0.001	10.75	0.005	2.29	0.153	3.07	0.102	3.38	0.087	4.61	0.05

[a] DAT – Days After Transplanting

- **Biomass and water productivity of OFSP**

Biomass, raw edible biomass, marketable tubers, crop ETa, and WP were measured for the 2013/14 and 2014/15 seasons. For the 2013/14 season, results indicate that water, fertility, and leaf harvesting had a significant difference ($p \leq 0.05$) on the measured plant parameters (Table 3.11). The highest dry marketable storage root yield (6.4 t ha^{-1}) were observed from the combination of no water and fertility stresses and no leaf harvesting (2013/14), whereas, for the 2014/15 season, the highest marketable dry storage yield was obtained from the combination of no water stress, fertility stress, and no leaf harvesting (Table 3.12). Crop ETa remained lower under severe water and fertility stressed treatments and higher under unstressed water and fertility treatments. Another important observation between the two seasons is that crop ETa values were higher in season 2 (2014/15) when compared to season 1 (2013/14). This can be attributed to the difference in growing period: The growing period for the 2013/14 season was shorter compared to the 2014/15 season (Table 3.12). Water productivity ranged from 1.5 to 3.7 kg m^{-3} for the 2013/14 season and from 2.8 to 5 kg m^{-3} for the 2014/15 season. These results suggest that WP for season 2 was higher compared to season 1. The High Level Panel of Experts (HLPE) (2015) reports WP values for other vegetables: potatoes: 3-7; tomatoes: 5-20 and onions: 3-10 kg m^{-3}, respectively.

Table 3.11: Analysis of variance for different plant parameters of OFSP (2013/14 and 2014/15 seasons)

	Water (W)		**Fertility (F)**		**Harvesting (H)**		**W x F**		**W x H**		**F x H**		**W x F X H**	
Parameters	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}
2013/14														
Tuber fresh mass	10.69	0.006	3.35	0.09	7.09	0.019	0.00	0.97	1.9	0.19	16.72	0.001	0.74	0.4
Tuber dry mass	8.36	0.012	2.2	0.16	8.18	0.013	0.15	0.7	2.08	0.17	21.88	< 0.001	0.29	0.6
Biomass fresh mass	0.44	0.52	14.67	0.002	66.67	< 0.001	2.21	0.16	5.38	0.04	4.85	0.05	0.00	0.95
Biomass dry mass	10.48	0.006	26.49	< 0.001	110.06	< 0.001	0.47	0.51	6.21	0.03	8.22	0.01	3.1	0.10
Leaf fresh mass	1.15	0.3	2.87	0.11	52.9	< 0.001	1.78	0.2	5.23	0.04	1.31	0.27	0.2	0.66
Leaf dry mass	0.89	0.36	11.26	0.005	128	< 0.001	0.69	0.42	5.39	0.04	1.76	0.21	0.04	0.85
Evapotranspiration	725	< 0.001	3.79	0.072	2.66	0.13	1.54	0.24	9.9	0.007	2.19	0.16	2.47	0.14
Water productivity	58.72	< 0.001	8.65	0.011	0.00	0.96	0.09	0.07	1.27	0.28	25.01	< 0.001	7.85	0.014
2014/15														
Tuber fresh mass	28.64	< 0.001	8.87	0.01	0.87	0.37	9.44	0.008	1.4	0.26	24.03	< 0.001	4.16	0.061
Tuber dry mass	26.62	< 0.001	5.69	0.03	0.47	0.5	18.22	< 0.001	8.4	0.012	23.41	< 0.001	0.6	0.45
Biomass fresh mass	2.68	0.12	4.09	0.063	7.05	0.019	2.13	0.17	0.1	0.76	0.03	0.86	0.82	0.38
Biomass dry mass	1.58	0.23	3.45	0.08	7.97	0.014	0.81	0.38	0.0	0.96	0.03	0.87	2.65	0.13
Leaf fresh mass	1.09	0.32	1.34	0.27	6.37	0.024	0.89	0.36	0.11	0.75	1.04	0.32	3.22	0.09
Leaf dry mass	0.67	0.43	0.22	0.64	0	0.96	0.04	0.85	0.13	0.73	0.03	0.87	1.63	0.22
Evapotranspiration	277	< 0.001	1.44	0.25	6.61	0.02	1.49	0.24	1.96	0.18	4.9	0.04	29.49	< 0.001
Water productivity	9.63	0.008	0.08	0.78	3.84	0.07	18.25	< 0.001	26.85	< 0.001	12.45	0.003	4.2	0.06

Table 3.12: Tubers, biomass, raw edible biomass (leaves), ETa and WP for OFSP

Treatments	**Tubers marketable**		**Biomass**		**Leaves**		**ETa**	**WP**
Season 1	**FM**	**DM**	**FM**	**DM**	**FM**	**DM**		
	t ha^{-1}	t ha^{-1}	t ha^{-1}	t ha^{-1}	t ha^{-1}	t ha^{-1}	mm	kg m^{-3}
W1 F1 H1	**28^{a}**	**6.4^{a}**	12^{bc}	2.4^{bc}	4.2^{cd}	1.1^{c}	**491^{a}**	2.3^{bc}
W1 F1 H2	13^{bcd}	2.5^{cd}	24^{a}	**4.4^{a}**	8.1^{a}	2^{ab}	427^{b}	1.8^{cd}
W1 F2 H1	**6^{d}**	4^{bc}	12^{bc}	2.4^{bc}	4.9^{bc}	1^{cd}	460^{ab}	**1.5^{d}**
W1 F2 H2	16^{bc}	3.8^{bc}	17^{b}	3^{b}	6.9^{ab}	1.7^{b}	446^{b}	1.7^{d}
W2 F1 H1	20^{ab}	4.8^{ab}	10^{cd}	1.9^{c}	3.2^{cd}	0.9^{cd}	244^{cd}	**3.7^{a}**
W2 F1 H2	7^{cd}	1.7^{d}	**29^{a}**	4.1^{a}	**9.4^{a}**	**2.2^{a}**	257^{c}	2.7^{b}
W2 F2 H1	17^{b}	**1.5^{d}**	**5^{d}**	**1.2^{c}**	**1.8^{d}**	**0.6^{d}**	**219^{d}**	2.1^{bcd}
W2 F2 H2	14^{bcd}	3.3^{bcd}	17^{b}	3^{b}	7.1^{ab}	1.7^{b}	230^{cd}	3.4^{a}
Season 2								
W1 F1 H1	21^{cd}	5.4^{c}	15^{a}	2.8^{abc}	**4.7^{a}**	0.9^{a}	**543^{a}**	**3^{d}**
W1 F1 H2	35^{b}	6.8^{b}	14^{ab}	2.5^{abcd}	4.1^{abc}	0.8^{a}	409^{b}	3.6^{cd}
W1 F2 H1	**58^{a}**	**14.3^{a}**	16^{a}	2.9^{ab}	4.2^{abc}	0.9^{a}	426^{b}	4.5^{ab}
W1 F2 H2	32^{bc}	7.6^{b}	12^{ab}	2.1^{cd}	3.8^{bc}	1^{a}	469^{ab}	2.8^{d}
W2 F1 H1	**17^{d}**	**3.1^{c}**	**16^{a}**	**3.1^{a}**	4^{abc}	0.8^{a}	257^{c}	4^{bc}
W2 F1 H2	26^{bcd}	7.8^{b}	12^{ab}	2.2^{bcd}	4.1^{abc}	0.9^{a}	280^{c}	**5^{a}**
W2 F2 H1	25^{bcd}	4.8^{bc}	12^{ab}	2.2^{bcd}	4.5^{ab}	1^{a}	294^{c}	**3^{d}**
W2 F2 H2	**17^{d}**	3.4^{c}	**9^{b}**	**2^{d}**	**3.5^{c}**	0.8^{a}	**243^{c}**	3.2^{d}

Column values followed by the same symbol are not statistically different at $p \leq 0.05$. The bold and underlined values indicate highest treatment means, whereas, the bold values indicate the lowest treatment means.

3.4.2.2 Amaranth and Spider flower

- **Leaf area index**

Leaf area index was monitored throughout the growing period for Amaranth and Spider flower for both seasons (2013/14 and 2014/15). The results of the study indicate that water and fertility stresses had a significant effect ($p \leq 0.05$) on canopy growth for Amaranth and Spider flower for both seasons (Table 3.13). The observed trend was that LAI remained lower under water and fertility stressed treatments and higher under the unstressed water and fertility treatments (Figure 3.10). However, LAI was higher for the 2014/15 season compared to the 2013/14 season (Figure 3.10).

- **Chlorophyll content index**

Chlorophyll content was measured during different periods for the 2013/14 and 2014/15 growing seasons. Results indicate that water and fertility stresses had a significant effect ($p \leq 0.05$) on

CCI for Amaranth and Spider flower (Table 3.14) during different sampling periods. There was no significant difference (*p*>0.05) between the interaction of water, fertility, and crops. The trend which was observed was that CCI remained lower under water and fertility stresses and higher under no water and fertility stresses (Figure 3.11), while Spider flower indicated higher CCI compared to Amaranth. The CCI for the 2013/14 season was higher compared to the 2014/15 season. This can be attributed to different weather conditions and management practices.

Table 3.13: Leaf area index analysis of variance for Amaranth and Spider flower, measured at different periods during the 2013/14 and 2014/15growing seasons

LAI	**Water (W)**		**Fertility (F)**		**Crop (C)**		**W x F**		**W x C**		**F x C**		**W x F X H**	
DAT[a]	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}
2013/14														
23	22.05	<.001	3.95	0.067	2.57	0.132	1.14	0.304	7.96	0.014	1.21	0.291	1.63	0.223
30	5.59	0.033	3.41	0.086	24.83	<0.001	0.46	0.509	1.86	0.195	1.22	0.288	0.73	0.407
35	46.38	<0.001	19.4	<0.001	12.48	0.003	0.14	0.717	15.99	0.001	7.18	0.018	1.26	0.281
47	46.36	<0.001	14.36	0.002	7.94	0.014	5.58	0.033	13.03	0.003	3.85	0.07	2.17	0.163
67	17.3	<0.001	8.53	0.011	13.43	0.003	0.12	0.731	4.16	0.061	2.00	0.179	1.13	0.305
74	27.13	<0.001	5.68	0.032	10.83	0.005	0.05	0.827	5.73	0.031	0.51	0.487	0.46	0.511
78	32.43	<0.001	12.92	0.003	15.93	0.001	0	0.989	7.85	0.014	1.75	0.207	0.15	0.701
85	22.14	<0.001	11.52	0.004	0.14	0.717	0	0.977	0.64	0.437	1.35	0.265	1.15	0.301
2014/15														
22	39.79	<0.001	14.03	0.002	6.65	0.022	0.06	0.805	8.33	0.012	3.87	0.069	2.31	0.151
31	31.4	<0.001	13.49	0.003	13.55	0.002	1.86	0.194	18.12	<0.001	6.97	0.019	2.58	0.13
61	8.25	0.012	3.39	0.087	22.58	<0.001	0.88	0.364	3.22	0.094	1.47	0.245	0.95	0.347
68	21.33	<0.001	2.65	0.126	27.06	<0.001	0.03	0.873	10.33	0.006	0.76	0.399	0.03	0.865
73	8.79	0.01	4.27	0.058	0.00	0.975	0.25	0.623	0.81	0.383	0.45	0.513	0.13	0.724
81	31.44	<0.001	14.15	0.002	0.91	0.357	3.15	0.097	0.12	0.738	0.02	0.885	0.41	0.53
88	30.89	<0.001	13.47	0.003	26.75	<0.001	3.67	0.076	7.93	0.014	0.35	0.562	2.72	0.121
97	15.88	0.001	3.36	0.088	0.75	0.40	0.80	0.386	0.01	0.912	0.42	0.529	1.24	0.285
102	53.08	<0.001	8.63	0.011	38.33	<0.001	2.12	0.167	2.54	0.133	0.97	0.342	0.18	0.674
109	16.35	0.001	9.09	0.009	0.79	0.39	0.04	0.835	2.76	0.119	2.32	0.15	1.03	0.328
116	56.03	<0.001	19.14	<0.001	9.69	0.008	4.97	0.043	8.3	0.012	4.31	0.057	1.6	0.226

[a] DAT – Days After Transplanting

Table 3.14: Chlorophyll content index analysis of variance for Amaranth and Spider flower, measured at different periods during the 2013/14 and 2014/15 growing seasons

CCI	**Water (W)**		**Fertility (F)**		**Crop (C)**		**W x F**		**W x C**		**F x C**		**W x F X C**	
DAT[a]	**F_{value}**	**P_{value}**	**F_{value}**	**P_{value}**	**F_{value}**	**P_{value}**	**F_{value}**	**P_{value}**	**F_{value}**	**P_{value}**	**F_{value}**	**P_{value}**	**F_{value}**	**P_{value}**
2013/14														
30	6.58	0.022	4.23	0.059	0.18	0.68	5.82	0.03	6.36	0.024	1.76	0.206	2.44	0.14
38	45.7	< 0.001	8.35	0.012	1.19	0.29	0.84	0.38	0.99	0.34	0.04	0.85	0.06	0.81
46	58.31	< 0.001	8.17	0.013	3.49	0.09	0.09	0.77	1.33	0.27	0.28	0.61	0.47	0.5
62	30.6	< 0.001	5.56	0.03	0.32	0.58	0.09	0.77	0.17	0.69	0.03	0.87	0.08	0.79
85	102	< 0.001	25.89	< 0.001	74.61	< 0.001	0.23	0.63	6.66	0.022	3.01	0.11	0.66	0.43
97	54.98	< 0.001	4.53	0.05	0	0.97	3.72	0.07	0	0.95	0.59	0.46	0.34	0.57
2014/15														
24	8.79	0.01	0.09	0.77	3.93	0.067	0.1	0.75	2.28	0.15	0.08	0.78	1.36	0.26
31	28.61	< 0.001	3.76	0.07	0.02	0.9	0.03	0.88	0.11	0.75	0.07	0.8	0.03	0.87
36	23.43	< 0.001	2.38	0.15	0.99	0.34	3.03	0.1	2.28	0.15	0.8	0.39	1.77	0.2
44	14.05	0.002	1.61	0.23	0.01	0.91	0.35	0.57	1.64	0.22	0.07	0.8	0.001	0.91
49	12.77	0.003	5.43	0.04	8.83	0.01	3.1	0.1	2.17	0.16	0	0.96	0.66	0.43
59	15.26	0.002	3.37	0.09	0.57	0.46	0.19	0.67	6.63	0.022	1.23	0.29	2.75	0.12
63	11.74	0.004	0.91	0.36	0.69	0.42	0	0.96	3.08	0.1	0.42	0.52	1.17	0.29
70	25.49	< 0.001	0.67	0.43	12.92	0.003	0.66	0.43	12.12	0.004	0	0.95	0.08	0.79
76	10.2	0.006	2.98	0.106	6	0.028	0.48	0.5	0.72	0.41	1.05	0.32	1.07	0.32
84	7.28	0.017	0.54	0.47	5.88	0.029	0.23	0.64	1.16	0.22	3.76	0.07	1.33	0.27
91	79.08	< 0.001	31.59	< 0.001	6.39	0.02	9.94	0.007	0.36	0.56	5.78	0.031	8.79	0.01

[a] DAT – Days After Transplanting

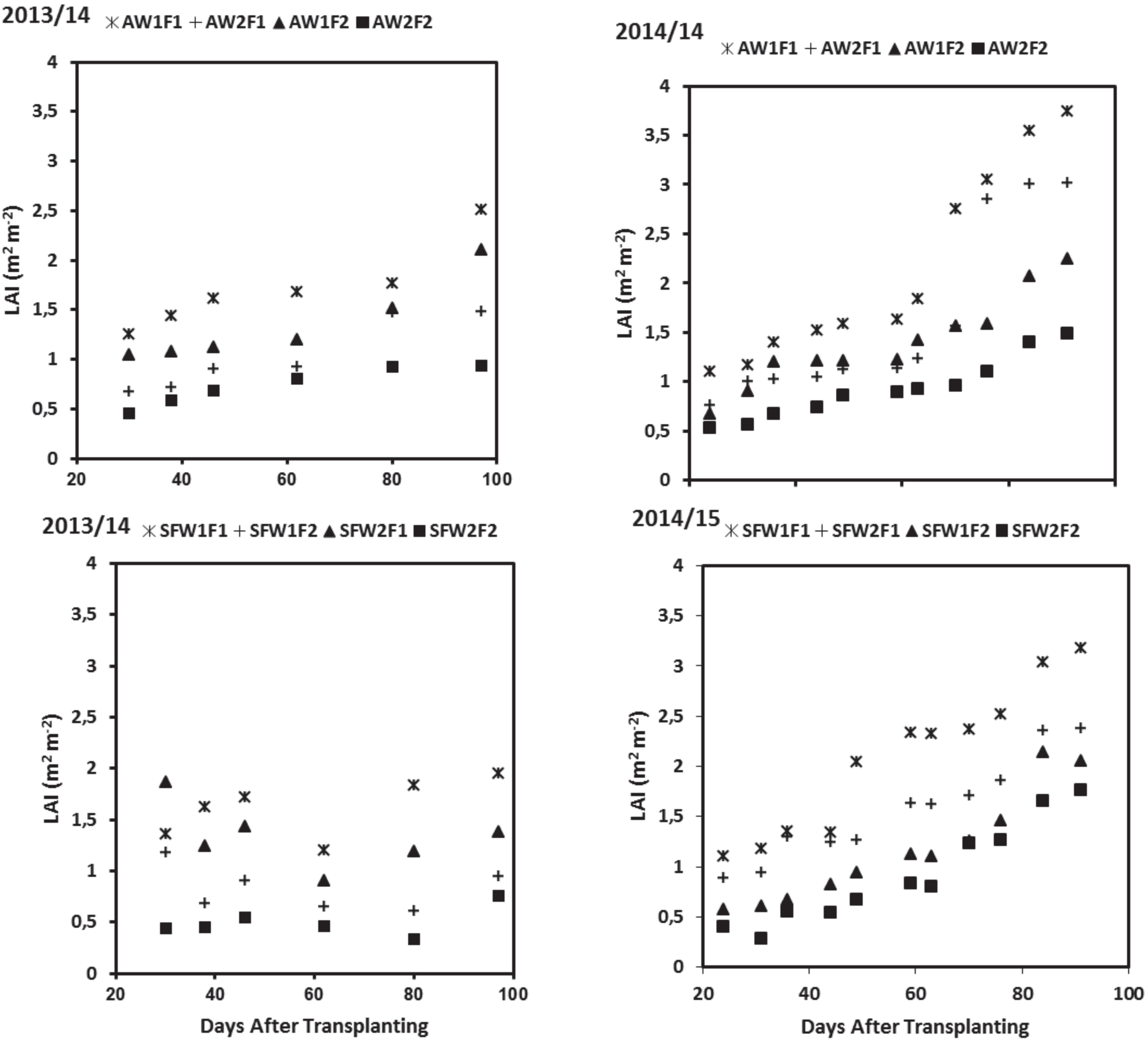

Figure 3.10: Leaf area index for Amaranth (A) and Spider flower (SF), 2013/14 and 2014/15 season. W1-irrigation to field capacity, W2- rainfed, F1- full NPK fertilizer application, F2- no fertilizer application

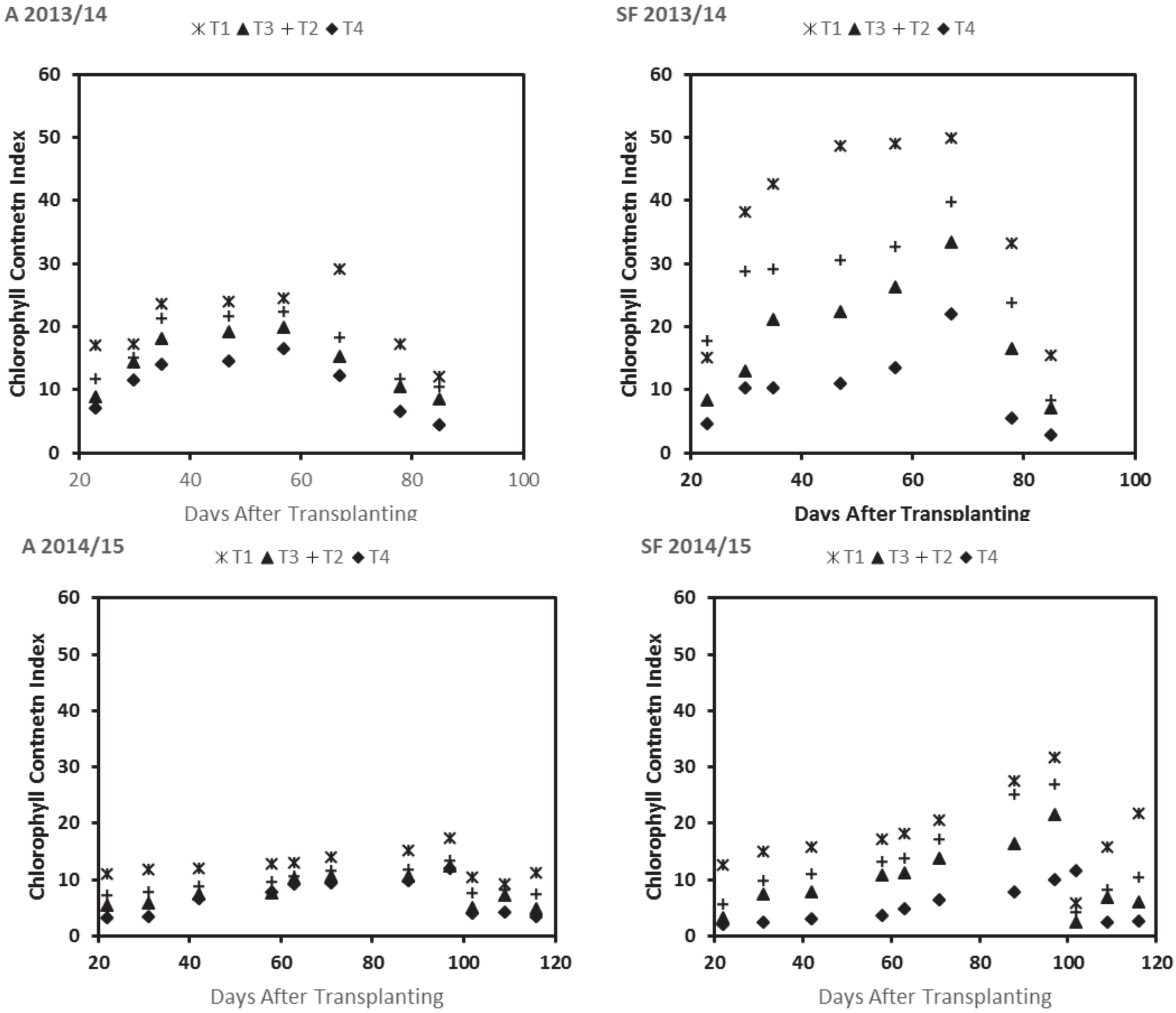

Figure 3.11: Chlorophyll content index for Amaranth (A) and Spider flower (SF), 2013/14 and 2014/15 season. T1= W1F1; T2= W1F2; T3= W2F1; T4= W2F2

- **Biomass and water productivity of Amaranth and Spider flower**

Biomass, raw edible biomass, crop ETa and WP were measured for the 2013/14 and 2014/15 seasons. For the 2013/14 season, results indicate that water and fertility stresses had a significant effect ($p<0.001$) on biomass (fresh and dry) and raw edible biomass (fresh and dry). There was no significant effect ($p>0.05$) on crop ETa and WP (Table 3.15). For the 2014/15 season, water and fertility treatments had a significant effect ($p \leq 0.05$) on biomass (fresh and dry), raw edible biomass (fresh and dry), ETa, and WP (Table 3.15). For the 2013/14 season, the highest dry mass of edible leaves was obtained for Amaranth (0.99 t ha^{-1}) under no water and fertility stresses, and the lowest for Spider flower (0.14 t ha^{-1}) under severe water and fertility stresses. For the 2014/15 season, the highest dry mass of edible leaves was obtained for Amaranth (1.9 t ha^{-1}) under no water and fertility stresses, and the lowest from Spider flower (0.19 t ha^{-1}) under severe water and fertility stresses (Table 3.16). These results suggest that dry raw edible biomass was reduced because of decreasing SWC.

Crop ETa remained lower under the severe water and fertility stressed treatments and higher under no water stress and full fertility treatments for Amaranth and Spider flower. Another important observation between the two seasons is that crop ETa values were higher in season 2 when compared to season 1. This can be attributed to the difference in growing period. The growing period for season 1 was shorter when compared to season 2. The results indicate that different plant species utilize different amounts of water: Amaranth utilized more water compared to Spider flower (Table 3.16). Water productivity ranged from 0.04 to 1.24 kg m^{-3} for the 2013/14 season and from 0.19 to 1.71 kg m^{-3} for the 2014/15 season. For both seasons, the highest WP was observed for Amaranth under no water and fertility stresses, whereas, the lowest WP for the 2013/14 season was obtained for Spider flower under water and fertility stresses. For 2014/15 the lowest WP was observed for Spider flower under no water stress and full fertility (Table 3.16).

Table 3.15: Analysis of variance for different plant parameters of Amaranth and Spider flower, 2013/14 and 2014/15 growing seasons

	Water (W)		**Fertility (F)**		**Crop (C)**		**W x F**		**W x C**		**F x C**		**W x F X C**	
Parameters	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}
2013/14														
Biomass fresh mass	20.8	<0.001	0.2	0.655	123.2	<0.001	0.02	0.904	8.66	0.011	10.6	0.006	5.28	0.04
Biomass dry mass	18.24	<0.001	0	0.935	55.1	<0.001	0.38	0.546	3.26	0.092	0.01	0.924	0.53	0.48
Leaves fresh mass	21.13	<0.001	0.3	0.57	90.8	<0.001	1.29	0.275	10.33	0.006	3.8	0.072	3.43	0.09
Leaves dry mass	21.71	<0.001	0.4	0.52	59.5	<0.001	0.07	0.796	12.05	0.004	0.59	0.456	3.7	0.08
Evapotranspiration	0.05	0.83	3.4	0.089	2.1	0.172	2.38	0.145	0.75	0.401	0.95	0.347	0.04	0.85
Water productivity	3.59	0.08	52.45	<.001	11.59	0.004	0.069	3.89	0.251	1.43	0.005	11.27	0.026	6.22
2014/15														
Biomass fresh mass	16.07	0.001	214	< 0.001	11.85	0.003	9.94	0.006	0.19	0.67	0.24	0.63	0.01	0.93
Biomass dry mass	7.97	0.014	267	< 0.001	64.21	< 0.001	6.94	0.02	0.15	0.7	0.81	0.38	0.13	0.72
Leaves fresh mass	7.58	0.016	245	< 0.001	20.53	< 0.001	8.01	0.013	0.06	0.81	0.01	0.91	0.03	0.87
Leaves dry mass	3.39	0.09	134	< 0.001	24.73	< 0.001	0.43	0.52	4.54	0.05	0.45	0.51	0.39	0.54
Evapotranspiration	283	< 0.001	62.07	< 0.001	15.33	0.002	0.06	0.81	3.25	0.09	1.11	0.31	3.74	0.07
Water productivity	45.22	< 0.001	193	< 0.001	46.75	< 0.001	19.93	< 0.001	1.19	0.29	2.24	0.16	0.02	0.89

Table 3.16: Biomass, raw edible biomass (leaves), evapotranspiration (ETa) and WP for TVCs

Treatments	**Biomass**		**Leaves**		**ETa**	**WP**
2013/14	**FM**	**DM**	**FM**	**DM**		
	t ha^{-1}	t ha^{-1}	t ha^{-1}	t ha^{-1}	mm	kg m^{-3}
Amaranth W1 F1	24.75^{b}	2.45^{ab}	4.11^{ab}	0.84^{ab}	223^{a}	0.88^{ab}
Amaranth W1 F2	11.14d^{e}	0.77^{c}	1.13^{c}	0.30^{c}	**251^{a}**	**1.24^{a}**
Amaranth W2 F1	**34.18^{a}**	**2.75^{a}**	**5.96^{a}**	**0.99^{a}**	144de	0.23^{cd}
Amaranth W2 F2	2.78^{f}	0.75^{c}	0.43^{c}	0.11^{c}	154^{cd}	0.091^{cd}
Spider flower W1 F1	16.21^{cd}	1.50^{abc}	2.5^{bc}	0.46^{bc}	191^{b}	0.53^{bc}
Spider flower W1 F2	4.67^{ef}	**0.26^{c}**	0.43^{c}	**0.12^{c}**	182^{bc}	0.49^{bcd}
Spider flower W2 F1	18.67^{bc}	1.27^{bc}	2.35^{bc}	0.33^{c}	130de	0.071^{cd}
Spider flower W2 F2	**4.06^{f}**	0.27^{c}	**0.21^{c}**	0.14^{c}	**121^{e}**	**0.04^{d}**
2014/15						
Amaranth W1 F1	16.5^{a}	3.2^{b}	7.3^{b}	1.7^{a}	**326^{a}**	0.99^{bc}
Amaranth W1 F2	4.6^{b}	1.5^{c}	2.5^{c}	0.9^{cd}	282^{b}	0.54^{d}
Amaranth W2 F1	**24.5^{a}**	**4.1^{a}**	**9.5^{a}**	**1.9^{a}**	240^{c}	**1.71^{a}**
Amaranth W2 F2	6.1^{b}	1.5^{c}	2.3^{cd}	0.8^{d}	214^{d}	0.73^{cd}
Spider flower W1 F1	13.7^{a}	2.4^{c}	5.6^{b}	1.6^{ab}	311^{a}	0.76^{cd}
Spider flower W1 F2	**0.96^{e}**	**0.3^{d}**	0.6^{e}	0.5^{de}	276^{b}	0.11^{e}
Spider flower W2 F1	21^{a}	3^{b}	7.8^{b}	1.3^{bc}	226^{cd}	1.24^{b}
Spider flower W2 F2	1.3^{e}	0.3^{d}	**0.7^{de}**	**0.19^{e}**	**193^{d}**	0.19^{e}

Column values followed by the same symbol are not statistically different at $p \leq 0.05$. The bold and underlined values indicate highest treatment means, whereas, the bold values indicate the lowest treatment means.

3.5 Summary and conclusions

The objective of the present study was to assess WP of TVCs from two experimental sites, namely the rain-shelter and Rooiland open field experiment. Key findings from the rain-shelter experiment are that the TVCs utilized in this study were more productive in terms of biomass production compared to Swiss chard, and that under limited soil water availability, TVCs were able to reduce their stomatal conductance and canopy size, compared to Swiss chard which is a commercial crop in South Africa. However, future research should focus on increasing the edible above-ground edible biomass of TVCs. Other key findings were that WP of TVCs was comparable to the WP of Swiss chard, and that water stress had an effect on biomass accumulation as well-watered plants obtained higher biomass than highly water-stressed plants, which was on par with LAI, stomatal conductance and chlorophyll content data. From the results of the open field Rooiland experiment, it can be concluded that OFSP can be utilized as a dual crop, *i.e*. leafy vegetable crop and also as a storage root crop. Although storage root yield would decline, more food will be available to be consumed during the dry season. Furthermore, water and fertility stresses had an effect on dry raw edible biomass accumulation of TVCs, *i.e.* dry raw edible biomass declined under low input agricultural practices (no fertilizer and irrigation). By applying fertilizer and scheduling irrigation based on climatic conditions, yield of TVCs could improve significantly. For RPHs to improve food insecurity, they are encouraged to practice low input agriculture. However, in doing so, they will obtain lower yields. The perception that TVCs require no fertilizer and water is dismissed by findings of this study.

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4 NUTRITIONAL WATER PRODUCTIVITY OF TRADITIONAL VEGETABLE CROPS

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4.1 Introduction

Food and nutrition security (FNS) is a persistent problem in sub-Saharan Africa (sSA) and it is expected to escalate in the next 20 years because of predicted population growth, climate change (drought and extreme weather events), and limited resources for crop production (Van Wijk, 2002; Bodner et al., 2015). The most deficient micronutrients in SSA concern Fe, Zn, and Vitamin A. Consensus had been reached that food production had to increase in the coming decades in order to cope with the severity of micronutrient deficiency in SSA (Rockstrom and Barron, 2007; Bodner et al., 2015; Chivenge et al., 2015; Jacobsen et al., 2015). The proposed increase in food production is focused on major starchy crops such as rice, maize, millet, wheat, and sorghum, which had been promoted by the green revolution with known effect of high external input requirements including water, fertilizer, agro-chemicals, and high yielding varieties (Welch and Graham, 2004). There are abundant species in the world which had been underutilized, despite unique advantages for FNS in SSA. Chivenge et al. (2015) indicated that there are approximately 30 000 underutilized edible plants in SSA. To solve the challenge of FNS, agriculture needs to re-think agro-biodiversity solutions by considering the use of TVCs. Chapter 3 had explained in detail the advantages and weaknesses of TVCs.

The objective of this study was to assess nutritional content (NC), nutritional yield (NY), and nutritional water productivity (NWP) of *Amaranthus cruentus* (Amaranth), *Cleome gynandra* (Spider flower), as well as leaves and storage roots of *Ipomoea batatas* var*. Bophelo* (orange fleshed sweet potato, OFSP, using *Beta vulgaris* subsp. *vulgaris* (Swiss chard) as a reference crop. Although it was part of the present study, cognizance is taken of the fact that, in addition to considering the nutrient content of food, nutrient bioavailability (amount of a nutrient absorbed and available for normal physiological functions) should also be taken into consideration. Different nutrients react differently once ingested into the human gastro-intestinal tract, and can be influenced by various factors including the quality of the food source and the matrix in which it is consumed, the composition of the whole meal, inhibitors, enhancers and the status of the host. Bioavailability cannot attain a constant calculated value, and needs to be considered with caution as multiple factors, both intrinsic and extrinsic, can notably affect the bioavailability of nutrients present in food and non-food sources of nutrients (Schönfeldt et al., 2016).

4.2 Nutritional yield and nutritional water productivity

Nutritional yield (NY= NC x raw edible yield) is an emerging concept that relates to the amount of nutrients which can be harvested per unit area of land; its units are g m^{-2} or g ha^{-1}

(Bumgarner et al., 2012). The potential of crops to meet human nutrition has been assessed based on nutrient composition of edible plant parts. However, NC and raw edible yield are intertwined, thus they need to be assessed simultaneously. Evaluating NY of crops provides an opportunity to commercialize these vegetables and be marketed as high quality crops. Water is an important resource in agricultural production. Major focus has been on increasing dry matter production of crops (Mabhaudhi et al., 2016). Progress had been made since the early 1950s (Nin-Pratt et al., 1984) when irrigation efficiency, which emanated from the engineering background, was considered to be a solution of saving water in agricultural production. Irrigation efficiency is measured as water diverted from the source (dams, lake, river or ground water) to the water delivered at the farm level. However, at catchment level, higher irrigation efficiencies do not necessarily relate to real water savings because irrigation efficiency on one farm can be lower, thus water lost from this farm is being utilized by an adjacent farm. Therefore, organizations like the International Water Management Institute (IWMI), as well as the Food and Agricultural Organization (FAO) came with the slogan of "more crop per drop", meaning increasing water productivity (WP) of crops (Renault and Wallender, 2000; Ali and Talkder, 2008; Vincent and van Halsema, 2012; Mabhaudhi et al., 2016). Details on how to calculate WP had been explained in chapter 3 of this report. Recently, the HLPE (2015) report on Food and Nutrition realized the need of linking agronomy, food, and nutrition. However, they argued that WP is a concept which is can be expressed in many ways depending on the field of expertise, *i.e.* yield per unit of water used (kg m^{-3}), monetary value (USD m^{-3}) and nutritional value (mg m^{-3}). In the present study, the concept of the High Level Panel of Experts (HLPE) (2015) approach to WP, which links WP and nutrition, has been followed. Nutritional water productivity (NWP) is a novel concept which relates water use and nutrient content of crops. Nutritional water productivity is explained in detail by Renault and Wallender (2000) and calculated as water productivity multiplied by the nutrient content of crops (NWP = WP x nutrient content of crops) – its units are nutritional unit per volume of water used (mg m^{-3}). Traditional vegetable crops present an opportunity of being introduced as new commercial crops which can alleviate nutritional food insecurity of resource poor households (RPHs) in sSA, because they are highly nutritious in micronutrients (Fe and Zn) and β-carotene. Moreover, they are more productive because they can grow in marginal environments – some are C4 crops which are well-known for their higher water use efficiency compared to C3 crops (Bodner et al., 2015; Chivenge et al., 2015; Vincent and van Halsema, 2012; Renault and Wallender, 2000). No previous study has assessed NWP of TVCs using soil, water, and meteorological data sets from the same location. The present study is the first attempt to benchmark NWP of Amaranth, Spider flower, and OFSP at the ARC-VOP.

4.3 Materials and methods

4.3.1 Plant material

During the 2013/14 and 2014/15 seasons, three experiments were conducted at ARC-VOP, Roodeplaat, Pretoria. For the rain-shelter study, a randomized complete block design was used as an experimental design. The treatment design was a 4 x 3 factorial with two factors/treatments, namely crops and water levels, replicated three times. Four crops (*Amaranthus cruentus* (Amaranth), *Cleome gynandra* (Spider flower), *Ipomoea batatas* var. *Bophelo* (orange fleshed sweet potato, OFSP) and *Beta vulgaris* subsp. *vulgaris* (Swiss chard)) and three water levels (Irrigation (I_1) that refilled the water extraction depth (WED) of 60 cm to FC when 30% of plant available water (PAW) was depleted; Irrigation (I_2) that refilled the WED to FC when 50% of PAW was depleted; and Irrigation (I_3) that refilled the WED to FC when 80% of PAW was depleted).

A 35 m x 40 m field was laid out the open field trial at a site called Rooiland to accommodate 48 plots of 3 m x 3 m. The experimental design for the OFSP was a randomized complete block design. The treatment design was a 2 x 2 x 2 factorial design with 3 replicates: 2 water levels (Full (W1) and supplemental irrigation (W2)), 2 fertility levels (Full: F1 and no fertilizer: F2), and 2 harvesting methods (Harvesting of OFSP leaves every 4 weeks (H1) and no harvesting (H2)) = 24 plots. The experimental design used for Amaranth and Spider flower was the same as for OFSP, but the treatment design was a 2 x 2 x 2 factorial design with 3 replicates: 2 water levels x 2 fertility levels x 2 crops = 24 plots. Details of the rain-shelter and Rooiland experiments are explained in the materials and methods section of Chapter 3. Leaves of Amaranth, Spider flower, OFSP and medium marketable OFSP storage roots were collected.

4.3.2 Analytical procedure

The collected samples were washed with distilled water to remove debris. The stalks were removed from Amaranth and Spider flower leaves. Thereafter, they were enclosed in transparent plastic polythene bags and sent immediately to NviroTek Labs to be analyzed for Fe and Zn content. Duplicate samples were sent to the ARC-VOP Biotechnology Laboratory to be analyzed for β-carotene content. Following the recording of the sample fresh weights, Amaranth, Spider flower and OFSP leaves and sliced peeled storage roots were frozen at -80°C before freeze-drying. Extraction of β-carotene was done using tetrahydrofuran: methanol (1:1, vol/vol) according to the method explained by Biehler et al. (2010). Extracts were analyzed using an HPLC-DAD (Shimadzu) at 450 nm wavelength. A 5-point standard curve that bracketed the concentration of the samples was constructed for quantitative analysis of β-carotene. At NviroTek Labs, Fe and Zn content was determined by following a method suggested by the Association of Official Analytical Chemists (AOAC) (1990) whereby leaf samples were oven-dried for 24 hours at 80°C, water contents calculated, ground in a Wiley mill with No. 20 stainless steel sieve, and stored in air tight containers. Details of the reagents and extraction method used for determining Fe and Zn content are explained in AOAC (1990). The latter elements were determined with an inductively coupled plasma atomic emission spectrometer, and the results converted to fresh mass basis using the pre-determined water content values.

4.3.3 Statistical analysis

Statistical analysis was conducted for the: (i) rain-shelter experiment, (ii) Amaranth and Spider flower experiment (Rooiland), and (iii) OFSP experiment (Rooiland). For the rain-shelter experiment, data from the 4 x 3 factorial design were analyzed using a two-way analysis of variance (ANOVA) which was meant to evaluate the interaction effect of crops and water on moisture (plant water content), NC and NWP of TVCs. For the Spider flower and Amaranth experiments at Rooiland, data were analyzed using a 2 x 2 x 2 factorial design to evaluate the interaction effect of water, fertility and crops, whereas for the OFSP experiment at Rooiland, data were analyzed utilizing a 2 x 2 x 2 factorial design to evaluate the interaction of water, fertility, and leaf harvesting. GenStat version 14, VSN, UK was used to calculate the Least Significant Difference (LSD) at 5% confidence interval. *Post hoc* analysis was conducted using the Tukey HSD test (VSN International, 2012).

4.4 Results and discussion

4.4.1 Rain-shelter experiments

4.4.1.1 Nutritional content

Moisture (plant water) content, Fe, Zn, and β-carotene content (fresh and dry mass) for three TVCs (Amaranth, Spider flower, and OFSP leaves) and Swiss chard (reference crop) were measured. The 2013/14 season results indicated that there was a statistically significant ($p \leq 0.05$) interaction effect between crops and water for Fe (fresh and dry mass), β-carotene (fresh and dry mass), Zn (fresh mass), except for Zn (dry mass and moisture content. For the 2014/15 season, results of the study indicated that there was a statistically significant ($p \leq 0.05$) interaction effect between water and crops for moisture content, Fe, Zn, and β-carotene on fresh and dry mass basis (Table 4.1). Moreover, there were statistically significant differences in the NC treatment means in terms of Fe, Zn, and β-carotene, whether expressed per crop or per water level (Table 4.2). For example, for Amaranth: (i) Zn NC decreased significantly from 1.41 to 1.00 mg 100g^{-1} during 2014/15, while (ii) β-carotene NC decreased significantly from 29.10 to 12.03 mg 100g^{-1} during 2014/15, with increased water stress. For Spider flower: (i) Fe NC increased significantly during both seasons, while (ii) β-carotene NC decreased significantly during both seasons with increased water stress. For sweet potato (OFSP) leaves: (i) Fe NC decreased significantly from 17.39 to 8.86 mg 100g^{-1} during 2013/14, while (ii) β-carotene NC decreased significantly from 22.72 to 9.91 mg 100g^{-1} during 2014/15, with increased water stress. During the 2013/14 and 2014/15 seasons, NC for Fe, Zn, and β-carotene ranged as follows; 3.08 to 20.24 mg 100g^{-1}, 0.47 to 2.21 mg 100 g^{-1}, and 1.83 to 33.61 mg 100 g^{-1}, respectively. The highest NC for Fe and Zn were obtained for Spider flower with the severe stressed water treatment (80%), whereas, for β-carotene the highest NC was obtained for Spider flower in combination with the optimum water treatment (30%) (Table 4.2). The observed trend was that Swiss chard indicated lower NC values for Fe, Zn, and β-carotene compared to TVCs, which suggest that TVCs are higher in NC when equated to Swiss chard. However, a major issue which needs to be addressed is the determination of the total amount of micronutrients which can be harvested during the entire season. This can be assessed by determining nutritional yield (NY = raw edible biomass x nutrient content) of these crops which is explained in detail in Section 4.3. Nutritional content values on fresh mass basis are comparable with those reported by Wenhold et al. (2012) and the United States Department of Agriculture (USDA) (2014) (Table 4.4).

Water plays a major role in the process of photosynthesis. If plants are water stressed, they tend to reduce the size of their stomata in trying to minimize water loss through the process of transpiration, which would result in a reduction of biomass production. The severity to withstand water stress depends on the crop type (C3 and C4). C4 plants (tropical grasses) have lower intercellular CO_2 concentration (C_{ci}) compared to C3 plants, thus they produce more dry matter per unit of water than C3 plants. Amaranth and Spider flower are C4 plants, and under water limiting conditions; they close their stomata to reduce water loss and in turn produce more dry matter compared to Swiss chard, and OFSP which are C3 plants (Vincent and van Halsema, 2012). Statistically significant differences in NC expressed on a dry mass basis could be observed for the treatment means in terms of Fe, Zn, and β carotene, whether expressed per crop or per water level (Table 4.3). For example, for Amaranth: (i) Zn NC decreased significantly from 6.85 to 4.64 mg $100g^{-1}$ during 2014/15 with increased water stress, while (ii) β-carotene NC decreased significantly from 141.2 to 55.3 mg $100g^{-1}$ during 2014/15 with increased water stress. For Spider flower, Fe NC increased significantly from 51.11 to 77.92 mg $100g^{-1}$ during 2014/15 with increased water stress. For sweet potato leaves: (i) Fe NC decreased significantly from 104.30 to 60.67 mg $100g^{-1}$ during 2013/14 with increased water stress, while β-carotene NC decreased significantly from 90.7 to 51.8 mg $100g^{-1}$ during 2014/15 with increased water stress.

Table 4.1: Analysis of variance to evaluate treatment effects on various parameters of TVCs

Parameters	**Water (W)**		**Crops (C)**		**C x W**	
2013/14	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}
Moisture	0.05	0.956	24.86	<0.001	1.81	0.144
Fe (dry mass)	41.74	<0.001	3.19	0.061	3.67	0.011
Zn (dry mass)	8.21	<0.001	0.12	0.886	0.93	0.492
β-carotene (dry mass)	182.96	<0.001	1.88	0.177	4.72	0.003
Fe (fresh mass)	2.21	0.133	26.89	<0.001	5.03	0.002
Zn (fresh mass)	0.34	0.715	91.33	<0.001	4.23	0.006
β-carotene (fresh mass)	3.58	0.045	80.06	<0.001	3.1	0.023
Fe nutritional yield (fresh mass)	36.48	<0.001	18.7	<0.001	9.42	<0.001
Zn nutritional yield (fresh mass)	10.01	<0.001	10.71	<0.001	1.14	0.375
β-carotene nutritional yield (fresh mass)	19.19	<0.001	37.12	<0.001	5.6	0.001
Fe NWP	0.91	0.418	27.91	<0.001	2.7	0.04
Zn NWP	2.89	0.077	50.11	<0.001	1.35	0.277
β-carotene NWP	4.22	0.028	102.62	<0.001	7.11	<0.001
2014/15						
Moisture	1.9	0.174	89.9	<0.001	3.11	0.023
Fe (dry mass)	4.23	0.028	32.62	<0.001	3.75	0.01
Zn (dry mass)	1.88	0.177	53.48	<0.001	5.02	0.002
β-carotene (dry mass)	33.44	<0.001	149.16	<0.001	16.35	<0.001
Fe (fresh mass)	1.29	0.295	60.99	<0.001	3.39	0.016
Zn (fresh mass)	3.15	0.063	153.09	<0.001	4.45	0.004
β-carotene (fresh mass)	18.34	<0.001	86.77	<0.001	8.12	<0.001
Fe nutritional yield (fresh mass)	8.12	0.002	31.59	<0.001	1.93	0.121
Zn nutritional yield (fresh mass)	25.78	<0.001	130.65	<0.001	3.51	0.014
β-carotene nutritional yield (fresh mass)	29.3	<0.001	38.22	<0.001	6.44	<0.001
Fe NWP	4.42	0.024	32.41	<0.001	2.1	0.094
Zn NWP	4.25	0.028	63.95	<0.001	2.38	0.063
β-carotene NWP	4.52	0.023	66.02	<0.001	3.44	0.015

Table 4.2: Nutritional content of TVCs expressed on fresh mass basis (mg 100 g^{-1})

Treatments		2013/14			2014/15		
		Fe	**Zn**	**β-carotene**	**Fe**	**Zn**	**β-carotene**
Amaranth	30	8.27^{cde}	1.08^{de}	26.95^{ab}	6.27^{cd}	1.41^{b}	29.1^{abc}
Amaranth	50	9.84^{c}	1.23^{cd}	**28.56^{a}**	8.27^{c}	1.13^{c}	33.08^{ab}
Amaranth	80	7.01^{cde}	0.97^{de}	23.14^{b}	5.2^{cd}	1^{c}	12.03^{f}
Spider flower	30	10.3^{bc}	1.53^{bc}	10.2^{de}	14.58^{b}	1.57^{b}	**33.61^{a}**
Spider flower	50	14.14^{ab}	1.84^{b}	17.71^{c}	14.47^{b}	1.47^{b}	23.18^{cde}
Spider flower	80	14.63^{a}	**2.21^{a}**	6.8^{efg}	**20.24^{a}**	**1.78^{a}**	27.16^{bcd}
Sweet potato leaves	30	**17.39^{a}**	0.85^{ef}	14.7^{cd}	15.01^{b}	0.69^{d}	22.72^{de}
Sweet potato leaves	50	10.05^{c}	0.55^{fg}	8.69^{ef}	12^{b}	0.60^{d}	18.97^{e}
Sweet potato leaves	80	8.86^{cd}	0.60^{fg}	10.51^{de}	13.05^{b}	0.57^{d}	9.91^{f}
Swiss chard	30	5.32^{def}	0.53^{fg}	3.52^{fg}	5.3^{cd}	0.54^{d}	**1.83^{g}**
Swiss chard	50	4.68^{ef}	0.49^{g}	**3.15^{g}**	**4.29^{d}**	**0.52^{d}**	1.91^{g}
Swiss chard	80	**3.08^{f}**	**0.47^{g}**	4.51^{fg}	5.92^{cd}	0.65^{d}	2.52^{g}

Column values followed by the same symbol are not statistically different at *p*≤0.05. The bold and underlined values indicate highest treatment means, whereas, the bold values indicate the lowest treatment means.

Table 4.3: Nutritional content of TVCs expressed on dry mass basis (mg 100 g^{-1})

Treatments		2013/14				2014/15			
		Moisture	**Fe**	**Zn**	**β-carotene**	**Moisture**	**Fe**	**Zn**	**β-carotene**
Amaranth	30	0.82^{cde}	45.23^{cd}	5.86^{bcd}	145.4^{a}	0.79^{bc}	30.43^{f}	6.85^{a}	**141.2^{a}**
Amaranth	50	0.79^{def}	46.61^{bcd}	5.86^{bcd}	136.7^{a}	0.76^{cde}	34.79^{ef}	4.75^{c}	138.5^{a}
Amaranth	80	0.84^{bcd}	45.76^{bcd}	6.03^{bc}	**147.3^{a}**	0.78^{bcd}	24.11^{f}	4.64^{c}	55.3^{d}
Spider flower	30	0.79^{cdef}	49.45^{bcd}	7.47^{ab}	49.2^{bc}	0.72^{f}	51.11^{cd}	5.57^{bc}	117^{ab}
Spider flower	50	0.76^{ef}	58.55^{bc}	7.60^{ab}	73.1^{b}	0.76^{de}	59.11^{bc}	6.04^{ab}	94.8^{bc}
Spider flower	80	0.74^{f}	55.52^{bcd}	**8.38^{a}**	39.7^{c}	0.74^{ef}	77.92^{a}	6.87^{a}	104.3^{bc}
Sweet potato leaves	30	0.80^{cde}	**104.3^{a}**	4.26^{cde}	75.4^{b}	0.75^{ef}	60.41^{bc}	2.76^{d}	90.7^{bc}
Sweet potato leaves	50	0.85^{abc}	70.5^{b}	**3.78^{e}**	62^{bc}	0.76^{cde}	50.92^{cd}	2.54^{d}	79.1^{cd}
Sweet potato leaves	80	0.84^{bcd}	60.67^{bc}	3.96^{de}	46.1^{bc}	0.81^{b}	67.72^{ab}	3.0^{d}	51.8^{de}
Swiss chard	30	0.91^{a}	56.74^{bc}	5.28^{cde}	37.5^{c}	0.90^{a}	51.96^{cd}	5.2^{bc}	**17.9^{f}**
Swiss chard	50	0.91^{a}	50.08^{bcd}	4.63^{cde}	**34.3^{c}**	0.90^{a}	44.09^{de}	5.37^{bc}	22.8^{ef}
Swiss chard	80	0.90^{ab}	**30.94^{d}**	4.24^{cde}	45.2^{bc}	089^{a}	53.52^{cd}	5.88^{ab}	19.1^{f}

Column values followed by the same symbol are not statistically different at *p*≤0.05. The bold and underlined values indicate highest treatment means, whereas, the bold values indicate the lowest treatment means.

Table 4.4: Micronutrient (Fe, Zn) and β-carotene content of selected TVCs

Crop Species	Fe mg 100 g^{-1}	Zn mg 100 g^{-1}	β-carotene mg 100 g^{-1}
Wenhold et al. (2012)			
Amaranth	4.8	1.51	60
Spider flower	2.6	0.76	33
OFSP leaves	0.5	0.29	17
Swiss chard	4.4	0.73	78
USDA (2014)			
Amaranth	2.32	0.90	24
Spider flower	nd	nd	nd
OFSP leaves	0.97	nd	31.7
Swiss chard	2.71	0.53	78

nd = not determined

4.4.1.2 Nutritional yield

Nutritional yield (NY) of Fe, Zn, and β-carotene for selected TVCs (Amaranth, Spider flower, and OFSP leaves) and Swiss chard were calculated and analysis of variance conducted. Results (2013/14) indicated that there was an interaction effect ($p \leq 0.05$) between water (irrigation application level) and fertility for Fe NY and β-carotene NY, whereas, there was no interaction effect ($p > 0.05$) for Zn NY. For the 2014/15 season, there was an interaction (crops x water) effect ($p \leq 0.05$) for Zn and β-carotene NY, whereas, there was no interaction effect ($p > 0.05$) for Fe NY (Table 4.1). There were statistically significant differences in the nutritional yield (NY) treatment means of Fe, Zn, and β carotene at water and crop levels (Table 4.5). Amaranth NY decreased significantly as follows with increasing water stress for the 2013/14 (i) from 1361 to 743 g ha^{-1} for Fe, (ii) 174 to 102 g ha^{-1} for Zn, and 4285 to 2299 g ha^{-1} for β-Carotene. A similar trend for Amaranth NY was observed for the 2014/15 season, whereby increasing water stress resulted in decreasing NY for Fe, Zn, and β-carotene. However, there were no marked differences in treatment means with increasing water stress for Spider flower Fe NY and Zn NY for the 2013/14 and 2014/15 seasons, except for β-carotene NY which decreased significantly from 1330 to 915 g ha^{-1} for the 2013/14 season and from 3820 to 2166 g ha^{-1} for the 2014/15. In addition, the sensitivity of increasing water stress on Fe NY and Zn NY treatment means was observed up to the moderate water stress (50%) for the 2013/14 and 2014/15 seasons. Orange fleshed sweet potato leaves showed a sharp decrease in β-carotene NY for the 2013/14 (3610 to 1200 g ha^{-1}) and 2014/15 (1932 to 1149 g ha^{-1}) seasons as water stress was increased. During the 2013/14 and 2014/15 seasons, NY for Fe, Zn, and β-carotene ranged as follows: 743 to 3610 g ha^{-1}, 50 to 317 g ha^{-1} and 865 to 5509 g ha^{-1}, respectively. The highest NY for Fe was obtained for OFSP leaves in combination with the no water stress treatment (30) for the 2013/14 season, whereas, for the 2014/15 season, it was obtained for Swiss chard in combination with the no water stress treatment. The highest Zn NY for 2013/14 and 2014/15 seasons were obtained for Swiss chard under the no water stress treatment, whereas, the highest β-carotene NY was obtained for the combination of Amaranth with no water stress (30) (Table 4.5). The results of the study suggest that under optimum conditions, TVCs are lower when compared with Swiss chard in terms of the amount of nutrients which can be harvested per unit area. Spider flower, specifically, does not react as negatively to water stress as Swiss chard and is, therefore, better adapted to low input conditions. Therefore, these crops can alleviate nutritional food insecurity of RPHs. Limited information exists on NY of TVCs and Swiss chard for data collected from the same location. This was a first attempt to benchmark NY of selected TVCs.

Table 4.5: Nutritional yield of Fe, Zn and β-carotene for TVCs (g ha^{-1})

Treatments		**2013/14**			**2014/15**		
		Fe	**Zn**	**β-carotene**	**Fe**	**Zn**	**β-carotene**
Amaranth	30	1361^{cde}	174^{b}	**4285^{a}**	1182^{cd}	262^{a}	**5509^{a}**
Amaranth	50	1283de	157^{bc}	3563^{ab}	1156^{cd}	160^{bc}	4744^{ab}
Amaranth	80	**743^{f}**	102^{cd}	2299^{c}	692^{d}	133^{bc}	1567de
Spider flower	30	1350^{cde}	203^{ab}	1330de	1692^{bcd}	178^{b}	3820^{abc}
Spider flower	50	1461^{cde}	190^{ab}	1823^{cd}	1602^{bcd}	162^{b}	2566^{cde}
Spider flower	80	1266^{def}	190^{ab}	**915^{e}**	1621^{bcd}	143^{bc}	2166^{cde}
Sweet potato leaves	30	**3610^{a}**	177^{ab}	3160^{b}	1932^{bc}	89^{cd}	2881^{bcd}
Sweet potato leaves	50	1705^{cd}	97^{d}	1592^{cde}	1156^{cd}	58^{d}	1811de
Sweet potato leaves	80	1200^{def}	**80^{d}**	923^{e}	**1149^{cd}**	**50^{d}**	**865^{e}**
Swiss chard	30	2351^{b}	**234^{a}**	1557^{cde}	**3147^{a}**	**317^{a}**	1088de
Swiss chard	50	1829^{bc}	192^{ab}	1254de	2091^{abc}	254^{a}	889^{e}
Swiss chard	80	1046^{ef}	160^{bc}	1526^{cde}	2444^{ab}	266^{a}	1031de

Column values followed by the same symbol are not statistically different at $p \leq 0.05$. The bold and underlined values indicate highest treatment means, whereas, the bold values indicate the lowest treatment means.

4.4.1.3 Nutritional water productivity

Nutritional water productivity values of Fe, Zn, and β-carotene for selected TVCs (Amaranth, Spider flower, and OFSP leaves) and Swiss chard were calculated and analysis of variance conducted. Results (2013/14) indicate that there was a significant difference ($p \leq 0.05$) for Fe and β-carotene NWP, whereas, there was no significant difference for Zn NWP. For the 2014/15 season, there was a significant ($p \leq 0.05$) difference for β-carotene NWP only and there was no significant difference for Fe and Zn NWP (Table 4.1). There were statistically significant differences in the NWP treatment means of Fe, Zn, and β carotene at water and crop levels (Table 4.6). For the 2013/14 season, Amaranth NWP increased as follows with increased water stress: (i) 918 to 1579 mg m^{-3} for Fe, (ii) 117 to 217 mg m^{-3} for Zn, and (3) 2851 to 4846 mg m^{-3} for β-carotene. A similar trend was observed for the 2014/15 season for Fe NWP and Zn NWP, whereby increased water stress resulted in increased Fe NWP and Zn NWP, except for β carotene NWP which indicated a decrease at the severe water stressed treatment (80%). Moreover, Spider flower showed a similar trend whereby increasing water stress resulted in an increase in Fe, Zn, and β carotene NWP for the 2013/14 and 2014/15 seasons. The severity of water stress on OFSP leaves indicated that the severe water stress (80%) will result in a decrease of approximately 50% in NWP of Fe, Zn, and β carotene NWP (Table 4.6). During the 2013/14 and 2014/15 seasons, NWP for Fe, Zn, and β-Carotene ranged as follows; 371 to 2174 mg m^{-3}, 25 to 268 mg m^{-3}, and 260 to 4846 mg m^{-3}, respectively. The highest Fe and Zn NWPs were obtained for Spider flower in combination with the severe water stress treatment, whereas, the highest β carotene NWP was obtained for Amaranth in combination with the moderate water stress treatment (50%) (Table 4.6).

Annandale et al. (2012) reported NWP values for Fe, Zn and β-carotene as follows; OFSP leaves- 29 mg m^{-3}, 15 mg m^{-3}, and 681 mg m^{-3}; Amaranth- 106 mg m^{-3}, 33 mg m^{-3}, and 40 mg m^{-3}; and Swiss chard- 86.4 mg m^{-3}, 17 mg m^{-3}, and 89 mg m^{-3}. These values are lower when compared to the results of the present study which could be attributed to parameters used to calculate NWP (*i.e.* biomass, water use and NC) of selected crops were derived from different literature sources. Spider flower had higher Fe and Zn NWP, and Amaranth higher β-carotene NWP. The results of the present study suggest that if water scarcity becomes a salient issue in the next coming decades, a deficit irrigation practice can be implemented and NWP will not be affected. These results suggest that TVCs are more efficient in utilizing water for Fe, Zn, and β-carotene production compared to a commercial crop like Swiss chard. Moreover, TVCs can be ideal for cropping systems in water scarce areas such as South Africa.

Table 4.6: Nutritional water productivity in terms of Fe, Zn and β-carotene for TVCs (mg m^{-3})

Treatments		2013/14			2014/15		
		Fe	**Zn**	**β-carotene**	**Fe**	**Zn**	**β-carotene**
Amaranth	30	918^{defg}	117^{c}	2854^{bc}	**569^{e}**	127^{cd}	2641^{a}
Amaranth	50	1213^{cde}	149^{bc}	3377^{b}	764^{e}	106^{def}	**3135^{a}**
Amaranth	80	1579^{abc}	217^{a}	**4846^{a}**	622^{e}	119^{cde}	1392^{b}
Spider flower	30	1417^{bcd}	213^{ab}	1372^{d}	1366^{bc}	141^{bc}	3030^{a}
Spider flower	50	**2000^{a}**	256^{a}	2468^{c}	1738^{ab}	175^{ab}	2782^{a}
Spider flower	80	1788^{ab}	**268^{a}**	1282^{de}	**2174^{a}**	**191^{a}**	2898^{a}
Sweet potato leaves	30	664^{fgh}	32^{d}	594^{efg}	816^{de}	37^{g}	1197^{bc}
Sweet potato leaves	50	432^{gh}	26^{d}	442^{fg}	723^{e}	36^{g}	1116^{bc}
Sweet potato leaves	80	**371^{h}**	**25^{d}**	**286^{g}**	757^{e}	**33^{g}**	572^{cd}
Swiss chard	30	1087^{cdef}	109^{c}	720d^{efg}	748^{e}	76^{f}	513^{cd}
Swiss chard	50	1085^{cdef}	114^{c}	736^{defg}	735^{e}	90^{ef}	310^{d}
Swiss chard	80	733^{efgh}	112^{c}	1072^{def}	1219^{cd}	132^{cd}	**260^{d}**

Column values followed by the same symbol are not statistically different at $p \leq 0.05$. The bold and underlined values indicate highest treatment means, whereas, the bold values indicate the lowest treatment means.

4.4.2 Rooiland field experiments

4.4.2.1 Nutritional content

- **Orange fleshed sweet potato leaves:**

Moisture content, Fe, Zn, and β-carotene content on fresh and dry mass basis for OFSP leaves were measured. The 2013/14 season results indicate that there was no statistically significant interaction effect ($p>0.05$) between Water (W), Fertility (F) and leaf Harvesting (H) for the measured parameters (Table 4.7). No statistically significant interaction effects could be determined for all the parameters when expressed on a fresh basis (Table 4.8). The 2013/14 and 2014/15 results indicate that there were no statistically significant differences between treatment means in terms of Fe, Zn, and β-carotene NC, whether expressed per W, F, and leaf H or the combinations of W and F, W and H, and F and H. However, only H showed a significance difference ($p \leq 0.05$) for the 2013/14 season. Although there were no significant differences between treatment means, a trend which was observed for OFSP leaves that increased fertility stress resulted in increased in Fe NC for the 2013/14 season. The latter parameter increased from 9.74 to 11.85 mg 100 g^{-1}, whereas for the 2014/15 season the value increased from 10.75 to 16.01 mg 100 g^{-1}. Moreover, increasing both water and fertility stresses resulted in decreased Fe NC for the 2013/14 season. The latter parameter decreased from 12.40 to 7.84 mg 100 g^{-1}, while for the 2014/15 season it decreased from 14.78 to 10.79 mg 100 g^{-1}. Increased soil fertility stress for Zn and β-carotene showed general decreasing trends: (i) for Zn it was from 0.75 to 0.52 mg 100 g^{-1} for the 2013/14 season and from 0.63 to 0.60 mg 100 g^{-1} for the 2014/15 season, (ii) for β-carotene, it was from 1.35 to 1.83 mg 100 g^{-1} for the 2013/14 season and from 10.33 to 9.72 mg 100 g^{-1} for the 2014/15 season. A similar trend was observed, whereby increasing water and fertility stresses showed some degree of stability in Zn NC and β-carotene NC for the 2013/14 and 2014/15 seasons (Table 4.9). Over the two seasons, NC for Fe, Zn, and β-carotene ranged as follows: 6.54 to 17.61 mg $100g^{-1}$, 0.43 to 0.75 mg 100 g^{-1}, and 1.04 to 11.20 mg 100 g^{-1}, respectively. The highest Fe, Zn, and β-carotene NCs were obtained from the W2F1H2, W1F1H1, and W1F1H2 treatment combinations (Table 4.9). Nutritional content values for OFSP leaves on dry mass basis are presented in Table 4.10. The values for Fe are higher, Zn values compare favourably, while β-carotene values are lower than those reported by Wenhold et al. (2012) and the USDA (2014) (Table 4.4). OFSP leaves NC values obtained from the rain-shelter experiment ranged as follows; Fe from 8.7-17 mg 100 g^{-1}, Zn from 0.6-2.6 mg 100 g^{-1}, and β-carotene from 8.7-23 mg 100 g^{-1} (Table 4.2). Iron and Zn values from the rain-shelter and Rooiland experiments are comparable, whereas, for β-carotene content there was a huge variation between the two experimental sites with values from the Rooiland experiment indicating a higher β-carotene range for the 2014/15 season (Tables 4.2 and 4.9).

Table 4.7: Analysis of variance to evaluate treatment effects on various parameters of OFSP for the 2013/14 season

Parameters	**Water (W)**		**Fertility (F)**		**Harvests (H)**		**W x F**		**W X H**		**F x H**		**W x F x H**	
2013/14	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}
Moisture	0.4	0.54	0.82	0.38	10.65	0.01	0.59	0.45	0.84	0.37	0.04	0.85	0.72	0.41
Fe (dry mass)	8.83	**0.01**	2.36	0.15	0.48	0.50	12.57	**0.00**	6.42	**0.02**	1.60	0.23	0.56	0.47
Zn (dry mass)	1.28	0.28	4.51	**0.05**	1.81	0.20	3.83	0.07	0.64	0.44	1.33	0.27	2.75	0.12
β-carotene (dry mass)	1.95	0.18	0.00	1.00	13.20	0.00	2.99	0.11	0.75	0.40	0.00	0.95	1.76	0.21
Fe (fresh mass)	2.91	0.11	1.57	0.23	5.81	0.03	2.26	0.16	2.71	0.12	0.17	0.69	1.13	0.31
Zn (fresh mass)	1.76	0.21	1.38	0.26	9.78	0.01	3.93	0.07	0.13	0.72	1.88	0.19	0.05	0.83
β-carotene (fresh mass)	4.56	**0.05**	0.69	0.42	13.91	0.00	9.58	**0.01**	2.93	0.11	0.24	0.63	3.79	0.07
Fe nutritional yield (fresh mass)	12.76	0.003	2.82	0.115	94.84	<0.001	7.74	0.02	0.18	0.68	0.08	0.78	0.25	0.63
Zn nutritional yield (fresh mass)	2.05	0.174	19.44	<0.001	115.32	<0.001	0.01	0.94	6.74	**0.02**	1.13	0.31	0.19	0.67
β-carotene nutritional yield (fresh mass)	1.53	0.237	0.81	0.383	29.51	<0.001	2.05	0.17	0.32	0.58	0.31	0.59	1.72	0.21
Fe NWP	23.46	<0.001	1.86	0.194	86.32	<0.001	6.23	0.03	2.02	0.18	0.07	0.80	0.60	0.45
Zn NWP	46.21	<0.001	7.98	0.013	92.72	<0.001	0.03	0.86	16.79	**0.00**	0.72	0.41	0.02	0.90
β-carotene NWP	1.70	0.214	0.07	0.794	22.97	<0.001	1.74	0.21	0.58	0.46	0.01	0.91	1.61	0.23

Table 4.8: Analysis of variance to evaluate treatment effects on various parameters of OFSP for the 2014/15 season

Parameters	**Water (W)**		**Fertility (F)**		**Harvests (H)**		**W x F**		**W X H**		**F x H**		**W x F x H**	
2014/15	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}
Moisture	0.35	0.56	6.16	0.03	10.47	0.01	2.38	0.15	0.84	0.38	1.46	0.25	0.15	0.71
Fe (dry mass)	5.97	0.03	0.05	0.84	1.13	0.31	0.06	0.81	1.49	0.24	0.99	0.34	5.57	0.03
Zn (dry mass)	0.50	0.49	25.66	<0.001	0.47	0.51	18.21	<0.001	5.33	0.04	18.74	<0.001	8.52	0.01
β-carotene (dry mass)	1.74	0.21	2.55	0.13	0.32	0.58	0.31	0.59	3.92	0.07	2.91	0.11	0.42	0.52
Fe (fresh mass)	2.39	0.15	0.00	0.99	0.08	0.78	1.83	0.20	0.61	0.45	0.00	0.96	3.23	0.09
Zn (fresh mass)	0.06	0.81	1.42	0.25	4.60	0.05	2.65	0.13	0.57	0.46	12.87	0.00	4.02	0.07
β-carotene (fresh mass)	1.57	0.23	0.16	0.69	1.32	0.27	0.00	0.96	3.15	0.10	5.01	0.04	0.34	0.57
Fe nutritional yield (fresh mass)	1.55	0.23	0.00	1.00	0.24	0.63	0.58	0.46	0.79	0.39	0.06	0.82	4.07	0.06
Zn nutritional yield (fresh mass)	0.34	0.57	2.39	0.15	0.28	0.60	2.86	0.11	0.33	0.57	2.18	0.16	6.52	0.02
β-carotene nutritional yield (fresh mass)	0.06	0.81	1.74	0.21	0.39	0.54	0.27	0.61	3.16	0.10	1.62	0.22	2.97	0.11
Fe NWP	19.22	<0.001	2.65	0.13	3.00	0.11	3.60	0.08	1.78	0.20	0.05	0.83	0.11	0.74
Zn NWP	35.51	<0.001	11.99	0.00	4.78	0.05	0.38	0.55	0.29	0.60	5.30	0.04	9.06	0.01
β-carotene NWP	29.66	<0.001	6.08	0.03	3.18	0.10	2.02	0.18	0.10	0.76	3.73	0.07	8.56	0.01

Table 4.9: Nutrient content (mg 100 g^{-1}) for OFSP on fresh mass basis

Treatments	**2013/14**			**2014/15**		
	Fe	**Zn**	**β-Carotene**	**Fe**	**Zn**	**β-Carotene**
W1 F1 H1	9.74^{abc}	**0.75^{a}**	1.35^{bc}	10.75^{a}	**0.63^{a}**	10.33^{ab}
W1 F1 H2	9.62^{abc}	0.58^{bc}	**2.40^{a}**	**9.03^{a}**	0.53^{abc}	**8.19^{b}**
W1 F2 H1	**13.35^{a}**	0.57^{bc}	1.22^{bc}	9.65^{a}	**0.43^{c}**	8.36^{b}
W1 F2 H2	11.85^{ab}	0.52^{bc}	1.83^{ab}	16.01^{a}	0.60^{ab}	9.72^{ab}
W2 F1 H1	12.4^{a}	0.63^{ab}	1.11^{c}	14.87^{a}	0.54^{abc}	9.68^{ab}
W2 F1 H2	**6.54^{c}**	**0.45^{c}**	**1.04^{c}**	**17.61^{a}**	0.56^{ab}	10.46^{ab}
W2 F2 H1	10.57^{abc}	0.61^{ab}	1.34^{bc}	15.72^{a}	0.51^{bc}	8.36^{b}
W2 F2 H2	7.84^{bc}	0.53^{bc}	2.02^{a}	10.79^{a}	0.61^{a}	**11.20^{a}**

Column values followed by the same symbol are not statistically different at *p*≤0.05. The bold and underlined values indicate highest treatment means, whereas, the bold values indicate the lowest treatment means (W1 (full irrigation amount); F1 (full NPK fertiliser application); H1 (no leaf harvesting of OFSP); W2 (supplemental irrigation); F2 (no NPK fertiliser application); H2 (leaf harvesting of OFSP)).

Table 4.10: Nutrient content (mg 100 g^{-1}) for OFSP on a dry mass basis

Treatments	**2013/14**				**2014/15**			
	Moisture	**Fe**	**Zn**	**β-Carotene**	**Moisture**	**Fe**	**Zn**	**β-Carotene**
W1 F1 H1	080^{b}	49.3^{cd}	**3.76^{a}**	6.78^{bc}	**0.80^{a}**	54.12^{b}	**3.18^{a}**	**52.1^{a}**
W1 F1 H2	0.82^{ab}	53.1^{bcd}	3.19^{b}	**14.98^{a}**	0.78^{ab}	**41.39^{b}**	2.45^{bc}	37.95^{b}
W1 F2 H1	**0.79^{b}**	62.5^{ab}	**2.97^{b}**	6.13^{bc}	0.78^{ab}	44.47^{b}	**1.99^{d}**	38.52^{b}
W1 F2 H2	0.83^{ab}	**69.2^{a}**	3.05^{b}	10.73^{abc}	**0.74^{c}**	60.6^{ab}	2.30^{cd}	**37.34^{b}**
W2 F1 H1	0.80^{b}	60.4^{abc}	3.13^{b}	**5.46^{c}**	0.79^{ab}	70.45^{ab}	2.55^{bc}	46.47^{ab}
W2 F1 H2	**0.86^{a}**	**45.3^{d}**	3.12^{b}	7.42^{bc}	0.78^{ab}	81.82^{ab}	2.57^{bc}	47.56^{ab}
W2 F2 H1	**0.79^{b}**	48.9^{cd}	3.16^{b}	5.95^{bc}	0.79^{ab}	**105.7^{a}**	2.39^{bc}	40.17^{ab}
W2 F2 H2	0.83^{ab}	**45.3^{d}**	3.04^{b}	11.86^{ab}	0.77^{bc}	46.02^{a}	2.61^{b}	47.6^{ab}

Column values followed by the same symbol are not statistically different at *p*≤0.05. The bold and underlined values indicate highest treatment means, whereas, the bold values indicate the lowest treatment means (W1 (full irrigation amount); F1 (full NPK fertiliser application); H1 (no leaf harvesting of OFSP); W2 (supplemental irrigation); F2 (no NPK fertiliser application); H2 (leaf harvesting of OFSP)).

- **Orange fleshed sweet potato storage roots:**

Moisture content, Fe, Zn, and β-carotene content on fresh and dry mass basis for OFSP storage root yield were measured. Results of the study indicate that there was no statistically significant (*p*>0.05) interaction effect between W, F, and H for Fe and Zn for the 2013/14 and 2014/15 seasons, except for moisture content (*p*=0.008) for the 2014/15 season (Tables 4.11 and 4.12). Table 4.13 presents treatment means of OFSP storage root NC for Fe, Zn, and β-carotene on a fresh mass basis. There were no significant differences for W, F, H, W and F, W and H, as well as F and H combinations. The results also indicate that soil fertility and water stresses did not affect NC for Fe, Zn, and β-carotene for both seasons. During the 2013/14 and

2014/15 seasons, NC for Fe, Zn, and β-carotene ranged as follows: 6.54 to 17.61 mg 100g^{-1}, 0.43 to 0.75 mg 100 g^{-1}, and 1.04 to 11.20 mg 100 g^{-1}, respectively. The highest Fe, Zn, and β-carotene NCs were obtained from the W2F1H2, W1F1H1, and W1F1H2 treatment combinations (Table 4.13). During the 2013/14 and 2014/15 seasons, NC for Fe, Zn, and β-Carotene OFSP storage root ranged as follows: 0.71 to 2.36 mg 100 g^{-1}, 0.19 to 0.43 mg 100 g^{-1}, and 32.3 to 65.4 mg 100 g^{-1}, respectively. The highest Fe and Zn NCs were obtained from the W2F2H1 treatment combination, whereas, the highest β-carotene NC were observed from the W2F1H2 treatment combination (Table 4.13). Table 4.14 presents treatment means of OFSP storage root NC for Fe, Zn, and β-carotene on a dry mass basis. Significant differences for W, F, H combinations can be gleaned from the table. For example: (i) Fe NC increased significantly from 2.94 to 4.26 mg 100 g^{-1} going from W1F1H1 to W1F1H2 during 2013/14, indicating that no harvesting of the potato leaves (H2) had a beneficial effect on Fe NC, (ii) β-carotene decreased significantly from 235.1 to 193.2 mg 100 g^{-1} going from W1F1H1 to W2F2H2 during 2013/14, while (3) Zn NC decreased significantly from 1.28 to 0.94 mg 100 g^{-1} going from W1F1H1 to W1F1H2 during 2014/15, indicating that harvesting of the potato leaves (H1) had a beneficial effect on Fe NC. Laurie et al. (2012) reported β-carotene of 97 mg 100 g^{-1}, Fe content ranging from 0.4 to 1 mg 100 g^{-1}, and Zn content ranging from 0.5 to 0.7 mg 100 g^{-1} for OFSP storage root, which were collected from Hazyview, Giyani, Empangeni, and Roodeplaat. These results are comparable with the results (Table 4.13) of the present study. Comparing Fe, Zn, and β-carotene between of OFSP storage root and leaves, results of this study suggest that OFSP leaves are higher in Fe and Zn when compared with the tubers, while the tubers are higher in β-carotene content. One crucial finding of the study is that leaf harvesting does not affect the NC of the storage roots which suggest that OFSP can be utilized as a dual crop.

Table 4.11: Analysis of variance to evaluate treatment effects on various parameters of OFSP for the 2013/14 season

Parameters	**Water (W)**		**Fertility (F)**		**Harvests (H)**		**W x F**		**W X H**		**F x H**		**W x F x H**	
2013/14	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}
Moisture	1.77	0.20	1.91	0.19	0.41	0.53	0.42	0.53	0.03	0.87	1.14	0.30	1.35	0.26
Fe (dry mass)	14.10	0.00	0.39	0.54	0.35	0.56	2.97	0.11	0.02	0.90	7.43	0.02	1.36	0.26
Zn (dry mass)	0.79	0.39	0.06	0.81	0.15	0.71	2.22	0.16	1.39	0.26	0.10	0.76	0.99	0.34
β-carotene (dry mass)	0.78	0.39	3.71	0.08	3.57	0.08	12.61	0.00	0.08	0.78	0.08	0.78	0.89	0.36
Fe (fresh mass)	11.08	0.01	4.83	0.05	0.14	0.72	5.25	0.04	0.10	0.76	4.70	0.05	2.43	0.14
Zn (fresh mass)	0.04	0.85	0.36	0.56	0.29	0.60	5.90	0.03	1.84	0.20	0.09	0.77	0.01	0.91
β-carotene (fresh mass)	0.50	0.49	0.02	0.88	1.24	0.28	2.01	0.18	0.40	0.54	0.24	0.63	4.40	0.06
Fe nutritional yield (fresh mass)	16.33	0.00	0.37	0.55	3.65	0.08	0.76	0.40	1.44	0.25	5.77	0.03	0.13	0.73
Zn nutritional yield (fresh mass)	8.89	0.01	1.73	0.21	6.93	0.02	0.08	0.78	1.18	0.30	17.46	<0.001	0.11	0.74
β-carotene nutritional yield (fresh mass)	12.36	0.00	5.06	0.04	10.85	0.01	0.57	0.46	4.49	**0.05**	22.94	<0.001	0.08	0.78
Fe NWP	2.37	0.15	2.65	0.13	1.35	0.27	0.28	0.61	0.08	0.78	1.93	0.19	0.00	0.97
Zn NWP	13.23	0.00	2.42	0.14	4.60	0.05	2.19	0.16	0.12	0.74	14.17	0.00	1.07	0.32
β-carotene NWP	18.95	<0.001	6.47	**0.02**	4.03	0.06	2.10	0.17	0.53	0.48	13.82	0.00	1.14	0.30

Table 4.12: Analysis of variance to evaluate treatment effects on various parameters of OFSP for the 2014/15 season

Parameters	**Water (W)**		**Fertility (F)**		**Harvests (H)**		**W x F**		**W X H**		**F x H**		**W x F x H**	
2014/15	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}
Moisture	1.66	0.219	2.7	0.123	0.91	0.356	8.85	0.01	15.12	0.002	1.57	0.231	9.71	0.008
Fe (dry mass)	7.36	0.017	0.08	0.785	0.16	0.693	0.15	0.705	0.08	0.785	0.19	0.668	0.71	0.415
Zn (dry mass)	2.55	0.133	0.19	0.667	3.43	0.085	1.83	0.197	0.12	0.737	8.94	0.01	0.08	0.78
β-carotene (dry mass)	7.98	0.014	0.78	0.392	0.07	0.789	0.85	0.372	0.37	0.551	3.26	0.093	0.01	0.941
Fe (fresh mass)	8.09	0.013	0	0.997	0.11	0.746	0.16	0.699	0	0.961	0.34	0.568	1.38	0.26
Zn (fresh mass)	0.86	0.369	0.57	0.462	2.7	0.123	0.15	0.703	0.01	0.943	3.62	0.078	1.54	0.235
β-carotene (fresh mass)	2.13	0.167	0	0.964	0.15	0.708	0.9	0.36	5.34	0.037	0.42	0.525	3.12	0.099
Fe nutritional yield (fresh mass)	2.15	0.164	0.18	0.681	0.00	0.992	0.78	0.391	0.39	0.542	3.34	0.089	1.73	0.21
Zn nutritional yield (fresh mass)	21.41	<.001	3.94	0.067	1.8	0.2	8.84	0.01	6.26	0.025	9.08	0.009	0.02	0.901
β-carotene nutritional yield (fresh mass)	3.52	0.082	2.63	0.127	0.24	0.633	6.37	0.024	4.2	0.06	6.33	0.025	0.02	0.889
Fe NWP	4.04	0.064	3.41	0.086	0.01	0.913	10.41	0.006	0.98	0.339	2.71	0.122	2.88	0.112
Zn NWP	0.03	0.874	9.52	0.008	0.05	0.819	3.86	0.07	7.68	0.015	1.67	0.217	0.68	0.424
β-carotene NWP	2.25	0.155	0.28	0.604	0.06	0.813	3.9	0.068	3.29	0.091	0.65	0.434	0.04	0.84

Table 4.13: Nutrient content (mg 100 g^{-1}) for OFSP storage roots on a fresh` mass basis

Treatments	2013/14			2014/15		
	Fe	**Zn**	**β-carotene**	**Fe**	**Zn**	**β-carotene**
W1 F1 H1	0.88^{b}	0.38^{ab}	**54.56^{a}**	1.04^{ab}	**0.30^{a}**	54.5^{a}
W1 F1 H2	0.97^{ab}	0.40^{ab}	**40.89^{b}**	**0.71^{b}**	**0.19^{b}**	**32.3^{b}**
W1 F2 H1	**1.23^{a}**	**0.33^{ab}**	42.41^{ab}	0.67^{b}	0.24^{ab}	46.7^{ab}
W1 F2 H2	1.24^{a}	0.34^{ab}	45.07^{ab}	0.78^{ab}	0.27^{ab}	49.2^{ab}
W2 F1 H1	0.72^{b}	0.34^{ab}	43.71^{ab}	1.54^{ab}	0.28^{ab}	45.9^{ab}
W2 F1 H2	0.98^{ab}	0.30^{b}	47.25^{ab}	2.07^{ab}	0.23^{ab}	**65.4^{a}**
W2 F2 H1	0.97^{ab}	**0.43^{a}**	53.72^{ab}	**2.36^{a}**	0.29^{a}	46.6^{ab}
W2 F2 H2	**0.71^{b}**	0.37^{ab}	47.15^{ab}	1.55^{ab}	0.27^{ab}	54.6^{a}

Column values followed by the same symbol are not statistically different at $p \leq 0.05$. The bold and underlined values indicate highest treatment means, whereas, the bold values indicate the lowest treatment means (W1 (full irrigation amount); F1 (full NPK fertiliser application); H1 (no leaf harvesting of OFSP); W2 (supplemental irrigation); F2 (no NPK fertiliser application); H2 (leaf harvesting of OFSP)).

Table 4.14: Nutrient content (mg 100 g^{-1}) for OFSP storage roots on a dry mass basis

Treatments	2013/14				2014/15			
	Moisture	**Fe**	**Zn**	**β-carotene**	**Moisture**	**Fe**	**Zn**	**β-carotene**
W1 F1 H1	0.77^{ab}	3.87^{ab}	1.66^{a}	235.1^{a}	0.74^{cd}	4.46^{a}	1.28^{a}	22.06^{ab}
W1 F1 H2	0.81^{a}	4.56^{a}	1.60^{a}	214^{ab}	0.80^{ab}	3.52^{a}	0.94^{b}	17.27^{b}
W1 F2 H1	0.77^{ab}	5.06^{a}	1.35^{a}	185.3^{b}	0.75^{bc}	2.56^{a}	0.92^{b}	18.74^{b}
W1 F2 H2	0.75^{ab}	4.80^{a}	1.60^{a}	182.4^{b}	0.76^{abc}	3.05^{a}	1.04^{ab}	20.46^{ab}
W2 F1 H1	0.76^{ab}	2.94^{b}	1.40^{a}	197.2^{b}	0.81^{a}	7.59^{a}	1.30^{a}	24.16^{ab}
W2 F1 H2	0.76ab	4.26^{a}	1.29^{a}	186^{b}	0.70^{d}	8.65^{a}	0.95^{b}	21.76^{ab}
W2 F2 H1	0.75^{b}	3.79^{ab}	1.68^{a}	214.2^{ab}	0.81^{a}	10.06^{a}	1.18^{ab}	24.3^{ab}
W2 F2 H2	0.76^{ab}	2.75^{b}	1.42^{a}	193.2^{b}	0.80^{ab}	6.58^{a}	1.21^{ab}	27.88^{a}

Column values followed by the same symbol are not statistically different at $p \leq 0.05$. The bold and underlined values indicate highest treatment means, whereas, the bold values indicate the lowest treatment means (W1 (full irrigation amount); F1 (full NPK fertiliser application); H1 (no leaf harvesting of OFSP); W2 (supplemental irrigation); F2 (no NPK fertiliser application); H2 (leaf harvesting of OFSP)).

- **Amaranth and Spider flower:**

Moisture content, Fe, Zn, and β-carotene content on fresh and dry mass basis for Amaranth and Spider flower were measured. Results of the study indicate that there was no statistically significant ($p > 0.05$) interaction effect between water, fertility, and leaf harvesting for moisture, Zn (dry and fresh mass), and β-carotene (dry and fresh mass) for the 2013/14 and 2014/15 seasons, whereas, there was an interaction effect for Fe (fresh and dry mass) the 2013/14 season (Tables 4.15 and 4.16). However, soil fertility indicated significant differences in treatment means for Fe NC, Zn NC and β-Carotene NC for the 2014/15 season, whereas, for the 2013/14 season, there were significant differences for Fe NC and Zn NC treatment means on a fresh mass basis (Tables 4.15 and 4.16). From Table 4.17 the following NC increases can be gleaned with increasing water and soil fertility stresses: For the 2013/14 season, for Fe (6.96 to 19.48 mg 100 g^{-1}), for Zn (0.36 to 0.77 mg 100 g^{-1}), and for β-carotene (4.29 to 6.90 mg 100 g^{-1}). For Amaranth, Fe NC increased from 6.96 to 19.48 mg 100 g^{-1}, for Zn NC from 0.36 to 0.77 mg 100 g^{-1}, and from 4.29 to 6.90 mg 100 g^{-1} for β-carotene NC. For Spider flower, NC increased from 8.39 to 24.36 mg 100 $g^{-}1$ for Fe, 0.40 to 0.76 mg 100 g^{-1} for Zn, and slight decrease from 4.03 to 2.95 for β-NC. A similar trend was observed for the 2014/15 season, whereby an increase in water and soil fertility stresses resulted in an increase in Fe, Zn, and β-carotene NC (Table 4.18). Table 4.18 presents treatment means on a dry mass basis for Amaranth and Spider flower NC. During the 2013/14 and 2014/15 seasons, Amaranth and Spider flower NC for Fe, Zn, and β-carotene ranged as follows: 44.23 to 185.1 mg $100g^{-1}$, 3.08 to 7.02 mg 100 g^{-1} and 23.71 to 75.04 mg 100 g^{-1}, respectively. A wider nutritional range for Amaranth and Spider flower was obtained from the Rooiland experimental site compared to the rain-shelter site. This phenomenon might have been caused by different environmental conditions in terms of soil fertility, management practices, and also different seasons.

Table 4.15: Analysis of variance to evaluate treatment effects on various parameters of Amaranth and Spider flower for the 2013/14 season

Parameters	**Water (W)**		**Fertility (F)**		**Crop (C)**		**W x F**		**W X C**		**F x C**		**W x F x C**	
2013/14	**F_{value}**	**P_{value}**	**F_{value}**	**P_{value}**	**F_{value}**	**P_{value}**	**F_{value}**	**P_{value}**	**F_{value}**	**P_{value}**	**F_{value}**	**P_{value}**	**F_{value}**	**P_{value}**
Moisture	0.6	0.45	0.68	0.422	0.78	0.389	2.01	0.175	0.45	0.51	0.24	0.63	0.48	0.50
Fe (dry mass)	0.6	0.45	21.94	<0.001	9.62	0.008	1.18	0.295	2.47	0.138	1.13	0.306	5.64	0.032
Zn (dry mass)	0.28	0.602	16.27	0.001	6.89	0.02	0.76	0.398	2.31	0.151	0	0.96	2.26	0.155
β-carotene (dry mass)	5.4	0.036	54.95	<0.001	14.81	0.002	0	1.00	0.46	0.51	7.12	0.018	1.32	0.271
Fe (fresh mass)	0.57	0.462	21.01	<0.001	7.76	0.015	0.01	0.934	1.79	0.202	0.12	0.732	9.33	0.009
Zn (fresh mass)	1.2	0.292	8.17	0.013	2.49	0.137	1.72	0.211	0.67	0.427	0.27	0.609	1.92	0.188
β-carotene (fresh mass)	1.03	0.327	0.09	0.765	2.08	0.172	2.15	0.165	0.62	0.442	0.85	0.371	0.26	0.62
Fe nutritional yield (fresh mass)	1.42	0.252	32.12	<0.001	5.36	0.036	1.34	0.267	0.04	0.839	1.51	0.239	1.18	0.297
Zn nutritional yield (fresh mass)	0.89	0.362	39.87	<0.001	9.3	0.009	0.06	0.808	0.1	0.759	5.63	0.033	2.57	0.131
β-carotene nutritional yield (fresh mass)	0.02	0.9	43.44	<0.001	14.91	0.002	0.72	0.412	0.57	0.461	7.52	0.016	3.22	0.094
Fe NWP	4.29	**0.052**	16.74	0.001	0.63	0.439	1.42	0.253	0.08	0.778	0.61	0.449	0.14	0.718
Zn NWP	4.48	**0.053**	27.35	<0.001	2.6	0.129	0.29	0.60	1.48	0.245	0.1	0.756	0.2	0.665
β-carotene NWP	6.87	**0.02**	52.84	<0.001	10.47	0.006	3.2	0.095	3.39	0.087	2.88	0.112	2.54	0.133

Table 4.16: Analysis of variance to evaluate treatment effects on various parameters of Amaranth and Spider flower for the 2014/15 season

Parameters	**Water (W)**		**Fertility (F)**		**Crop (C)**		**W x F**		**W X C**		**F x C**		**W x F x C**	
2014/15	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}	F_{value}	P_{value}
Moisture	3.61	0.078	17.49	<0.001	1.07	0.319	0.95	0.347	0.48	0.499	0.09	0.772	0.48	0.502
Fe (dry mass)	12.5	0.003	66.29	<0.001	1.83	0.198	2.02	0.178	1.92	0.187	0.14	0.714	0.01	0.912
Zn (dry mass)	0.06	0.814	37.99	<0.001	5.42	0.035	1.33	0.268	3.19	0.096	6.03	0.028	0.03	0.857
β-carotene (dry mass)	22.47	<0.001	87.79	<0.001	1.62	0.224	3.43	0.085	1.35	0.265	7.89	0.014	0.25	0.623
Fe (fresh mass)	0.02	0.89	27.06	<0.001	0.93	0.352	0	0.964	0.07	0.797	0.09	0.774	0.3	0.59
Zn (fresh mass)	1.76	0.205	12.17	0.004	2.16	0.164	1.31	0.271	1.07	0.319	1.48	0.244	0.55	0.471
β-carotene (fresh mass)	0.66	0.429	4.62	0.05	0.89	0.361	0.78	0.392	0.62	0.443	0.67	0.428	0.44	0.517
Fe nutritional yield (fresh mass)	1.21	0.289	4.49	0.053	27.03	<0.001	1.37	0.262	9.17	0.009	0.89	0.363	0	0.965
Zn nutritional yield (fresh mass)	2.33	0.149	18.59	<0.001	28.83	<0.001	2.37	0.146	0.02	0.896	6.86	0.02	0.05	0.827
β-carotene nutritional yield (fresh mass)	0.19	0.665	134.33	<0.001	8.12	0.012	2.25	0.153	2.42	0.139	0.94	0.348	0.32	0.582
FeNWP	137.49	<0.001	37.8	<0.001	171.25	<0.001	9.18	0.009	33.54	<0.001	9.56	0.008	0.09	0.765
Zn NWP	34.16	<0.001	54.75	<0.001	61.91	<0.001	15.27	0.002	0.66	0.43	20.51	<.001	1.16	0.30
β-carotene NWP	33.04	<0.001	113.37	<0.001	8.56	0.011	18.4	<.001	0.14	0.71	1.49	0.243	0.07	0.802

Table 4.17: Nutritional content (mg 100 g^{-1}) for Amaranth and Spider flower on a fresh mass basis

Treatments	2013/14			2014/15		
	Fe	**Zn**	**β-Carotene**	**Fe**	**Zn**	**β-Carotene**
W1 F1 A	6.96^{d}	0.36^{ab}	4.29^{ab}	9.42^{bc}	0.735^{b}	10.73^{b}
W1 F2 A	9.46^{cd}	0.32^{b}	2.82^{ab}	40.27^{a}	3.16^{a}	17.35^{a}
W2 F1 A	5.23^{d}	0.28^{b}	4.10^{ab}	11.84^{bc}	0.56^{b}	10.65^{b}
W2 F2 A	19.48^{ab}	0.77^{a}	6.90^{a}	36.63^{a}	1.597^{ab}	12.73^{ab}
W1 F1 SF	8.39^{d}	0.40^{ab}	4.03^{ab}	7.5^{c}	0.534^{b}	10.36^{b}
W1 F2 SF	24.36^{a}	0.74^{a}	1.67^{b}	29.8^{ab}	1.52^{b}	12.64^{ab}
W2 F1 SF	13.45^{bcd}	0.44^{ab}	3.24^{ab}	6.98^{c}	0.574^{b}	10.64^{b}
W2 F2 SF	17^{abc}	0.76^{a}	2.95^{ab}	34.4^{a}	1.262^{b}	12.28^{ab}

Column values followed by the same symbol are not statistically different at $p \leq 0.05$. The bold and underlined values indicate highest treatment means, whereas, the bold values indicate the lowest treatment means (W1 (full irrigation amount); F1 (full NPK fertiliser application); W2 (supplemental irrigation); F2 (no NPK fertiliser application); A (Amaranth); SF (Spider flower)).

Table 4.18: Nutritional content (mg 100 g^{-1}) for Amaranth and Spider flower on dry mass basis

Treatments	2013/14				2014/15			
	Moisture	**Fe**	**Zn**	**β-Carotene**	**Moisture**	**Fe**	**Zn**	**β-Carotene**
W1 F1 A	0.90^{a}	70.7^{c}	3.61^{d}	43.36^{abc}	0.80^{ab}	47.45^{d}	3.71^{cde}	54.2^{cd}
W1 F2 A	0.92^{a}	119.5^{b}	4.13^{cd}	36.68^{cd}	0.59^{c}	91.86^{bc}	7.02^{a}	44.04^{ef}
W2 F1 A	0.92^{a}	65.3^{c}	3.51^{d}	51.06^{a}	0.83^{a}	71.59^{cd}	3.35^{de}	63.83^{b}
W2 F2 A	0.83^{a}	142.3^{ab}	5.48^{ab}	40.12^{bc}	0.74^{abc}	137.81^{a}	5.99^{ab}	48.39^{de}
W1 F1 SF	0.91^{a}	107.5^{bc}	4.43^{bcd}	44.56^{abc}	0.83^{ab}	44.23^{d}	3.08^{e}	58.93^{bc}
W1 F2 SF	0.92^{a}	185.1^{a}	5.84^{a}	23.71^{e}	0.68^{bc}	95.55^{bc}	4.82^{bcd}	39.76^{f}
W2 F1 SF	0.93^{a}	119.7^{b}	4.32^{bcd}	45.48^{ab}	0.86^{a}	50.23^{d}	4.07^{cde}	75.04^{a}
W2 F2 SF	0.90^{a}	121.4^{b}	5.34^{abc}	28.9d^{e}	0.74^{abc}	120.17^{ab}	4.89^{bc}	46.67^{def}

Column values followed by the same symbol are not statistically different at $p \leq 0.05$. The bold and underlined values indicate highest treatment means, whereas, the bold values indicate the lowest treatment means (W1 (full irrigation amount); F1 (full NPK fertiliser application); W2 (supplemental irrigation); F2 (no NPK fertiliser application); A (Amaranth); SF (Spider flower)).

4.4.2.2 Nutritional yield

- **Orange fleshed sweet potato leaves:**

Nutritional yield for Fe, Zn, and β-carotene were calculated and analyses of variance were conducted. Results for the 2013/14 season indicate that there were no statistically significant ($p > 0.05$) interaction effects between W, F and H for Fe, Zn and β-carotene NY (Table 4.15). For the 2014/15 season, there was a statistically significant ($p \leq 0.05$) interaction effect for Zn NY, whereas, there was no interaction effect ($p > 0.05$) for Fe and β-carotene NY between W, F, and

H (Table 4.16). Table 4.19 presents treatment means for Fe, Zn and β-carotene NY for OFSP leaves. The 2013/14 results indicate that under optimum conditions (W1F1), Fe NY, Zn NY and β-Carotene NY will be 526 g ha^{-1}, 40 g ha^{-1}, and 72 g ha^{-1}, respectively. With increasing soil fertility stress (W1F2), Fe, Zn and β-carotene NYs were 1076 g ha^{-1}, 50 g ha^{-1}, and 180 g ha^{-1} (Table 4.19). The combined effect of water and fertility stresses (W2F2) decreased Fe (769 g ha^{-1}) and Zn (52 g ha^{-1}) NYs and increased β-carotene NY to 208 g ha^{-1} (Table 4.19). However, for the 2014/15 season, the results indicate that water and fertility stresses decreased Fe, Zn and β-carotene NYs by approximately 26% for both Fe and Zn and 25% for β-carotene. The highest Fe (1060 g ha^{-1}) and Zn (64 g ha^{-1}) NYs were obtained from the W1F1H2 treatment combination during the 2013/14 season, whereas for β-carotene (489 g ha^{-1}) was obtained for the W1F1H1 treatment combination during the 2014/15 season (Table 4.19). These results suggest that soil fertility stress increased NY of micronutrients (Fe and Zn), as well as that of and β-carotene. Orange fleshed sweet potato leaf NY values obtained from the rain-shelter experiment ranged as follows; (i) Fe from 743 to 3610 g ha^{-1}, Zn from 50 to 317 g ha^{-1}, and β-carotene from 915 to 5509 g ha^{-1} (Table 4.5). These NY ranges are higher than those from the Rooiland experiment.

Table 4.19: Nutritional yield (g ha^{-1}) in terms of Fe, Zn and β-carotene for OFSP leaves

Treatments	**2013/14**			**2014/15**		
	Fe	**Zn**	**β-carotene**	**Fe**	**Zn**	**β-carotene**
W1 F1 H1	526^{d}	40^{cd}	72^{cde}	510^{a}	**30^{a}**	**489^{a}**
W1 F1 H2	1060^{a}	64^{a}	**305^{a}**	**368^{a}**	22^{b}	**335^{b}**
W1 F2 H1	618^{cd}	29de	58^{cde}	404^{a}	**18^{b}**	351^{b}
W1 F2 H2	**1076^{a}**	50^{bc}	180^{abc}	629^{a}	23^{b}	368^{ab}
W2 F1 H1	532^{d}	28^{e}	48d^{e}	600^{a}	21^{b}	381^{ab}
W2 F1 H2	977^{ab}	**68^{a}**	170^{bcd}	690^{a}	23^{ab}	427^{ab}
W2 F2 H1	**303^{e}**	**20^{e}**	**42^{e}**	**754^{a}**	23^{ab}	372^{ab}
W2 F2 H2	769^{bc}	52^{b}	208^{ab}	379^{a}	22^{b}	392^{ab}

Column values followed by the same symbol are not statistically different at $p \leq 0.05$. The bold and underlined values indicate highest treatment means, whereas, the bold values indicate the lowest treatment means (W1 (full irrigation amount); F1 (full NPK fertiliser application); H1 (no leaf harvesting of OFSP); W2 (supplemental irrigation); F2 (no NPK fertiliser application); H2 (leaf harvesting of OFSP)).

- **Orange fleshed sweet potato storage roots:**

Nutritional yield of Fe, Zn, and β-carotene for OFSP tubers were calculated and analysis of variance conducted. Results indicated that there was no statistically significant ($p > 0.05$) interaction effect between W, F and H for Fe, Zn and β-carotene NY for the 2013/14 and 2014/15 seasons (Tables 4.11 and 4.12). However, there were significant differences for Fe, Zn and β-carotene NYs for OFSP storage root during the 2013/14 season (Table 4.11), whereas, there were no significant differences for Fe, Zn and β-carotene NYs (Table 4.13). Table 4.20 presents treatment means for Fe, Zn and β-carotene NYs. The 2013/14 results indicate that Fe (263 to 190 g ha^{-1}), Zn (106 to 62 g ha^{-1}) and β-Carotene (14961 to 7098 g ha^{-1}) NYs decreased with increasing soil fertility stress. The combined effect of water and fertility stresses (W2F2) indicates that NYs for Fe, Zn, and β-carotene will further decrease to 87 g ha^{-1}, 45 g ha^{-1}, and 6237 g ha^{-1}, respectively. A similar trend for the 2014/15 season was observed, whereby increasing W1F2 stresses resulted in decreased NY for Fe, Zn and β-carotene NYs (Table 4.20). During the 2013/14 and 2014/15 seasons, storage root NY for Fe, Zn and β-carotene ranged as follows: 52 to 732 g ha^{-1}, 22 to 130 g ha^{-1}, and 1322 to 27891 g ha^{-1}, respectively. The highest value for Fe, Zn, and β-carotene NYs (2014/15 season) were obtained from the W2 F1 H1, W2 F1 H2, and W1 F2 H1 treatment combinations (Table 4.20). These results suggest that OFSP storage roots are more sensitive to water and fertility stresses compared to OFSP leaves. Moreover, OFSP leaves is higher in Fe and Zn NYs compared to the storage roots, while an opposite result was obtained for β-carotene NY.

Table 4.20: Nutritional yield (g ha^{-1}) in terms of Fe, Zn and β-carotene for OFSP storage roots

Treatments	**2013/14**			**2014/15**		
	Fe	**Zn**	**β-carotene**	**Fe**	**Zn**	**β-carotene**
W1 F1 H1	**263.1^{a}**	**105.89^{a}**	**14961^{a}**	253.4^{ab}	71.2^{bcd}	1152^{b}
W1 F1 H2	113.2^{ab}	37.24^{bcd}	5170^{bcd}	239.3^{b}	64.02^{bcd}	1111^{b}
W1 F2 H1	199.4^{ab}	54.97^{bcd}	7419^{bc}	365.7^{ab}	**129.98^{a}**	**27089^{a}**
W1 F2 H2	190.3^{ab}	61.58^{bc}	7098^{bcd}	233.8^{b}	79.54^{b}	1556^{b}
W2 F1 H1	142.4^{ab}	66.85^{b}	8731^{b}	300.8^{ab}	**39.12^{d}**	**765^{b}**
W2 F1 H2	71.9^{ab}	**21.9^{d}**	3419^{cd}	**732.4^{a}**	71.32^{bc}	1824^{ab}
W2 F2 H1	**52.4^{b}**	26.15^{cd}	**3122^{d}**	511.7^{ab}	55.23^{bcd}	1206^{b}
W2 F2 H2	86.5^{ab}	45.32^{bcd}	6237^{bcd}	**221.7^{b}**	40.39^{cd}	931^{b}

Column values followed by the same symbol are not statistically different at $p \leq 0.05$. The bold and underlined values indicate highest treatment means, whereas, the bold values indicate the lowest treatment means (W1 (full irrigation amount); F1 (full NPK fertiliser application), H1 (no leaf harvesting of OFSP); W2 (supplemental irrigation); F2 (no NPK fertiliser application); H2 (leaf harvesting of OFSP)).

- **Amaranth and Spider flower:**

Nutritional yield for Fe, Zn, and β-carotene for Amaranth and Spider flower were calculated and analyses of variance conducted. Results indicate that there were no statistically significant ($p > 0.05$) interaction effect between W, F, and H for Fe, Zn, and β-carotene NY for the 2013/14 and 2014/15 seasons (Tables 4.15 and 4.16). However, there were significant differences for F and C, while there were no significant differences for W, W, and F, W and C, and F and C (Tables 4.15 and 4.16). Table 4.21 presents treatment means for Fe, Zn and β-carotene NY for Amaranth and Spider flower. The 2013/14 results show that under optimum (W1F1) conditions, Amaranth NYs for Fe, Zn, and β-Carotene were 593 g ha^{-1}, 31 g ha^{-1}, and 372 g ha^{-1}, respectively. However, by increasing fertility stress, Fe (346 g ha^{-1}), Zn (12 g ha^{-1}), and β-Carotene (111 g ha^{-1}) NYs decreased. The combined water and soil fertility stresses (W2F2) resulted in a sharp decrease in NY for Fe and Zn, as well as for β-carotene. These decreases were 152 g ha^{-1} for Fe NY, 5.53 g ha^{-1} for Zn NY, and 42.4 for β-carotene NY (Table 4.21). The highest Fe (638 g ha^{-1}), Zn (34 g ha^{-1}) and β-carotene (510 g ha^{-1}) NYs were obtained from the treatment combination of W2F1. For Spider flower, similar results were obtained, whereby increasing soil fertility stress resulted in a decrease in Fe (451 to 219 g ha^{-1}), Zn (21.2 to 6.9 g ha^{-1}) and β-carotene (214 to 26.8 g ha^{-1}) NYs. Moreover, the combined W2F2 stresses decreased Fe, Zn, and β-carotene NYs. The highest NYs for Spider flower were obtained from the W1F1 treatment combination for Fe, Zn and β-Carotene NYs (451 g ha^{-1}, 21.2 g ha^{-1} and 213 g ha^{-1}, respectively). For the 2014/15 season, similar trends for Amaranth and Spider flower were observed, whereby an increase in fertility stress resulted in a reduction in Zn and β-carotene NYs. Moreover, the combined W2F2 stresses decreased NYs for Fe, Zn and β-carotene (Table 4.21). Results of the study suggest that RPHs can harvest more Fe, Zn and β-carotene from Amaranth compared to Spider flower. In addition, Spider flower is more sensitive to fertility stress compared to Amaranth. Nutritional yield values obtained from the rain-shelter experiment are comparable with the Rooiland values for Fe, but are higher for Zn and β-carotene (Tables 4.5 and 4.21).

Table 4.21: Nutritional yield (g ha^{-1}) in terms of Fe, Zn and β-carotene for Amaranth and Spider flower

Treatments	2013/14			2014/15		
	Fe	Zn	β-carotene	Fe	Zn	β-carotene
W1 F1 A	593^{ab}	30.65^{ab}	372.1^{ab}	828.4^{bc}	**64.73^{a}**	944.6^{a}
W1 F2 A	345.5^{cde}	12.21^{cd}	110.9^{cd}	823.3^{bc}	62.91^{a}	397.2^{b}
W2 F1 A	**637.6^{a}**	**33.94^{a}**	**509.7^{a}**	**1346.6^{a}**	63.06^{a}	**1204.2^{a}**
W2 F2 A	151.9^{e}	**5.53^{d}**	42.4^{d}	1119.5^{ab}	**9.13^{b}**	**85.3^{c}**
W1 F1 SF	451.1^{abc}	21.2^{bc}	213.9^{bc}	702.7^{bc}	49.63^{a}	959.7^{a}
W1 F2 SF	219.2^{de}	6.91^{d}	**26.8^{d}**	520.8^{cd}	24.49^{b}	216.7^{bc}
W2 F1 SF	402.6^{bcd}	14.15^{cd}	152.4^{cd}	632.5^{cd}	51.42^{a}	948.4^{a}
W2 F2 SF	**162.9^{e}**	7.18^{d}	39.2^{d}	**211.2^{d}**	48.43^{a}	393.1^{b}

Column values followed by the same symbol are not statistically different at $p\leq0.05$. The bold and underlined values indicate highest treatment means, whereas, the bold values indicate the lowest treatment means (W1 (full irrigation amount); F1 (full NPK fertiliser application; W2 (supplemental irrigation); F2 (no NPK fertiliser application); A (Amaranth); SF (Spider flower)).

4.4.2.3 Nutritional water productivity

- **Orange fleshed sweet potato leaves:**

Nutritional water productivity values for Fe, Zn, and β-carotene were calculated and analyses of variance conducted. Results (2013/14) indicate that there were no statistically significant ($p>0.05$) interaction effect between W, F and H for Fe, Zn and β-carotene NWP. For the 2014/15 season, there was an interaction ($p\leq0.05$) effect between W, F and H for Zn and β-carotene NWP, whereas, there was no interaction ($p>0.05$) effect for Fe NWP (Table 4.7). However, for the 2014/15 season, there was a significant difference for W (Table 4.8), while were no significant differences F, H, W and F, W and H, F and H for both seasons (Tables 4.7 and 4.8). Table 4.22 presents treatment means for Fe, Zn and β-carotene NWP of OFSP leaves. For the 2013/14 season, Fe, Zn and β-carotene NWPs for OFSP leaves increased with increasing fertility stress. It increased from 107 to 258 mg m^{-3}, 8 to 11 mg m^{-3}, and 14.7 to 72.2 mg m^{-3}, respectively. Under combined water and soil fertility stresses (W2F2), NWPs for Fe, Zn, and β-carotene increased to 334 mg m^{-3}, 22.7 mg m^{-3}, and 90 mg m^{-3}, respectively. However, the highest NWPs for Fe and Zn were obtained from the W2F1H2 treatment combination, whereas, for β-carotene NWP the highest NWP was obtained from the W2F2H2 treatment combination. For the 2014/15 season, a similar trend was observed, whereby increasing soil fertility stress resulted in increasing NWPs for Fe and Zn, as well as for and β-carotene. However, the highest NWPs for Fe, Zn, and β-Carotene were obtained from the W2F1H1 treatment combination (Table 4.22). The main aim of NWP is to increase nutrition per unit of water used by crops (Renault and Wallender, 2000; Mabhaudhi et al., 2016). These results suggest that TVCs can be cultivated under low input (water and soil fertility stresses) agricultural practices and still obtain increased NWP for OFSP leaves for Fe, Zn and β-carotene. Annandale et al. (2012) reported OFSP leaves NWP values for Fe, Zn, β-carotene to be 29 mg m^{-3}, 15 mg m^{-3}, and 681 mg m^{-3}, respectively. These values are lower for Fe and Zn but higher for β-carotene when compared with the results of the present study. These differences could be attributed to the fact that the parameters (*i.e.* biomass, water use and NC used to calculate NWP were derived from different literature sources. Nutritional water productivity for OFSP leaves values obtained from the rain shelter experiment ranged as follows; (i) Fe from 371-816 mg m^{-3}, Zn from 25-37 mg m^{-3}, and β-carotene from 286-1197 mg 100 m^{-3} (Table 4.7). The NWP values from the rain-shelter experiment are comparable for Fe and Zn, whereas there is a large difference for β-carotene values, indicating a 10-fold higher NWP compared to the Rooiland experiment.

Table 4.22: Nutritional water productivity (mg m^{-3}) in terms of Fe, Zn and β-carotene for OFSP leaves

Treatments	2013/14			2014/15		
	Fe	**Zn**	**β-carotene**	**Fe**	**Zn**	**β-carotene**
W1 F1 H1	**107^{c}**	8.17^{cd}	**14.71^{c}**	277^{c}	16.49^{bc}	264.1^{bcd}
W1 F1 H2	248^{b}	15.03^{b}	72.22^{ab}	**257^{c}**	15.18^{bcd}	230.7^{cd}
W1 F2 H1	135^{c}	**6.41^{d}**	12.56^{c}	304^{bc}	13.5^{cd}	262.6^{bcd}
W1 F2 H2	258^{b}	11.22^{bc}	40.68^{bc}	268^{c}	**10.2^{d}**	**168.8^{d}**
W2 F1 H1	219^{b}	11.34^{bc}	19.92^{c}	**832^{a}**	**30.66^{a}**	**551.8^{a}**
W2 F1 H2	**382^{a}**	**26.59^{a}**	66.64^{ab}	579^{ab}	19.42^{bc}	359.8^{bc}
W2 F2 H1	137^{c}	8.93^{cd}	18.89^{c}	547^{abc}	17.52^{bc}	286.5^{bcd}
W2 F2 H2	334^{a}	22.65^{a}	**90.04^{a}**	371^{bc}	21.14^{b}	389.2^{b}

Column values followed by the same symbol are not statistically different at $p \leq 0.05$. The bold and underlined values indicate highest treatment means, whereas, the bold values indicate the lowest treatment means (W1 (full irrigation amount); F1 (full NPK fertiliser application; W2 (supplemental irrigation); F2 (no NPK fertiliser application); A (Amaranth); SF (Spider flower)).

- **Orange fleshed sweet potato storage roots:**

Nutritional water productivity for Fe, Zn, and β-carotene were calculated and analyses of variance conducted. Results indicate that there were no statistically significant ($p > 0.05$) interaction effect between W, F and H Fe, Zn, and β-carotene NWP for the 2013/14 and 2014/15 seasons (Tables 4.11 and 4.12). Table 4.23 presents treatments means for Fe, Zn and β-carotene NWPs for OFSP storage roots. The 2013/14 and 2014/15 results indicate that there was a slight reduction in Fe, Zn and β-carotene NWPs with increased water and soil fertility stresses (W2F2). For the 2013/14 season, the highest NWPs for Fe, Zn, and β-carotene of 100 mg m^{-3}, 46 mg m^{-3}, and 6129 mg m^{-3}, respectively, were induced by the W2F1H1 treatment combination. For the 2014/15 season, the highest NWPs for Fe, Zn and β-carotene were 2955 mg m^{-3}, 99 mg m^{-3}, and 900 mg m^{-3}, respectively, were induced by the W2F1H2 treatment combination (Table 4.23). These results suggest that deficit irrigation strategies can be implemented without negative effects on OFSP storage root NWPs for Fe, Zn and β-carotene. Moreover, OFSP leaves are more productive per unit of water for Fe and Zn NWPs, while an opposite result was observed for β-carotene NWP. Annandale et al. (2012) reported the following NWP values for OFSP tubers: 29 mg m^{-3} for Fe, 15 mg m^{-3} for Zn, and 221 mg m^{-3} for β-carotene. Except for Zn NWP, the values for Fe and β carotene reported in the present study are much higher than those of Annandale et al. (2012). An explanation for these discrepancies could be that the parameters used to derive NWP values were taken from diverse literature sources.

Table 4.23: Nutritional water productivity (mg m^{-3}) OFSP storage roots

Treatments	2013/14			2014/15		
	Fe	**Zn**	**β-carotene**	**Fe**	**Zn**	**β-carotene**
W1 F1 H1	84.39^{ab}	35.15^{abc}	4906^{ab}	1366^{b}	79.52^{ab}	5417^{ab}
W1 F1 H2	**61.12^{b}**	21.37^{de}	2875^{c}	1095^{b}	64.32^{bc}	**4130^{b}**
W1 F2 H1	64.05^{ab}	**17.64^{e}**	2401^{c}	1677^{b}	75.6^{abc}	7231^{ab}
W1 F2 H2	63.2^{b}	20.44^{de}	**2367^{c}**	1431^{b}	54.79^{bc}	4876^{b}
W2 F1 H1	**99.5^{a}**	**45.87^{a}**	**6129^{a}**	1964^{ab}	70.71^{bc}	6710^{ab}
W2 F1 H2	80.38^{ab}	23.75^{cde}	3841^{bc}	**2955^{a}**	**98.61^{a}**	**8998^{a}**
W2 F2 H1	69.73^{ab}	31.07^{bcd}	3911^{bc}	1557^{b}	**53.13^{c}**	5385^{ab}
W2 F2 H2	74.35^{ab}	38.1^{ab}	5234^{ab}	**979^{b}**	55.66^{bc}	5884^{ab}

Column values followed by the same symbol are not statistically different at $p \leq 0.05$. The bold and underlined values indicate highest treatment means, whereas, the bold values indicate the lowest treatment means (W1 (full irrigation amount); F1 (full NPK fertiliser application); H1 (no leaf harvesting of OFSP); W2 (Supplemental irrigation); F2 (no NPK fertiliser application); H2 (leaf harvesting of OFSP)).

- **Amaranth and Spider flower:**

Nutritional water productivity of Fe, Zn, and β-carotene for Amaranth and Spider flower was calculated and analysis of variance conducted. Results (2013/14) indicate that there were no statistically significant ($p>0.05$) interaction effect between W,F, and H for Fe, Zn, and β-carotene NWP for the 2013/14 and 2014/15 seasons. However, there were significant differences for W and F during the 2013/14 and 2014/15 seasons (Tables 4.15 and 4.16). Table 4.24 presents Fe, Zn, and β-carotene NWPs for Amaranth and Spider flower. For Amaranth and Spider flower, the 2013/14 and 2014/15 results indicate that W and F played a significant role in NWPs for Fe, Zn, and for β-Carotene. Increased F stress resulted in increased NWPs for Fe, Zn, and for β-carotene until it reached a threshold of water and no soil fertility stress (W2F1). Continued increase in water and soil fertility stresses (W2F2) resulted in decreased NWPs for Fe, Zn, and β-Carotene. A similar trend was observed for Spider flower, whereby, the highest threshold was reached under the W2F1 treatment combination. Thereafter, NWP for Fe and Zn, as well as for β-carotene decreased. The highest NWPs for the 2013/14 season were obtained with the W2F1C treatment combination for Fe (1247 mg m^{-3}), and with W2F1A for Zn (66 mg m^{-3}) and for β-carotene (984 mg m^{-3}). For the 2014/15 season, the highest NWPs for Fe (1208 mg m-3), Zn (57 mg m^{-3}) and for β-carotene (1105 mg m^{-3}) were obtained from the W2F1A treatment combinations (Table 4.26). Spider flower NWP values for the rain shelter experiment ranged from 1336 to 2174 mg m^{-3} for Fe, 141 to 268 mg m^{-3} for Zn, and 1282 to 3030 mg m^{-3} for β-carotene. Amaranth NWP values for the rain-shelter experiment ranged from 569 to 1579 mg m^{-3} for Fe, 106 to 217 mg m^{-3} for Zn, and 1392 to 4846 mg m^{-3} for β-carotene. These results suggest that there is a large variation in NWP values within the same species and climatic conditions. The major reason for this variation might have been caused by different experimental sites, which varied in management practices and soil fertility.

Table 4.24: Nutritional water productivity (mg m^{-3}) for Amaranth and Spider flower

Treatments	**2013/14**			**2014/15**		
	Fe	**Zn**	**β-carotene**	**Fe**	**Zn**	**β-carotene**
W1 F1 A	765.5^{ab}	39.5^{bc}	477.4^{b}	471.5^{b}	36.93^{c}	538.6^{b}
W1 F2 A	396.5^{b}	11.39^{d}	117.1^{de}	481.3^{b}	36.82^{c}	238^{cd}
W2 F1 A	1237.2^{a}	**66.04^{a}**	**983.9^{a}**	**1208.4^{a}**	**57.47^{a}**	**1104.7^{a}**
W2 F2 A	624.1^{ab}	25.86^{bcd}	186.6^{cde}	982.5^{a}	42.57^{bc}	354.7^{bc}
W1 F1 SF	750.9^{ab}	37.83^{bc}	380.8^{bcd}	333.7^{bc}	23.27^{c}	450.4^{bc}
W1 F2 SF	**260.4^{b}**	**8.18^{d}**	**33.7^{e}**	**103.5^{d}**	**5.13^{d}**	**42.4^{d}**
W2 F1 SF	**1246.6^{a}**	43.97^{ab}	443.7^{bc}	639.7^{a}	53.68^{ab}	1002.8^{a}
W2 F2 SF	293.5^{b}	13.15^{cd}	71.4^{e}	216.9^{cd}	9.5^{d}	88.3^{d}

Column values followed by the same symbol are not statistically different at $p \leq 0.05$. The bold and underlined values indicate highest treatment means, whereas, the bold values indicate the lowest treatment means (W1 (full irrigation amount); F1 (full NPK fertiliser application); W2 (supplemental irrigation); F2 (no NPK fertiliser application); A (Amaranth); SF (Spider flower)).

4.5 Summary and conclusions

The main aim of this study was to assess the NC, NY and NWP for Amaranth, Spider flower, OFSP leaves and storage roots, for selected micronutrients (Fe and Zn) and β-carotene. Swiss chard was used as a reference crop for the rain-shelter experiment. Main findings of the study indicate that Spider flower is highly nutritious in Fe, Zn and β-carotene when compared to Amaranth, OFSP leaves and Swiss chard. The highest nutrient contents for Fe and Zn were obtained from the severely water stressed treatment, whereas, and for β-carotene from the no water stress treatment. However, the highest NYs for Fe, Zn and β-carotene were obtained from OFSP leaves, Swiss chard and Amaranth under no water stress, respectively. The highest Fe and Zn NWPs were obtained for Spider flower with the severe water stress treatment, whereas and the highest β-carotene NWP was obtained for Amaranth with the moderate water stress treatment. These results suggest that TVCs are more productive per unit of water used in the production of Fe, Zn and β-carotene. Therefore, TVCs can be cultivated under rainfed conditions and contribute to NFS of RPHs.

The main findings of the open field experiment at Rooiland indicate that OFSP leaves are higher in Fe and Zn NCs, whereas, the storage roots are higher in β-carotene. Moreover, Amaranth and Spider flower are higher in Fe and Zn compared to OFSP leaves and storage roots, but lower in β-carotene content. When comparing the two production systems: (i) low optimum production (supplemental irrigation and no fertilizer application) and (ii) high optimum production (full irrigation and fertilizer application), the main findings of this study indicate that NC of OFSP leaves and storage root will be higher under supplemental irrigation. However, OFSP storage roots are more sensitive to low fertilizer input than the leaves. Moreover, Amaranth NC is higher in micronutrients (Fe, Zn, and β-carotene) compared to Spider flower. The selected crops can be ranked as follows from highest to lowest when considering the quantity micronutrients (Fe, Zn and β-carotene) which can be harvested per season: For Fe: (i) Amaranth (1347 g ha^{-1}), (ii) OFSP leaves (1076 g ha^{-1}), and (3)OFSP storage roots (732 g ha^{-1}); for Zn: (i) OFSP storage roots(129 g ha^{-1}), (ii) OFSP leaves (68 g ha^{-1}), and (3) Amaranth (65 g ha^{-1}); and for β-carotene: (i) OFSP storage roots (27089 g ha^{-1}), (ii) OFSP leaves (489 g ha^{-1}), and (3) Amaranth (345 g ha^{-1}). For NWP, the selected crops can be ranked as follows from highest to lowest: Fe: (i) OFSP storage roots (2955 mg m^{-3}), (ii) Spider flower- (1247 mg m^{-3}), and (3) OFSP leaves (832 mg m^{-3}); Zn: (i) OFSP storage roots (99 mg m^{-3}), (ii) Amaranth (66 mg m^{-3}), and (3) OFSP leaves (31 mg m^{-3}); β-carotene: (i) OFSP storage roots (8998 mg m^{-3}), (ii) Amaranth (1105 mg m^{-3}), and (3) OFSP leaves (552 mg m^{-3}). These results suggest that OFSP is highly productive per unit of water used in the production Fe, Zn, and β-carotene. Moreover, OFSP can be utilized as a leafy vegetable and for its storage roots.

Although it was part of the present study, cognizance is taken of the fact that, in addition to considering the nutrient content of foods, nutrient bioavailability (amount of a nutrient absorbed and available for normal physiological functions) should also be taken into consideration. Different nutrients react differently once ingested into the human gastro-intestinal tract, and can be influenced by various factors including the quality of the food source and the matrix in which it is consumed, the composition of the whole meal, inhibitors, enhancers and the status of the host. Bioavailability cannot attain a constant calculated value, and needs to be considered with caution as multiple factors, both intrinsic and extrinsic, can notably affect the bioavailability of nutrients present in food and non-food sources of nutrients.

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5 MODELLING CROP WATER PRODUCTIVITY OF TRADITIONAL VEGETABLE CROPS

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5.1 Introduction

South Africa is facing three interrelated challenges which are already pressing and need to be solved, namely population growth, water scarcity, and nutritional food insecurity. The human population is predicted to reach 68.8 million by the year 2030 (Go et al., 2013). Rainfall variability, drought, and extreme weather events are expected to reduce water availability, which will result in a gap of about 17% between water demand and supply by 2030 if no significant gains occur (WWF-SA, 2011; Muller et al., 2009). Food and nutrition security (FNS) at household level is also projected to worsen in the years to come. The SANHANES-1 survey of 2012 indicated that 45.6% of households were food secure, 28.3% at risk of hunger, and 26% were experiencing hunger (Shisana et al., 2014). However, South Africa still faces high rates of FNS at household level, particularly in rural areas, affecting resource poor households (RPHs). Agriculture has to play a major role in producing higher crop yield than the current yield levels. The major challenge is that agro-ecological zones vary in climate, soil quality, and access to water which determines their production potential (Ittersum et al., 2013). South Africa is left with no option other than introducing drought tolerant and nutritionally important crops that have a potential of improving crop water productivity (‘‘more crop per drop’’).

However, the agronomical characteristics (yield response to water and soil fertility) of traditional vegetable crops (TVCs) are unknown. Introducing TVCs to South African farming systems requires knowledge of yield response in different agro-ecological zones, soil type, and agronomic management practices. The ideal way to overcome such complex challenges is by conducting experiments in different part of the country where climate, soil and management practices (e.g. irrigation and nutrient management) varies. This approach, however, is an expensive and time consuming practice to implement (Lorite et al., 2013; Xiangxiang et al., 2013). In the last three decades, considerable progress has been made in advancing the scope and power of crop modelling. Properly calibrated crop models have been used to assess the impact of climate, soil, and management practices on crop growth. Predicting water productivity (WP) of TVCs, using a modelling approach, could assist to explore the extent of TVCs production under different climate, soil and management options in South Africa. In this study, the Food and Agricultural Organization (FAO) AquaCrop model (Raes et al., 2009) was used to assess the effect of climate, soil properties, and management factors (Lorite et al., 2013; Tittonell and Giller, 2013) on WP of TVCs in different locations and agro-ecological zones in South Africa (Lorite et al., 2013; Xiangxiang et al., 2013). The objective of this study was to calibrate and evaluate the FAO AquaCrop model and estimate WP of TVCs (Amaranth, Spider flower and OFSP for different irrigation schemes (Dingleydale, Dzindi and Tugela Ferry) situated in different climate zones in South Africa.

5.1.1 Main agro-ecological zones of South Africa

South Africa is divided into four main agro-ecological zones which differ mostly in rainfall distribution. The Northern Cape (desert) receives 200 mm of summer rainfall, whilst the Eastern Cape, Free State, Gauteng, Limpopo, Mpumalanga, and North West receive (steppe) rainfall ranging from 400-600 mm. KwaZulu-Natal (sub-tropical wet) receives the highest rainfall of 800 mm (Table 5.1).

Table 5.1: Main agro-ecological zones and provinces in South Africa (Adapted from Joint Agriculture weather facility, 1999)

Agro-ecological zone	**Provinces**	**Mean rainfall (mm)**	
		Summer	**Winter**
Desert	Northern Cape	200	100
Steppe (Arid)	Eastern Cape	400	150
	Free State	500	100
	Gauteng	600	150
	Limpopo	600	150
	Mpumalanga	400	200
	North West	600	150
Sub-tropical wet	KwaZulu-Natal	800	200
Mediterranean	Western Cape	150	400

5.2 Materials and methods

Two years data (2013/14 and 2014/15 growing seasons) collected from the rain-shelter experiment at the Agricultural Research Council, Vegetable and Ornamental Plant (ARC-VOP), Roodeplaat, Pretoria (25^o 60’ S; 28^o 35’ E; 1168 masl), Gauteng Province were used for the AquaCrop model calibration and validation to simulate biomass, storage root yield, and SWC. Experimental design, soil characteristics and climate, and agronomic practices for the rain-shelter experiment have been explained in Chapter 3, Section 3.3.1.

5.3 Data collection for model parameterisation

The experiment was designed to collect data that would be relevant to develop crop parameters for modelling of *Amaranthus cruentus* (Amaranth), and *Cleome gynandra* (Spider flower) and *var. Bophelo* OFSP. Soil physical characteristics such as soil texture, field capacity (FC), permanent wilting point (PWP), bulk density, and saturated hydraulic conductivity (K_s) were determined to develop the soil file for the AquaCrop model. Meteorological data were collected from an automatic weather station which is situated approximately 50 m away from the rain-shelter and the following sets of data were downloaded on a daily basis: Minimum and maximum temperature (^oC), minimum and maximum relative humidity (%), rainfall amount (mm), wind speed (m s^{-1}), solar radiation, and sunshine duration (hours). These were used to develop the climate file for the AquaCrop model. Leaf area index was measured weekly, using a LAI-2000 leaf area meter, to monitor the effect of different irrigation amounts on crop growth during the growing season. However, measurements of LAI were not used to calculate canopy cover

(CC) for AquaCrop. Instead, diffuse non-interceptance (DIFN), which is an output of the LAI 2200 canopy analyser, was used to determine CC. Diffuse non-interceptance is calculated by integrating the gap fraction (GAPS) to obtain a value indicative of the fraction of the sky that is not obscured by the plant canopy. The value of DIFN ranges from 0 (no sky visible to the sensor) to 1 (no canopy obscuring the sun). It may be argued that DIFN is more indicative of actual canopy cover than LAI, hence there was no need to convert LAI to CC (Mabhaudhi et al., 2013). Therefore, CC was obtained from DIFN as follows; CC = 1 – DIFN. Stomatal conductance was measured using a leaf porometer (model SC-1, decagon Devices, USA) and it was used to determine crop sensitivity to water stress for the AquaCrop model. The biomass, stomatal conductance, and DFIN datasets were used to develop the crop file for the AquaCrop model. Weather data (2009-2014), physical, and chemical soil characteristics for were obtained from the ARC-ISCW. The soil textural class characteristics (% sand, % silt, and % clay) were used to estimate hydraulic properties (FC, PWP, saturation, and K_s) using the soil water characteristics hydraulic properties calculator (Saxton and Rawls, 2009).

5.4 AquaCrop model description

AquaCrop is a water driven model which simulates yield response to water (i.e. WP). Prior to AquaCrop, the Doorenbos and Kassam (1979) approach was utilized to determine the yield response to water for herbaceous and tree crops – which led to the evolution of the AquaCrop model (Steduto et al., 2009). The added value of the AquaCrop model is that it separates evapotranspiration (ET) into two separate components, namely evaporation and transpiration. The model does not consider non-productive use of water (evaporation). Secondly, AquaCrop uses canopy cover (CC) instead of the LAI index – CC is directly involved in water loss. However, it is a challenge to measure CC directly from the field. During simulation the model calculates final yield as a result of dry biomass partitioned into the yield component, which is determined by the harvesting index (equation 1):

$$Y = WP\ (\sum Tr/ETo))\ x\ HI \ldots\ldots\ldots\ldots(1)$$

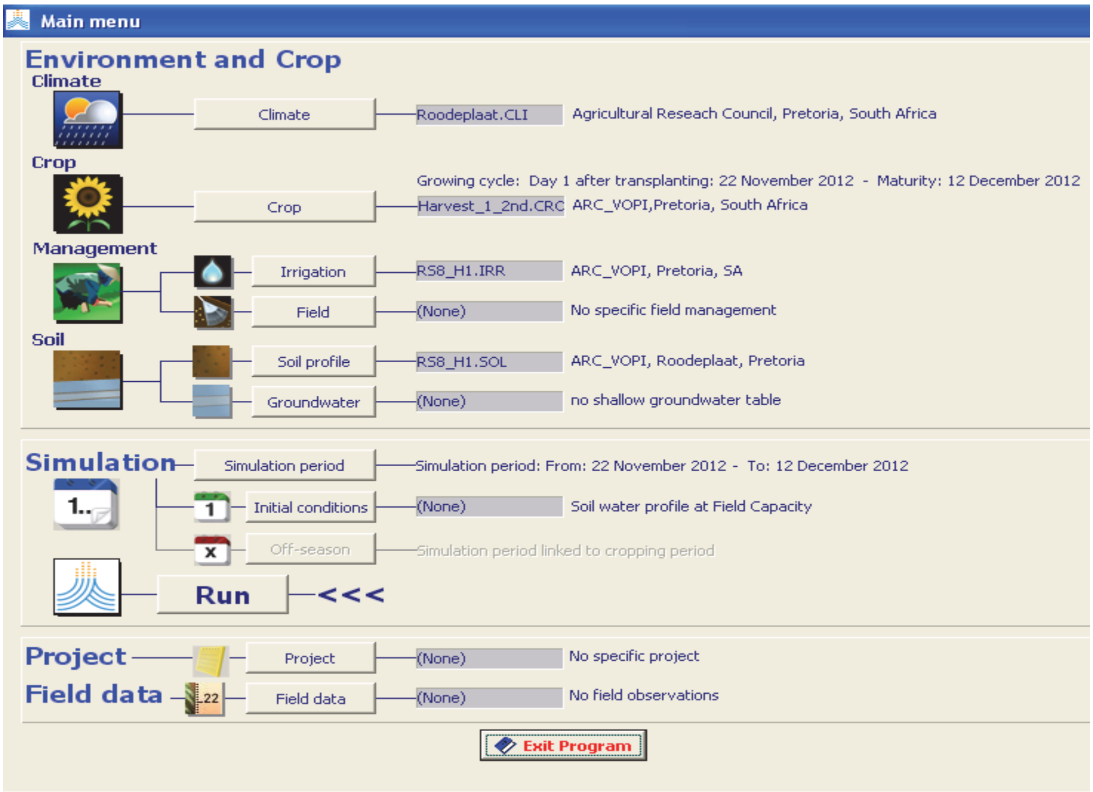
Where Y = yield, WP = water productivity, Tr = transpiration, ET_0 = reference evapotranspiration, and HI = harvesting index. Details of underlying concepts, principles and conceptual framework are explained in Steduto et al. (2009). The AquaCrop model consists of four important files which are menu driven and well developed for the user interface. These are climate, crop, irrigation scheduling, and soil files, respectively (Figure 5.1). To calibrate the AquaCrop model, these files have to be created in the model and input data based on actual measurements during experimentation be utilized.

5.4.1 Climate file

The climate file consists of temperature (minimum and maximum), reference evapotranspiration, rainfall amount, and atmospheric carbon dioxide concentration. When creating this file, the user has to select the above mentioned weather parameters individually, as well as daily input climatic data based on real dates of the experiment. The CO_2 is a default parameter (369.41 mg kg^{-1}) supplied with AquaCrop.

5.4.2 Crop file

This is one of the most important files in AquaCrop. When creating it, the modeller has to choose between various crop options which are fruit/grain crops, leafy vegetables and root or tuber crops. Moreover, the photosynthetic pathway (C3 or C4) of the crop is selected. This file consists of all the crop physiological components such as planting date, canopy development stages, the length of the root at harvest, base, and upper temperature. Details of this file are explained in FAO (2013). Amaranth, Spider flower, and OFSP files were created based on conditions under which the selected crops were grown.



Climate — Roodeplaat.CLI — Agricultural Reseach Council, Pretoria, South Africa

Growing cycle: Day 1 after transplanting: 22 November 2012 - Maturity: 12 December 2012

Crop — Harvest_1_2nd.CRC — ARC_VOPI,Pretoria, South Africa

Irrigation — RS8_H1.IRR — ARC_VOPI, Pretoria, SA

Field — (None) — No specific field management

Soil profile — RS8_H1.SOL — ARC_VOPI, Roodeplaat, Pretoria

Groundwater — (None) — no shallow groundwater table

Simulation period — Simulation period: From: 22 November 2012 - To: 12 December 2012

Initial conditions — (None) — Soil water profile at Field Capacity

Off-season — Simulation period linked to cropping period

Project — (None) — No specific project

Field data — (None) — No field observations

Figure 5.1: Main window menu for the AquaCrop model (Raes et al., 2009)

5.4.3 Irrigation scheduling file

When creating the irrigation scheduling file, the user has to select the type of irrigation system used, irrigation scheduling dates, the depth of application and the quality of water if drip irrigation system was used. In the rain-shelter experiment, compensating non-leaking (CNL) Urinam drip lines of 2.3 L h^{-1} were designed to irrigate each plot separately. The system consisted of the following components: a pump; filters, solenoid valves, water metres, water mark, control box, online drippers, 2000 litres JOJO tank, mainline, sub-main and laterals. Based on the soil water balance approach, irrigation was scheduled as a function of the three levels of application, namely when 30% (I_1), 50% (I_2) and 80% (I_3) of plant available water (PAW) was depleted.

5.4.4 Soil file

The soil file requires the following data: soil textural class description, depth of the soil (m), FC (%), PWP (%), saturation (%) and K_s (mm day^{-1}). Prior to the experiments, a soil profile was dug to a depth of 1 metre and soil samples were taken to be analysed for soil textural class characteristics. Field capacity and PWP values were determined using the gravimetric method as explained by Dasherberg and Dalton (2016). All these parameters were incorporated when creating the soil file based on soil characteristics of each rain shelter.

5.5 Model calibration and validation

The AquaCrop model was calibrated with the 2013/14 season optimum water treatment (irrigating back to field capacity when 30% of PAW was depleted) and validated with the 2014/15 season optimum water treatment. The model was calibrated by trial and error iterations, by fine tuning some parameters until the model matches measured data (Janssen and Heuberger, 1995). The calibration processes involved creating the crop file in AquaCrop and provide it with the initial canopy cover (CC_o), maximum CC reached, planting density, days to maturity (converted to growing day degree (GDD), maximum rooting depth, as well as base and maximum temperature for crop development. The model was able to estimate the canopy growth coefficient (CGC) and canopy decline coefficient (CDC). The normalized WP was chosen based on crop species whether it was a C3 or C4 crop, and the harvesting index was calculated from destructive data collected every harvest for Amaranth and Spider flower, and once for OFSP. The model was calibrated by comparing observed dry biomass (B), dry yield (Y), and CC with simulated B, Y, and CC. The procedure which was followed in calibrating the model for Amaranth and Spider flower was that each harvest was calibrated and validated separately. The assumption was made that after the first harvest, 5 to 10% of the CC was left on the soil surface, which was used as basis for initial CC for the other harvests.

The AquaCrop model estimates water use based on four stress factors (Ks) factors, namely canopy expansion, stomatal closure, early canopy senescence, and aeration stress (Mabhaudhi et al., 2014; Vanuytrecht et al., 2014). Amaranth and Spider flower are classified as C4 plants, meaning they can withstand water stress because of lower intercellular CO_2 concentration (C_{ci}) compared to C3 plants, thus they produce more dry matter per unit water than C3 plants (Vincent and van Halsema, 2012). These crops were classified as moderately sensitive to water stress for canopy expansion, stomatal closure, and extremely tolerant to early canopy senescence. Because these crops do not grow under saturated conditions, they are classified as very sensitive to water logging. Table 5.2 summarizes parameters developed for Amaranth, Spider flower, and OFSP for the AquaCrop model. To model for soil fertility stresses, AquaCrop uses a semi-quantitative assessment which determines the degree of stress that a crop experiences from nutrient deficiencies. This corresponds to maximum dry above ground biomass that can be expected in a soil fertility stressed environment with reference to stress free conditions (Van Gaelen et al., 2014). The effect of soil fertility stress in crop production affects canopy cover development and biomass production. Three adaptations for CC development can be handled by AquaCrop: (i) Reduced canopy expansion thus slower canopy development, (ii) reduced maximum canopy cover, hence less dense canopy, and (iii) steady decline of CC that is reached at mid-season. To simulate responses to soil fertility stress, AquaCrop uses three stress coefficients: canopy expansion (Ks_{exp}), maximum canopy cover

(Ks_{CCx}), biomass water productivity (Ks_{wp}), and canopy decline ($Fc_{Decline}$). To calibrate crop response to soil fertility stress, a calibration procedure has been incorporated in the latest AquaCrop software (version 4) which requires field measurements for Ks_{CCx} reached, biomass and description of observed $Fc_{Decline}$ during the season for a soil fertility stressed field in comparison to a reference field (Van Gaelen et al., 2014). Once crop response to soil fertility is calibrated, crop production can be simulated for specified soil fertility levels under different environmental and management conditions (Van Gaelen et al., 2014).

5.5.1 Model evaluation

Model evaluation is very important to test any crop model performance by comparing experimental data with simulated data. Crop models can be evaluated using statistics such as (i) coefficient of determination (R^2) that indicates the proportion of the variance in the dependent variable (Y_{var}) that is predictable from the independent variable (X). R^2 ranges from 0 to 1, with higher values indicating less error variance, with values > 0.5 regarded as acceptable, (ii) Root Mean Square Error (RMSE= $\sum \sqrt{(Yobs - Y\,sim)^2}$) is a frequently used measure of the difference between values predicted by a model and the values actually observed from the experiment that is being modelled. These individual differences are also called residuals, and the RMSE serves to aggregate them into a single measure of predictive power. The lower the RMSE, the better the model performance, and (iii) the RMSE observations standard deviation ratio (RSR=$^{RMSE}/_{STDVobs}$) which standardizes the RMSE, using the observations of standard deviation (STDVobs). It combines the error index and scaling/normalization factor such that the resulting statistic and reported values can apply to various constituents. It varies from 0 (indicating perfect simulation) to a large positive value. The lower the RSR, the better the model simulation performance (Moriasi et al., 2007).

5.6 Irrigation scheme selection

For the purpose of modelling growth and production of Amaranth, Spider flower, and OFSP for different scenarios and WP; three schemes which are representative of different agro-ecological zones of South Africa and potential locations, where the selected crops can be commercialized, were selected. These were Dingleydale, Dzindi and Tugela Ferry. Climate data (2009-2014), physical, and chemical soil characteristics for selected locations were obtained from the Agricultural Research Council- Soil, Climate, and Water (ARC-SCW). The soil textural class characteristics (% sand, % silt, and % clay) were used to estimate hydraulic properties (FC, PWP, saturation and K_s) using the Soil Water Characteristics Hydraulic Properties calculator. The following scenarios which represent the farming characteristics of RPHs were considered:

- Water regime 1 (irrigating back to field capacity when 30% of plant available water is depleted) x full fertilizer application (no soil fertility stress).
- Water regime 1 x no fertilizer application (severe soil fertility stress).
- Water regime 2 (Irrigating back to field capacity when 80% of plant available water is depleted) x full fertilizer application.
- Water regime 2 x no fertilizer application

Figure 5.2 shows a map of the locations of the irrigation schemes where crop modelling scenarios were carried out.

Table 5.2: Crop parameters for calibration of Amaranth, Spider flower and OFSP

Parameter	**Amaranth**				**Spider flower**				**OFSP**
	H1	**H2**	**H3**	**H4**	**H1**	**H2**	**H3**	**H4**	**H1**
Initial canopy cover (%)	2.27	4.07	4.07	3.57	0.17	5.07	4.07	4.07	0.63
Maximum canopy cover (%)	60	72	82	80	76	80	80	92	98
Canopy growth coefficient (%/GDD)	2.816	2.523	2.373	1.818	2.811	2.59	2.56	2.767	1.436
Canopy decline coefficient (%/GDD)	0.435	0.391	0.409	0.147	0.472	0.509	0.169	0.667	0.355
Minimum rooting depth (m)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Maximum Effective rooting depth (m)	0.8	0.9	0.9	0.9	0.6	0.8	0.9	0.9	2
Maximum rooting depth (DD)	235	244	249	263	111	177	199	168	1885
Rooting Depth shape factor (ratio)	1	1	1	1	1	1	1	1	1.5
Base Temperature (^oC)	8	8	8	8	8	8	8	8	10
Upper Temperature (^oC)	32	32	32	32	32	32	32	32	35
Upper Threshold for canopy expansion (Pupper)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	20
Lower Threshold for canopy expansion (Plower)	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55
Upper Threshold for stomata closure	0.55	0.55	0.55	0.55	0.45	0.45	0.45	0.45	0.55
Senescence stress coefficient (Pupper)	0.55	0.55	0.55	0.55	0.45	0.45	0.45	0.45	0.65
Aeration stress (%)	10	10	10	10	10	10	10	10	15
Normalized crop water productivity (g m^2)	30	30	30	30	30	32	30	30	16
Reference Harvesting Index (%)	80	85	75	80	70	80	80	90	50
Duration of biomass build up (harvest) (GDD)	235	260	265	355	307	204	215	204	2053
Start of canopy Senescence (GDD)	235	260	265	355	307	204	215	204	1708
Maximum canopy cover (GDD)	235	260	265	355	307	204	215	204	592

H1……Hn: harvesting period

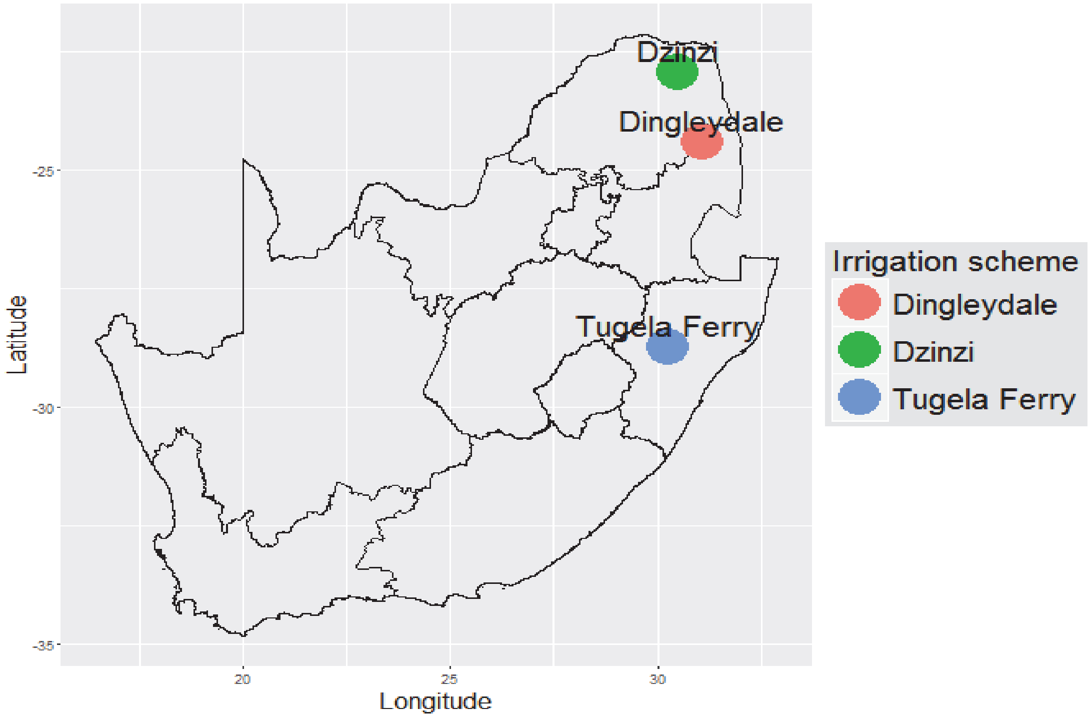


Figure 5.2: Map showing irrigation schemes where crop modelling scenarios were carried out

5.7 Results and discussion

5.7.1 Calibration and validation for OFSP

Calibration results for CC, profile soil water content (SWC), biomass (B), evapotranspiration (ETa), and storage root yield (Y) for OFSP are presented in Figure 5.3 and Table 5.3, respectively. Results show a good fit between measured and simulated values. The coefficient of determination (R^2) for CC and SWC was 0.77. The RMSE was 12.1 for CC, 26.9 for SWC, 1.26 for B, 0.12 for Y, and 27.1 for ETa. The RSR value for CC was 0.61 and 0.85 for SWC, which indicates a goodness of fit between measured and simulated values. Validation of the AquaCrop model showed a good fit for CC (R^2= 0.99; RMSE= 4.98; RSR=0.18), SWC (R^2= 0.64; RMSE= 26.9; RSR=0.89), B (RMSE= 1.26), ETa (RMSE= 19), and storage root yield (RMSE= 1.7).

5.7.2 Calibration and validation for Amaranth

Calibration results for CC, SWC, B, and ETa for Amaranth are presented in Table 5.4 and Figure 5.4. Results show a good relationship between measured and simulated values. The coefficient of determination (R^2) for CC was 0.96, 0.95 for biomass, 0.99 for ETa, and 0.73 for SWC, respectively. The RMSE was very low which indicate good model performance. It was 2.5 for CC, 0.04 for biomass, 15.29 for ETa, and 1.67 for SWC. The RSR showed a good model performance for CC (0.096), biomass (1.58), ETa (11.1), and SWC (0.29). The AquaCrop model was validated for CC, B, and ETa. The model showed good model performance and this is evidenced by high R^2 for CC (R^2= 0.94), B (0.73), and ETa (0.72). In addition, the RSR indicated a good relationship between measured and simulated values (0.22 for CC, 0.38 for SWC, 0.88 for B, and 15.3 for Eta). These results suggest that the AquaCrop model was successfully validated for CC, B, and ETa as demonstrated by good R^2, RMSE, and RSR values for selected parameters of Amaranth.

Table 5.3: Calibration and validation for OFSP

		Observed	Simulated	Deviation	RMSE
Calibration					
Biomass	(t ha^{-1})	20.5	21.76	-0.06	1.26
Storage root	t ha^{-1})	12.9	12.78	0.01	0.12
ETa	(mm)	586	558.9	0.05	27.1
Validation					
Biomass	(t ha^{-1})	27.3	23.5	0.14	3.8
Storage root	t ha^{-1})	14.7	13	0.12	1.7
ETa	(mm)	596.4	577.4	0.03	19

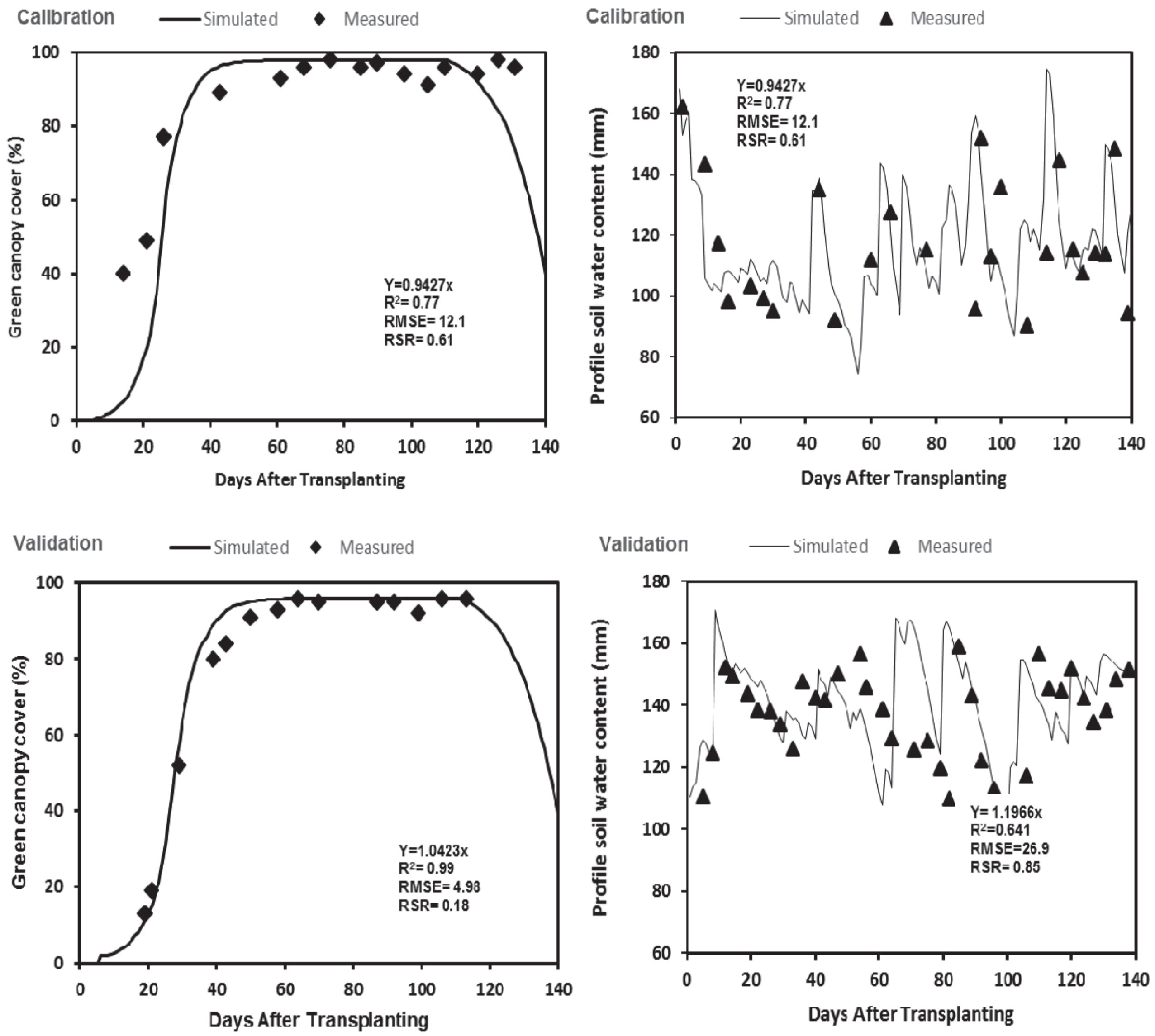


Figure 5.3: OFSP calibration and validation for canopy cover (CC) and soil water content (SWC)

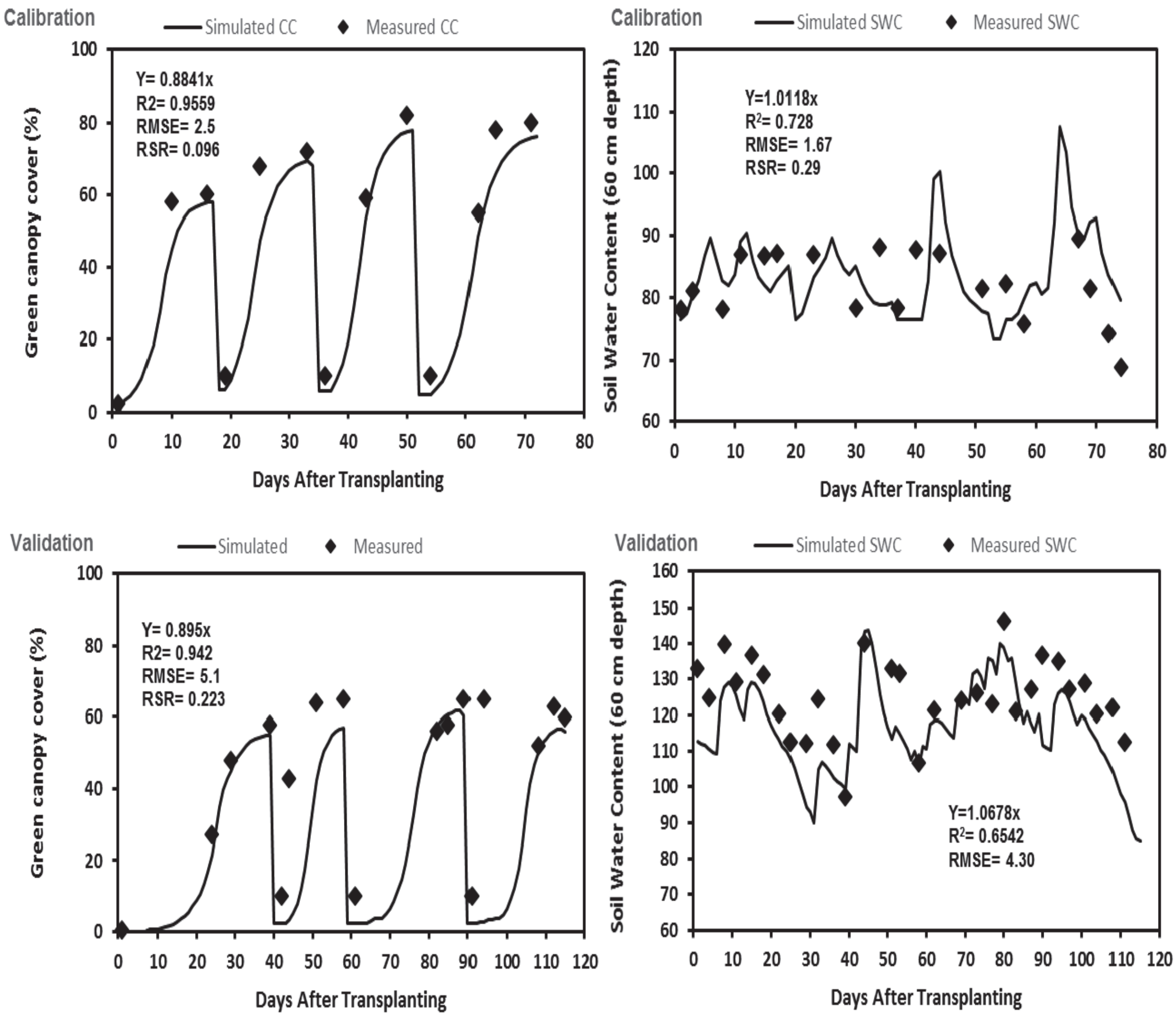


Figure 5.4: Amaranth calibration and validation for canopy cover (CC) and soil water content (SWC)

Table 5.4: Calibration and validation for Amaranth

	Biomass (t ha^{-1})						Evapotranspiration (mm)					
Calibration	**Obs**	**Sim**	**dev**	**RMSE**	**R^2**	**RSR**	**Obs**	**Sim**	**dev**	**RMSE**	**R^2**	**RSR**
H1	2.43	3.74	-0.54	1.31	0.95	1.58	72	78	-0.09	6.4	0.99	11.06
H2	2.98	2.47	0.17	0.51	-	-	53	55	-0.03	1.6	-	-
H3	2.80	2.76	0.01	0.04	-	-	56	55	0.03	1.5	-	-
H4	3.80	3.08	0.19	0.72	-	-	58	66	-0.15	8.8	-	-
Total	**12.0**	**12.1**	**0.00**	**0.04**	-	-	**239**	**254**	**-0.06**	**15.29**	-	-
Validation												
H1	3.09	3.7	-0.20	0.61	0.73	0.88	79	75	0.05	3.6	0.72	15.3
H2	2.46	2.35	0.04	0.11	-	-	67	53	0.21	13.9	-	-
H3	2.95	3.28	-0.11	0.33	-	-	82	86	-0.04	3.7	-	-
H4	2.34	2.88	-0.23	0.54	-	-	51.7	56	-0.08	4	-	-
Total	**11**	**12**	**-0.13**	**1.37**	-	-	**280**	**270**	**0.04**	**9.84**	-	-

H1……Hn: harvesting period

5.7.3 Calibration and validation for Spider flower

Calibration results for CC, SWC, B, and ETa for Spider flower are presented in Table 5.5 and Figure 5.5. Results show a good relationship between measured and simulated values. The coefficient of determination (R^2) for CC was 0.94, 0.99 for biomass, 0.98 for ETa, and 0.81 for SWC. The RMSE was very low which indicates good model performance. It was 2.72 for CC, 0.29 for biomass, 6.82 for ETa, and 1.53 for SWC. The RSR shows a good model performance for CC (0.094), B (0.51), ETa (10.8), and SWC (0.26). The AquaCrop model was validated for CC, B, and ETa. The model showed good model performance which was evidenced by higher R^2 for CC (0.94), B (0.96), and ETa (0.99). In addition, the RSR indicated a good relationship between measured and simulated values. It was 0.068 for CC, 0.26 for SWC, 0.78 for B, and 18.4 for ETa. These results suggest that the AquaCrop model was successfully validated for CC, B and evapotranspiration as demonstrated by good R^2, RMSE, and RSR for selected parameters of Spider flower.

Table 5.5: Calibration and validation for Spider flower

	Biomass (t ha^{-1})						Evapotranspiration (mm)					
Calibration	**Obs**	**Sim**	**dev**	**RMSE**	**R^2**	**RSR**	**Obs**	**Sim**	**dev**	**RMSE**	**R^2**	**RSR**
H1	2.78	2.47	0.11	0.31	0.99	0.51	53	64.3	-0.21	11.3	0.98	10.8
H2	2.90	2.76	0.05	0.14	-	-	65	67.1	-0.03	2.1	-	-
H3	2.61	2.95	-0.13	0.34	-	-	70	51.4	0.26	18.1	-	-
H4	3.35	3.17	0.05	0.18	-	-	62	59.9	0.03	2.1	-	-
Total	**11.6**	**11.4**	**0.02**	**0.29**	-	-	**250**	**243**	**0.03**	**6.82**	-	-
Validation												
H1	2.69	2.59	0.04	0.1	0.96	0.78	69	61	0.11	7.7	0.99	18.4
H2	5.10	4.47	0.12	0.63	-	-	90	83	0.08	7.5	-	-
H3	3.27	3.25	0.01	0.02	-	-	62	52	0.16	10.2	-	-
H4	3.48	3.02	0.13	0.46	-	-	68.6	58	0.16	11	-	-
Total	**15**	**13**	**0.08**	**1.21**	-	-	**290**	**253**	**0.13**	**36**	-	-

H1……Hn: harvesting period

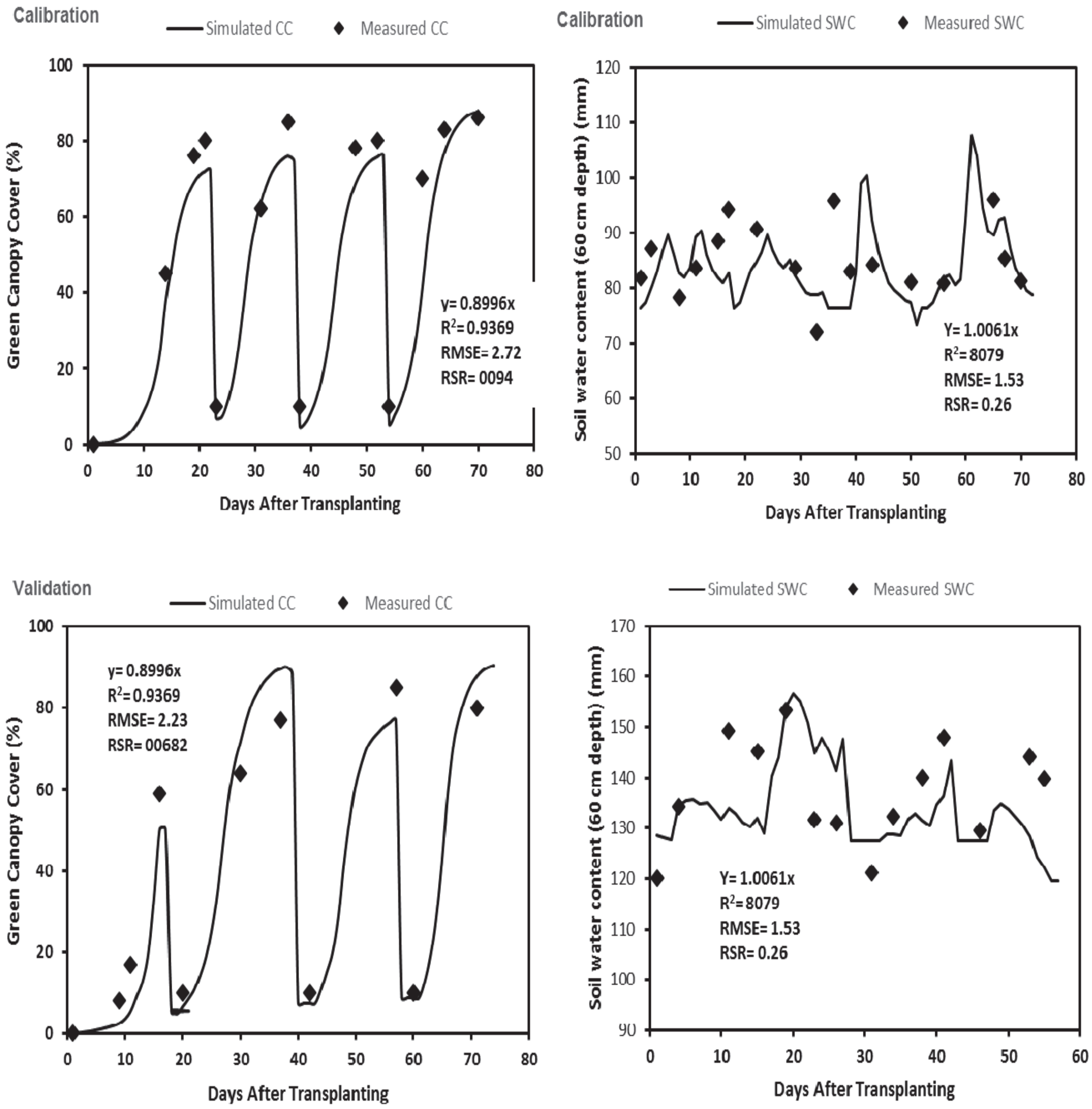


Figure 5.5: Spider flower calibration and validation for canopy cover (CC) and soil water content (SWC)

5.7.4 Irrigation scheme crop modelling

There are approximately 320 smallholder irrigation schemes covering 50, 000 ha of land in the former homelands of South Africa (Denison and Manona, 2007). These smallholder schemes were initiated for disadvantaged black people in resource poor areas, whose size is less than 5 ha per plot (Denison and Manona, 2007). The Dingleydale irrigation scheme is located in the former Bushbuckridge homeland, under the Bushbuckridge municipality. Major crops which are grown are vegetables (Cabbage, Swiss chard, onions, potatoes, and sweet potatoes) and maize. The Dzindi irrigation scheme is located in the former Venda homeland of South Africa, running from 6 km south west of Thohoyandou under the Thulamela municipality. Major crops that are grown are cabbage, Swiss chard, onions, Chinese cabbage, nightshade, groundnuts, sweet potato, and green pepper. The Tugela Ferry irrigation scheme is located in the midlands of KwaZulu-Natal, under the Msinga municipality. Msinga is situated in the dry to the semi-arid area and experiences very high temperatures of 44^{o}C in summer. Major crops that are produced are maize, pumpkins, beans, butternuts, Swiss chard, potatoes, onions, and sweet potatoes (Cousins, 2013). Table 5.6 below summarizes the characteristics of the selected irrigation schemes. Vapour pressure deficit is the difference between the vapour pressures inside the leaf compared to the vapour pressure of the air, *i.e.* the water in the leaf and the water and air mixture leaving the stomata is (more often than not) completely saturated (100% relative humidity). If the air outside the leaf is less than 100% relative humidity, there is potential for water vapour to enter the air because gasses and liquids like to move from areas of high concentration (in this example the leaf) into areas of lower concentration (the air). So, in terms of growing plants, the vapour pressure deficit can be thought of as the shortage of vapour pressure in the air compared to within the leaf itself (Just4growers, 2016). Figures 5.6, 5.7 and 5.8 present box plots showing the distribution of (a) monthly total rainfall, (b) monthly average minimum temperature, (c) monthly average maximum temperature, and (d) ET_0 for the Dingleydale, Dzindi and Tugela irrigation schemes, respectively. Edges of the boxes show the 25 and 75 percentile, the horizontal line inside the box is median, while the vertical line is minimum and maximum. The black dot lines are outliers. There is variation in terms of rainfall for the selected locations: Dzindi receives the highest rainfall (1166 mm), whilst Tugela Ferry receives the lowest rainfall (538 mm). The vapour pressure deficit for Dzindi, Tugela Ferry, and Dingleydale is higher during hundred DAT and lower towards the end of the growing period. Temperature and ET_0 plays a major role in plant growth. At high and very low temperatures plants tend to cease growth, whereas ET_0 determines how much water will the plant lose through the process of transpiration. Suitable temperatures (10°C to 35°C) are prevalent at the three locations for selected summer crops. For most of the selected summer TVCs, growth ceases below 8^{o}C, except for OFSP which have a base temperature of 10°C.

Table 5.6: Characteristics of the selected locations in South Africa

	Dzindi	**Tugela Ferry**	**Dingleydale**
Province	Limpopo	KwaZulu-Natal	Mpumalanga
Coordinates	23° 01’S; 30° 26’ E	28°44’0’’S, 30° 27’E	24°41’S, 31°10’E
Year established	1954	1902	1960
Community/ties	Itsani	Msinga	Dingleydale
Households	1080	37724	2227
Plot holders	106	1000	1317
Size of plot (ha)	1.28	3.37	3
Land size (ha)	136	837	1650
Area irrigated (ha)	136	540	-
Water source	Dzindi River	Thukela River	Sand River
Irrigation method	Gravity, pumped	Gravity, pumped	Gravity, pumped
Rainfall (mm)	< 500	700	600
Altitude (m)	712	699	478

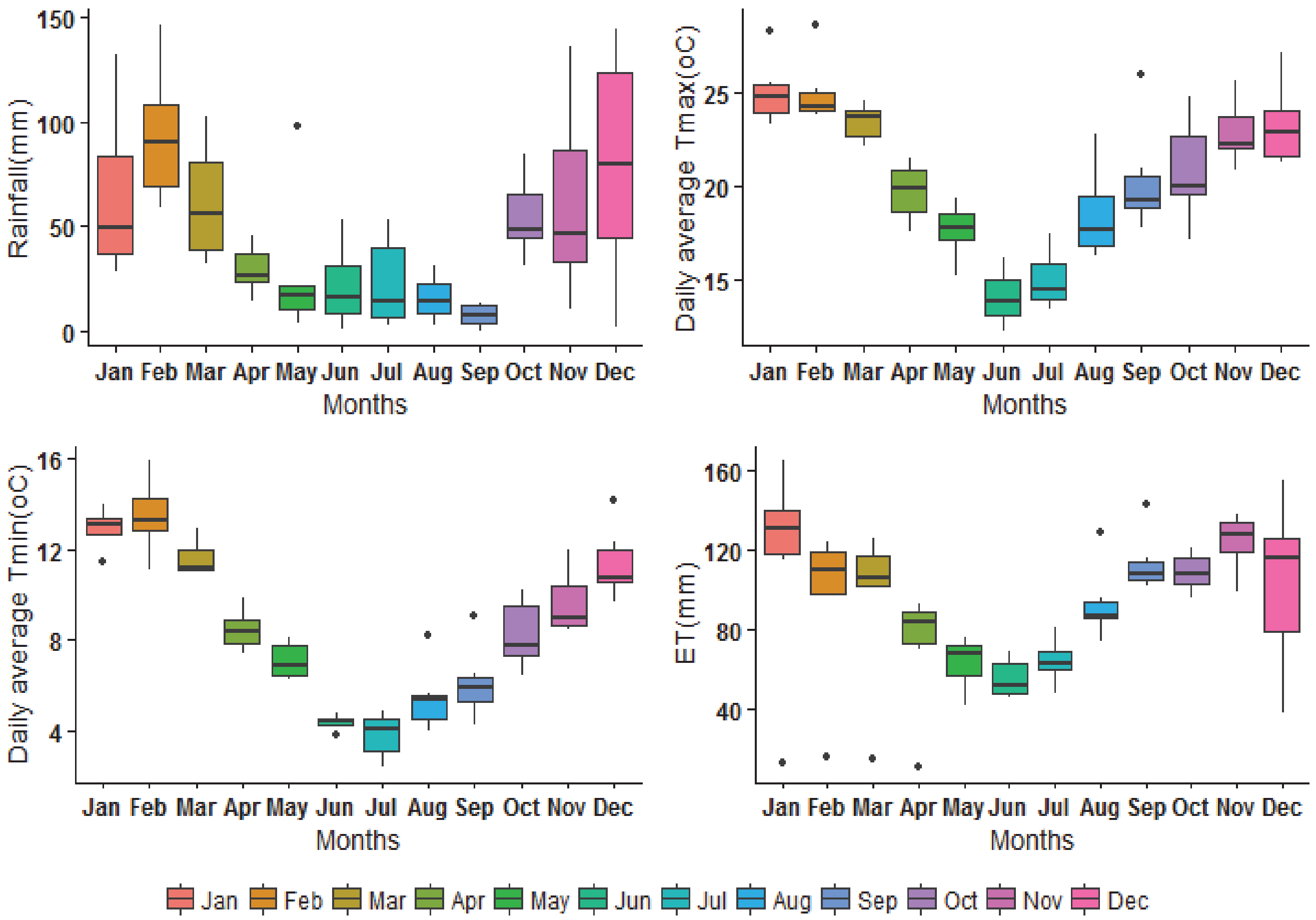


Figure 5.6: Box plot showing distribution of (a) monthly total rainfall, (b) daily average minimum temperature (T min) per month and (c) daily average maximum temperature (T max) per month, and (d) ET_0 for Dingleydale

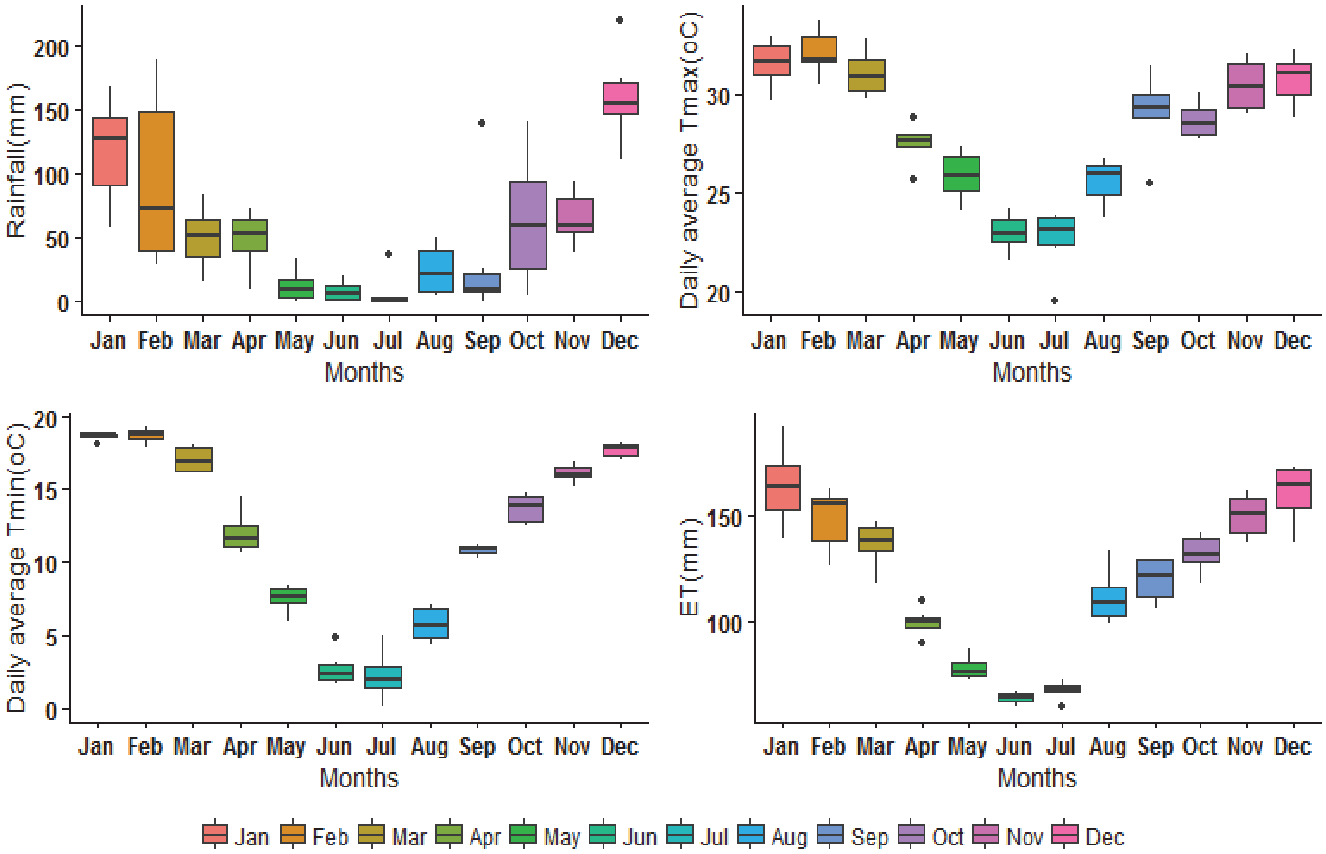


Figure 5.7: Box plot showing distribution of (a) monthly total rainfall, (b) daily average minimum temperature (T min) per month and (c) daily average maximum temperature (T max) per month, and (d) ET_0 for Dzindi

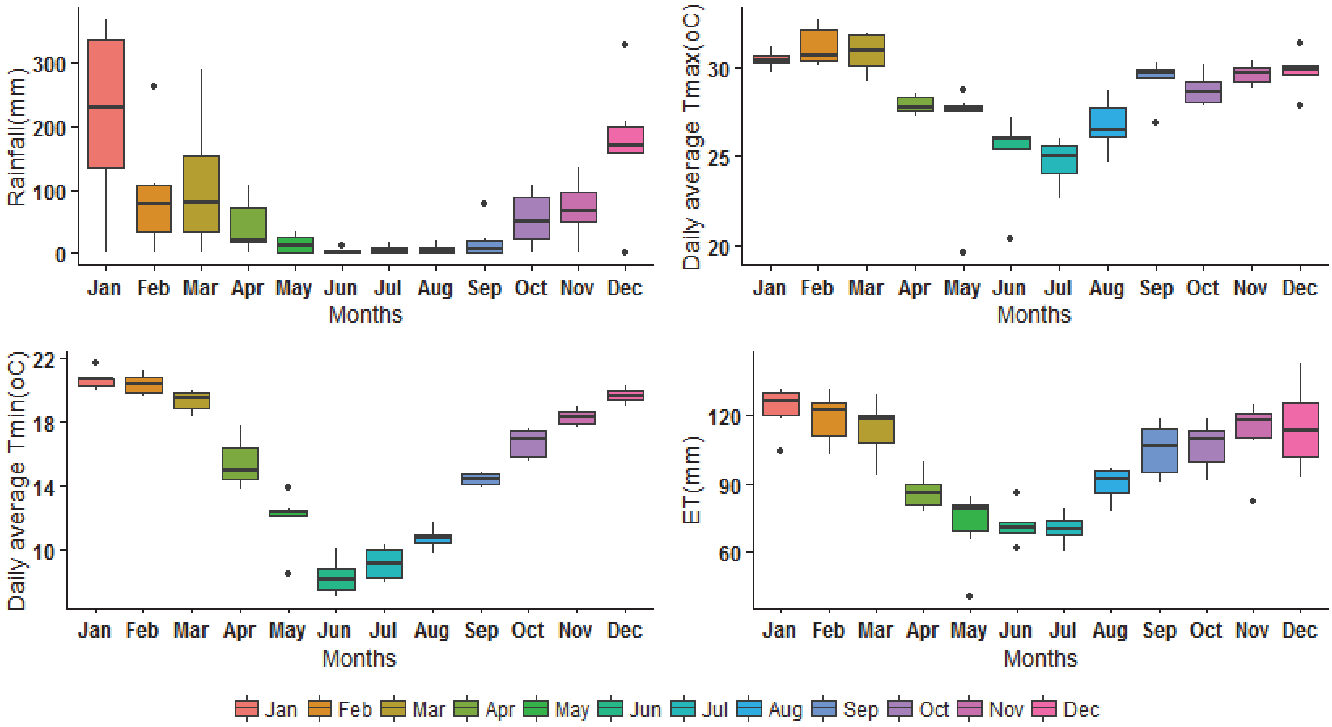


Figure 5.8: Box plot showing distribution of (a) monthly total rainfall, (b) daily average minimum temperature (T min) per month and (c) daily average maximum temperature (T max) per month, and (d) ET_0 for Tugela Ferry

5.7.4.1 Orange fleshed sweet potato

Orange fleshed sweet potato (OFSP) (*Ipomea batatas* var. *Bophelo*) belongs to the Convolvulaceae family and is one of the most frequently grown crops in sub-Saharan Africa (sSA), covering approximately 2.9 million hectares and producing 12.6 million tons (Low et al., 2009). The colour of sweet potato plays a significant role when related to its nutritional attributes. Through crop breeding, new OFSP varieties have been developed and mostly used in food intervention programmes to combat vitamin A deficiency. One crucial attribute of sweet potato is that it can grow in marginal soils, requiring fewer inputs in terms of water and fertilizer. It can be utilized as a dual crop in that its leaves and storage roots can be consumed. It grows within a period of 3 to 5 months, and is highly productive (24.6-28.4 t ha^{-1}) (Low et al., 2009; Laurie et al., 2012). However, limited information exists on the effect of water stress, temperature and different soil types in various agro-ecological zones of South Africa on the yield of OFSP. Conducting experiments in different agro-ecological zones of South Africa can be time consuming and very expensive in terms of costs. The AquaCrop model was calibrated and validated at the ARC-VOP. The calibrated model was used for up-scaling results to selected locations (Dingleydale, Dzindi, and Tugela Ferry). Results suggest that different environments have an effect on biomass and storage root yield. The highest storage root yield of OFSP was observed in Dingleydale (13.1 t ha^{-1}) and the lowest tuber yield at Tugela Ferry (7.1 t ha^{-1}) (Table 5.8). The reason for the variation in tuber yield might be the soil type and temperature. Soil texture in Dingleydale is silty loam while in Tugela Ferry it is silty clay (Table 5.7). Generally, clay soils tend to hold more water compared to loamy soils. This might have an effect on drainage which can lower the yield of sweet potato. In addition, minimum temperatures in Dingleydale and Dzindzi do not go below 14°C, whereas in Tugela Ferry minimum temperature can reach 10°C towards the end of the growing season which have a major effect on productivity of sweet potato (Figure 5.6). Motsa et al. (2015) indicated that in sSA, sweet potato is grown by RPHs. Two farming systems can be practiced; (i) low external input agriculture, which encourages the use of on-farm inputs, and (ii) high input agriculture (promotes the use of off-farm resources such as pesticides, fertilizer, and irrigation (Daberkow and Katherine 1988). Results suggest that under low input agriculture (no fertilizer application and severe water stress), the yield of OFSP would be 3.2 t ha^{-1} in Dingleydale, 3 t ha^{-1} in Dzindi, and 2.6 t ha^{-1} in Tugela Ferry. However, by applying fertilizer and water (full fertilizer application based on recommended rates and optimal irrigation), storage root yield of OFSP can be improved to 13.1 t ha^{-1} in Dingleydale, 10.5 t ha^{-1} in Dzindi, and 7.1 t ha^{-1} in Tugela Ferry. Water productivity ranged from 1.6 to 2.9 kg m^{-3} for Dzindi, 1.2 to 2.0 kg m^{-3} for Tugela Ferry, and 1.4 to 2.9 kg m^{-3} for Dingleydale. This result suggests that WP for OFSP would be higher in Dingleydale and Dzindi (Table 5.8).

Table 5.7: Soil descriptions and hydraulic properties for selected locations in South Africa

		Textural class				**Hydraulic Properties**				
Name	**Depth** (m)	**Sand** (%)	**Silt** (%)	**Clay** (%)	**Texture**	**PWP** (Vol%)	**FC** (Vol%)	**Sat** (Vol%)	**K$_s$** (mm day^{-1})	**BD** (g cm^{-3})
Dzindi	0-1	9	53	38	SiClL	23.1	39.1	51.7	122.4	1.3
Tugela Ferry	0-0.31	16	42	42	SiCl	25.3	39.6	50.8	84	1.3
	0.31-0.66	16	42	42	SiCl	25.3	39.6	50.8	84	1.3
	0.66-0.91	16	43	41	SiCl	25.8	40.0	50.9	79	1.3
	0.91-1.52	15	42	43	SiCl	25.8	40.0	51.1	82	1.3
Dingleydale	0-0.3	30	66	4	SiL	5.0	24.3	46.8	981	1.4
	0.3-1.0	28	63	9	SiL	7.7	26.5	46.9	659	1.4

SiClL – silty clay loam; SiCl – silty clay; SiL – silty loam

Table 5.8: Water and soil fertility scenarios of OFSP for selected locations in South Africa

Soil fertility x water	Biomass (t ha^{-1})		Yield (t ha^{-1})		ETa (mm)		WP (kg m^{-3})	
	Thirty	Eighty	Thirty	Eighty	Thirty	Eighty	Thirty	Eighty
Dingleydale								
Non limiting	24.3	20.0	13.1	11.3	482	390	2.7	2.9
Moderate	14.7	13.1	7.9	7.3	384	301	2.1	2.4
Very poor	6.2	5.8	3.3	3.2	231	173	1.4	1.9
Dzindi								
Non limiting	18.3	16.6	10.5	9.8	365	332	2.9	2.9
Moderate	12.4	11.9	6.7	6.6	302	273	2.2	2.4
Very poor	5.6	5.6	3.1	3.0	187	173	1.6	1.8
Tugela Ferry								
Non limiting	13.1	7.1	7.1	3.5	361	221	2.0	1.6
Moderate	10.8	6.9	6.3	2.9	328	214	1.9	1.3
Very poor	5.2	4.8	2.9	2.6	215	202	1.2	1.4

Biomass and storage root yield are on dry mass basis

5.7.4.2 Amaranthus

Amaranth (*Amaranthus cruentus*) belongs to the family Amaranthaceae and is mostly utilized as a leafy vegetable by RPHs. Amaranth leaves and the softest portions of the shoots are boiled in water, and then cooked with onions, tomatoes, and oil to make soup (Masariramb et al., 2012; Achigan-dako et al., 2014; Adebooye et al., 2008). One added value of Amaranth is that it is a C4 crop which is well-known for its higher water use efficiency, requiring less inputs in terms of water and fertilizer, while highly nutritious in micronutrients and Vitamin A. It also has the ability to withstand semi-arid conditions, which makes it ideal for a water-stressed country such as South Africa. It can, therefore, contribute significantly to the livelihoods of RPHs (Uusiku et al., 2010; Afari-Sefa et al., 2012; Onyango et al., 2012). The ARC-VOP have been conducting enormous research on plant spacing, planting date, water use, and fertilizer requirements of Amaranth. This research has been conducted on a research farm that has a specific set of climatic conditions. To promote the crop in all the provinces, it is crucial to understand how it would respond to different climate and environments, and crop modelling can play a major role. The calibrated AquaCrop model was used to simulate yield response for Amaranth in three selected locations (Dzindi, Tugela Ferry and Dingleydale), representing different agro-ecological zones of South Africa. There was no variation in biomass under optimum conditions (well-watered and full fertilizer application). However, in Tugela Ferry higher biomass (11.8 t ha^{-1}) was produced compared to Dingleydale (11.7 t ha^{-1}), and Dzindi (11.4 t ha^{-1}). The results of this study suggest that under water and soil fertility stresses, Amaranth biomass production would drop by approximately 80% when compared to optimal conditions. Water productivity for Dingleydale ranged from 2.2 to 5.5 kg m^{-3}, 1.9 to 5.9 kg m^{-3} for Dzindi, and 1.7 to 4.7 kg m^{-3} for Tugela Ferry. These results suggest that more biomass per amount of water would be produced in Dingleydale and Dzindi (Table 5.9).

Table 5.9: Water and soil fertility scenarios of Amaranth for selected locations in South Africa

	Biomass (t ha^{-1})		ETa (mm)		WP (kg m^{-3})	
	Thirty	Eighty	Thirty	Eighty	Thirty	Eighty
Dingleydale						
Non limiting	11.7	5.8	215.6	109.5	5.5	5.3
Moderate	6.9	4.9	186.1	101.7	3.9	4.9
Very poor	2.9	2.4	141.3	86.2	2.2	2.9
Dzindi						
Non limiting	11.4	8.9	218.1	168.0	5.5	5.5
Moderate	6.9	6.1	194.0	152.2	3.8	4.2
Very poor	2.9	2.4	161.1	128.1	2.0	1.9
Tugela Ferry						
Non limiting	11.8	5.7	266.2	145.3	4.7	4.0
Moderate	6.9	5.0	240.1	140.4	3.2	3.6
Very poor	2.9	2.4	192.2	125.7	1.7	2.0

Biomass is on dry mass basis

5.7.4.3 Spider flower

Cleome gynandra, known as cat whiskers or Spider flower, belongs to the Capparaceae family. It is native in the tropics and subtropical areas in Africa. In South Africa it is mostly known as *lerotho, murudi, rirudzu, bangala,* and *ulude* (van den Heever and Venter, 2007; van Rensburg et al., 2007). The leafy vegetable originated in tropical Africa and South East Asia. Major provinces cultivating it in the country are Limpopo, North West, Gauteng, Mpumalanga, KwaZulu-Natal, Free State, and Northern Cape (DAFF, 2010). Cleome utilises a C4 photosynthetic pathway, which is well-known for higher water use efficiency in semi-arid conditions (Mishra et al., 2011). Apart from being a leafy vegetable, it is also used for medicinal properties curing diseases such as dysentery, gonorrhoea, malaria, headache, worm infection and high blood pressure (Mishra et al., 2011). Chweya and Mnzava (1997) mentioned that in Kenya it is utilised to facilitate child birth. Throughout Africa, the tender leaves or young shoots, and often the flowers, are boiled as a pot herb, tasty relish, stew or side dish. Yields ranging from 1.5-3 t ha^{-1} had been reported by Masinde and Agong (2011) which are markedly different from those found by Chweya and Mnzava (1997) of 20-30 t ha^{-1}. The lower range of yield can be attributed to poor agronomic practices such as low fertiliser use and different varieties. Similar to Amaranth, the vegetable is rich in vitamins (A and C) and minerals (calcium and iron). The ARC-VOP had been conducting research on plant spacing, planting date, water use, and fertilizer requirements of Spider flower. However, most of the research has been conducted on a research farm that has a specific set of climatic conditions. To promote the crop to in all the provinces, it is crucial to understand how it would respond to different climate and environments, and crop modelling can play a significant role. The calibrated AquaCrop model was used to simulate yield response of Spider flower in three selected locations (Dingleydale, Dzindi, and Tugela Ferry) representing different Agro-ecological zones of South Africa. There was no variation in biomass under optimum conditions (well-watered and full fertilizer application).

However, at Tugela Ferry higher biomass (11.5 t ha^{-1}) production was achieved compared to Dingleydale (11.4 t ha^{-1}), and Dzindi (11.2 t ha^{-1}). The results of this study suggest that under water and soil fertility stresses, Spider flower biomass production would drop by approximately 50% for Dzindi, 68% for Tugela Ferry and 61% for Dingleydale compared to optimal conditions. Water productivity ranged from, 4.2 to 5.8 kg m^{-3} for Dzindi, 2.5 to 4.1 kg m^{-3} for Tugela Ferry, and Dingleydale for 5.0 to 6.3 kg m^{-3} (Table 5.10).

Table 5.10: Water and soil fertility scenarios of Spider flower for selected locations in South Africa

	Biomass (t ha^{-1})		**ETa (mm)**		**WP (kg m^{-3})**	
	Thirty	**Eighty**	**Thirty**	**Eighty**	**Thirty**	**Eighty**
Dingleydale						
Non limiting	11.38	5.94	181.3	101.9	6.3	5.7
Moderate	9.33	5.28	156.8	97.3	6.0	5.3
Very poor	6.47	4.45	120.7	86.6	5.3	5.0
Dzindi						
Non limiting	11.23	8.92	196.4	159.6	5.8	5.6
Moderate	9.14	7.73	177.2	147.8	5.2	5.2
Very poor	6.16	5.57	147.1	128.2	4.2	4.3
Tugela Ferry						
Non limiting	11.5	4.66	283.3	151	4.1	2.9
Moderate	9.31	4.27	244.3	146.3	3.8	2.7
Very poor	6.56	3.72	200.6	138.3	3.2	2.5

Biomass is on dry mass basis

5.8 Summary and conclusions

The main purpose of this study was to calibrate and validate the AquaCrop model for Amaranth (*Amaranthus cruentus*), Spider flower (*Cleome gynandra*), and orange fleshed sweet potato (*Ipomoea batatas* var. *Bophelo*), and thereafter to simulate the effect of different water and soil fertility levels in Dingleydale, Dzindi, and Tugela on yield and biomass The AquaCrop model was successfully calibrated and validated for all three crops for canopy cover, profile soil water content, biomass, storage roots yield, and evapotranspiration. This was proven by higher coefficients of determination (R^2s), lower root mean square errors (RMSEs) and RSRs. Values of R^2 ranged from 0.61 to 0.81, the RMSE ranged from 0.12 to 27.1, and the RSR from 0.20 to 0.85 for OFSP. For Amaranth, R^2 values ranged from 0.73 to 0.99, RMSE from 0.08 to 14.7, and RSR from 0.096 to 0.62, whilst for Spider flower, R^2 values ranged from 0.80 to 0.99, RMSE from 0.15 to 9.48, and the RSR from 0.09 to 0.51 for all calibrated and validated parameters. All these statistics suggest a good correlation between measured and simulated values. The simulated results of the AquaCrop model suggest that water and soil fertility management have an effect on WP of selected crops. Under low input agriculture (combination of water and soil fertility stresses), the productivity of the selected crops would markedly reduce, while under high input agriculture (no water and soil fertility stresses), the productivity of the selected crops would improve in all the selected locations. Higher yield of OFSP storage roots can be obtained in Dingleydale (13.1 t ha^{-1}), whereas high yields for Amaranth (11.8 t ha^{-1}) and Spider flower (11.5 t ha^{-1}) can be obtained in Tugela Ferry. Moreover, Spider flower (Table 5.10: 6.3 kg m^{-3}) is more productive in terms of water use when compared to Amaranth (Table 5.9: 5.5 kg m^{-3}) and OFSP (Table 5.7: 2.9 kg m^{-3}) and, therefore, more adapted to soil fertility and water stresses. The authors encourage agronomists, horticulturalists, policy makers, water managers, academics, and environmentalists to use the calibrated AquaCrop model for decision making, and also for identifying suitable locations where selected traditional vegetable crops can grow optimally.

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6 GENERAL CONCLUSIONS, RECOMMENDATIONS AND SUMMARY

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Food and nutrition security (FNS) is a major problem in South Africa. Moreover, extreme weather phenomena such as El Nino and El Nina, as well as higher temperatures, poor soil fertility and sporadic rainfall, will further exacerbate FNS which will affect resource poor households (RPHs). To alleviate FNS, RPHs have to utilize agricultural resources efficiently and also consider utilizing traditional vegetable crops (TVCs) in their food systems because they are highly nutritious in Fe, Zn, and β-carotene. Key findings are that under no water stress and severe water stress, Swiss chard produced the highest raw edible biomass because the TVCs produce bulky stems which are not suitable for human consumption. Moreover, under no water stress, evapotranspiration (ETa), or water use, of crops can be ranked as follows from highest to lowest: (i) OFSP leaves, (ii) Amaranth, (iii) Spider flower, and (iv) Swiss chard. However, under severe water stress, the crops can be ranked as follows from highest to lowest water use: (i) Orange flesh sweet potato (OFSP) leaves, (ii) Spider flower, (iii) Swiss chard, and (iv) Amaranth. These results suggest that Amaranth is more tolerant to water stress compared to other vegetables. However, water is a scarce resource and it can be concluded that water productivity (WP) of crops has to be improved. The selected crops can be ranked as follows from highest to lowest WP; (i) Spider flower, (ii) Amaranth, (iii) Swiss chard, and (iv) OFSP leaves. The findings of the study accept the notion that TVCs are drought tolerant and can withstand adverse climatic conditions when compared to a commercial vegetable crop like Swiss chard. Moreover, under low input agriculture (with low water and fertiliser inputs), WP of TVCs will decline but with addition of water and fertiliser it can be improved. The findings of the study dismiss the idea that TVCs do not require fertilizer and water because they grow on marginal soils, depending solely in sporadic rainfall. Under low input agricultural production (no water and fertiliser), biomass, storage root yield and WP decreased significantly, suggesting that water and soil fertility stresses have a major influence on the productivity of TVCs.

With respect to nutrient content (NC), the main findings of the study indicate that TVCs are higher in Fe, Zn and β-carotene when compared to Swiss chard. Under no water stress, average NC for selected micro-nutrients ranged from 5.3 (Swiss chard) to 16.2 (Spider flower) mg 100 g^{-1} for Fe, 0.5 (Swiss chard) to 1.6 (Spider flower) mg 100 g^{-1} for Zn, and 3 (Swiss chard) to 28 (Amaranth) mg 100 g^{-1} for β-carotene. Under severe water stress conditions, Fe and Zn indicated consistency, whereas, β-carotene decreased significantly, suggesting that β-carotene is more sensitive to water stress compared to Fe and Zn. Moreover, low input agricultural practices (with low water and fertiliser inputs), did not necessarily affect NC of crops negatively. In some instances, they actually led to increases in NC. For example, Fe content of Amaranth increased from 8.2 to 28.1 mg 100 g^{-1}, whereas, for Spider flower it increased from 7.5 to 34.4 mg 100 g^{-1}. From an agronomic perspective, NC of crops cannot be evaluated in isolation in terms of yield or raw edible biomass, because they are intertwined.

Nutritional yield (NY= raw edible biomass x NC) is a crucial agronomic parameter which indicates the quantity of nutrients which can be harvested during the entire season. Under severe water stress, the highest average NY for Fe was obtained from Spider flower (1444 g ha^{-1}), for Zn from Swiss chard (213 g ha^{-1}), and for β-carotene from Amaranth (1933 g ha^{-1}). These results suggest that more Fe and β-carotene can be harvested from TVCs compared to Swiss chard. In addition, under low input agricultural practices, NY of TVCs decreased with β-carotene NY showing a major decline under supplemental irrigation and no fertilizer application conditions. Major findings of this study indicate that OFSP storage root NYs for Fe, Zn and β-carotene would decrease by approximately 50% under supplemental irrigation (water stress), no fertilizer application and leaf harvesting treatment combinations. Although NY of OFSP storage roots would decrease significantly, it is recommended that RPHs should consider utilizing OFSP as a dual crop. There are more benefits attained when considering the dual crop option under sub-optimal production conditions. For example, OFSP leaf NY increased from 518 to 574 g ha^{-1} for Fe, 35 to 37 g ha^{-1} for Zn, and 281 to 300 g ha^{-1} for β-carotene under the latter conditions compared to optimal production conditions.

Under no water stress, average nutritional water productivity (NWP) for selected micro-nutrients ranged from: (i) 740 (OFSP leaves) to 1392 mg m^{-3} (Spider flower) mg 100 m^{-3} for Fe, (ii) 35 (OFSP leaves) to 177 (Spider flower) mg 100 m^{-3} for Zn, and (iii) 617 (Swiss chard) to 2748 (Amaranth) mg 100 mg m^{-3} for β-carotene. Under severe water stress conditions, an increase in NWP for Fe, Zn, and β-carotene was observed. The highest NWP for Fe (1981 mg m^{-3}) and Zn (230 mg m^{-3}) was obtained for Spider flower, whereas, for β-carotene (3119 mg m^{-3}) it was obtained for Amaranth. When ranking the crops from highest to lowest NWP, under severe water stressed conditions, Spider flower, Amaranth, Swiss chard, and OFSP leaves ranked 1st, 2nd, 3rd, and 4th, respectively, for Fe. For Zn, Spider flower, Swiss chard, Amaranth and OFSP leaves ranked 1st, 2nd, 3rd, and 4th, respectively. For β-carotene, Spider flower, Amaranth, Swiss chard, OFSP leaves and Swiss chard ranked 1st, 2nd, 3rd, and 4th, respectively. Key findings are that: (i) Spider flower and Amaranth can be grown under supplemental irrigation and still produce sufficient micronutrients (Fe and Zn) and β-carotene, (ii) TVCs (Amaranth and Spider flower) are highly productive when compared to Swiss chard, and (iii) under low input production (supplemental irrigation and no fertilizer application), NWP for OFSP storage roots would decrease for Fe and Zn, whereas, it would increase for β-carotene.

The AquaCrop model was successfully calibrated and validated for canopy cover (CC), profile soil water content (SWC), biomass, storage root yield, and ETa. This was proven by higher coefficients of determination (R^{2}s), lower root mean square errors (RMSEs) and RMSE standard deviation ratio (RSR). Values of R^2 ranged from 0.61 to 0.81, the RMSE ranged from 0.12 to 27.1, and the RSR from 0.20 to 0.85 for OFSP. For Amaranth, R^2 values ranged from 0.73 to 0.99, RMSE from 0.08 to 14.7, and RSR from 0.096 to 0.62, whilst for Spider flower, R^2 values ranged from 0.80 to 0.99, RMSE from 0.15 to 9.48, and RSR from 0.09 to 0.51 for all calibrated and validated parameters. All these statistics suggest a good relationship between measured and simulated values by the AquaCrop model. The calibrated model was used to estimate WP of TVCs at Dingleydale, Dzindi and Tugela Ferry irrigation schemes. Key findings suggested that under low input agricultural conditions, storage root yield, raw edible biomass and WP of the selected TVCs would decline significantly, while by increasing water and fertilizer inputs, yields could improve significantly.

From the key findings of this study, the following recommendations can be made:

- Nutritional content (NC) of the same crop species varied between more controlled (rain-shelter) and more variable (Rooiland open field) experimental conditions. Variation of NC between crops of the same species, conducted in the same location (Roodeplaat), is difficult to explain. Could it be caused by different soil types, environmental conditions or management practices? It is therefore recommended that further research, assessing the effects of soil fertility and water levels on NC of selected crops, be conducted in various locations having different externally impacting conditions.
- The results of this study suggest that OFSP can be utilized as a leafy vegetable and storage root crop. The main findings suggest that storage root yield will decrease if OFSP leaves are harvested during the growing season. One of the research gaps that was not addressed is the timing and frequency of the harvesting. Therefore, it is recommended that further research should be conducted to explore the possibility of OFSP as a dual crop. This research should look at the protocol of harvesting OFSP leaves, *inter alia* by investigating leaf harvesting frequencies as a factor to determine the threshold at which storage root yield would decrease.
- This research project was conducted at a research station under well-managed agricultural practices. The AquaCrop crop model that was used in this study was calibrated and validated from data generated from well-controlled experimental conditions. The model was consequently used to estimate total biomass, storage root yield and water productivity (WP) of selected TVCs from various agro-ecological locations. A shortcoming of AquaCrop is that it cannot calculate NC. A possible research initiative could be to compare crop models that can predict NC of TVCs under different production conditions. It is further recommended that participatory action research should be conducted with RPHs to avoid using a topdown approach, whereby researchers conduct research at a research station and then disseminate results to beneficiaries.
- The literature review of Chapter 2 suggests that TVCs are highly nutritious compared to Swiss chard and cabbage. However, data used to come up with this finding was collected from different locations where soil fertility, crop management and water use were unknown. It is recommended that research should be conducted at a well-managed location to assess the NWP of TVCs compared to popular exotic vegetables. Moreover, TVCs should be commercialized in South Africa by following the model that has been used by Eastern African countries. Recently, the Nestle company added value through the processing of Amaranth “morogo” to be included in 2 minute noodles. It is recommended that more TVCs be used in food-processing to add value and promote the production of TVCs in South Africa.
- This research project has assessed the value of micro-nutrients (Fe and Zn) and β-carotene from raw edible biomass. However, when TVCs are cooked by RPHs, the

bio-availability of nutrients might change depending on the method of food preparation, i.e. boiling, steaming, and frying. There is no study which had assessed the factors affecting bio-availability of micro-nutrients (Fe and Zn) and β-carotene for TVCs and the best method of preparing them. It is recommended that multi-disciplinary research should be conducted by agronomists, water resource managers, soil scientists, social scientists, nutritionists and food scientists to assess FNS from production up to human consumption.

Summaries are presented of mean measured biomass, storage root yield and Eta (Table 6.1), as well as WP, NC and NWP (Table 6.2) for the TVCs as a function of the various treatments. Table 6.3 provides a summary of the modelled parameters (biomass, yield, Eta and WP) for the TVCs in selected agro-ecological zones in South Africa.

Table 6.1: Summary of measured parameters for TVCs (Part 1)

TVC	Irri.	Fert.	Harv.	Bio FM $t\ ha^{-1}$	Bio DM $t\ ha^{-1}$	Leaf FM $t\ ha^{-1}$	Leaf DM $t\ ha^{-1}$	Tuber FM	Tuber DM $t\ ha^{-1}$	ETa mm
Amaranth	30%			56.5	7.1	20.0	3.4	nd	nd	340
Amaranth	80%			39.0	4.3	13.0	2.2	nd	nd	308
Amaranth	W1	F1	H1	20.7	2.8	5.7	1.3	nd	nd	275
Amaranth	W2	F2	H2	4.4	1.1	1.4	0.5	nd	nd	184
Spider flower	30%			51.5	8.3	14.5	3.0	nd	nd	308
Spider flower	80%			35.5	5.4	9.5	2.2	nd	nd	107
Spider flower	W1	F1		15.0	2.0	2.5	1.0	nd	nd	251
Spider flower	W2	F2		2.7	0.3	0.5	0.2	nd	nd	157
OFSP leaf	30%			35.5	5.7	17.5	3.7	nd	nd	520
OFSP leaf	80%			24.0	2.8	11.5	1.8	nd	nd	331
OFSP leaf	W1	F1	H1	13.5	2.6	4.5	1.0	24.5	5.9	517
OFSP leaf	W2	F2	H2	13.0	2.5	3.3	0.8	15.5	3.35	237
Swiss chard	30%			51.5	5.1	51.5	5.1	nd	nd	285
Swiss chard	80%			45.0	4.0	45.0	4.0	nd	nd	173

TVC – traditional vegetable crop; Irri – irrigation level; Fert. – fertility level; Harv. – harvesting method; Bio. – biomass; FM – fresh mass; DM – dry mass; mm – millimetres; nd – no data; OFSP – orange fleshed sweet potato; W1 – full irrigation; W2 –supplemental irrigation; H1 – no leaf harvesting; H2 – leaf harvesting; F1 – Full N, P and K fertiliser application; F2 – no fertiliser application; ETa –evapotranspiration

Table 6.2: Summary of measured parameters for TVCs (Part 2)

TVC	Irri.	Fer.	Harv.	WP	NC (mg 100 g^{-1})			NWP (mg m^{-3})		
				kg m^{-3}	Fe	Zn	β-carotene	Fe	Zn	β-carotene
Amaranth	30%			1.9	7.3	1.2	28.0	744	122	2748
Amaranth	80%			2.9	6.1	1.0	17.6	1101	168	3119
Amaranth	W1	F1	H1	0.9	8.2	0.6	7.8	619	38	508
Amaranth	W2	F2	H2	0.4	28.1	1.2	9.8	803	34	271
Spider flower	30%			2.7	12.4	1.6	21.9	1392	177	1351
Spider flower	80%			3.0	17.4	17.4	17.0	1981	230	2090
Spider flower	W1	F1	H1	0.6	8.2	0.5	7.2	542	31	416
Spider flower	W2	F2	H2	0.1	25.7	1.0	7.6	255	11	80
OFSP leaf	30%			1.0	16.2	0.8	18.7	740	35	896
OFSP leaf	80%			0.9	11.0	0.6	10.2	564	29	429
OFSP leaf	W1	F1	H1	2.7	10.2	0.7	5.8	192	12	139
OFSP leaf	W2	F2	H2	3.3	9.3	0.6	6.6	353	22	240
OFSP root	W1	F1	H1	2.7	1.0	0.3	54.5	725	57	5162
OFSP root	W2	F2	H2	3.3	1.1	0.3	50.9	527	47	5559
Swiss chard	30%			1.7	5.3	0.5	2.7	918	93	617
Swiss chard	80%			2.3	4.5	0.6	3.5	976	122	666

TVC – traditional vegetable crop; Irri – irrigation level; Fert. –fertility level; Harv. – harvesting method; OFSP – orange fleshed sweet potato; W1 – full irrigation; W2 –supplemental irrigation; H1 – no leaf harvesting; H2 – leaf harvesting; F1 – Full N, P and K fertiliser application; F2 – no fertiliser application; WP – water productivity; NC – nutrient content; NWP –nutritional water productivity

Table 6.3: Summary of modelled parameters for TVCs in selected agro-ecological zones in South Africa

	Biomass (t ha^{-1})		Yield (t ha^{-1})		ETa (mm)		WP (kg m^{-3})	
Soil fertility x water	Thirty	Eighty	Thirty	Eighty	Thirty	Eighty	Thirty	Eighty
OFSP								
Dingleydale								
Non limiting	24.3	20.0	13.1	11.3	482	390	2.7	2.9
Very poor	6.2	5.8	3.3	3.2	231	173	1.4	1.9
Dzindi								
Non limiting	18.3	16.6	10.5	9.8	365	332	2.9	2.9
Very poor	5.6	5.6	3.1	3.0	187	173	1.6	1.8
Tugela Ferry								
Non limiting	13.1	7.1	7.1	3.5	361	221	2.0	1.6
Very poor	5.2	4.8	2.9	2.6	215	202	1.2	1.4
Amaranth								
Dingleydale								
Non limiting	11.7	5.8		215.6	109.5		5.5	5.3
Very poor	2.9	2.4		141.3	86.2		2.2	2.9
Dzindi								
Non limiting	11.4	8.9		218.1	168.0		5.5	5.5
Very poor	2.9	2.4		161.1	128.1		2.0	1.9
Tugela Ferry								
Non limiting	11.8	5.7		266.2	145.3		4.7	4.0
Very poor	2.9	2.4		192.2	125.7		1.7	2.0
Spider flower								
Dingleydale								
Non limiting	11.38	5.94		181.3	101.9		6.3	5.7
Very poor	6.47	4.45		120.7	86.6		5.3	5.0
Dzindi								
Non limiting	11.23	8.92		196.4	159.6		5.8	5.6
Very poor	6.16	5.57		147.1	128.2		4.2	4.3
Tugela Ferry								
Non limiting	11.5	4.66		283.3	151		4.1	2.9
Very poor	6.56	3.72		200.6	138.3		3.2	2.5

ETa – evapotranspiration; OFSP – orange fleshed sweet potato; WP – water productivity

LIST OF APPENDICES

Appendix 1: Capacity building report

Project No: K5/2171//4

Project Title: Nutritional water productivity of indigenous food crops

Project leader: Dr CP Du Plooy

Student	Gender	Race	Nationality	Degree	University	Status
a) Nyathi Melvin	Male	African	SA	PhD	Wageningen	To be completed
b) Nembudane Stella	Female	African	SA	MSc	Pretoria	Completed
c) Khoza Joshua	Male	African	SA	B-Tech	TUT	Completed
d)Molopo Kabelo	Male	African	SA	B-Tech	UNISA	Completed

Organisation: Agricultural Research Council, Vegetables and Ornamental Plants

a) Traditional leafy vegetables for alleviating nutritional food insecurity for rural households in South Africa- Transformational agronomic research for resource poor households

By
M.K. Nyathi
Degree: PhD in water resources management
Status: To be finished by December 2016

Structure of the PhD thesis to be submitted:

Chapter 1: Introduction and background information

Chapter 2: **The role of TLV's in improving the socio-economic or household food security of the RPH's in South Africa**
Nyathi MK, van Halsema GE, Beletse YG, Vincent L, Annandale JG (Food Security Journal, Elsievier)

Chapter 3: **Methodology for assessment of nutritional water productivity: A new approach of tackling malnutrition in South Africa**

Nyathi MK, van Halsema GE, Beletse YG, Vincent L, Annandale JG (Journal of Agriculture Water Management)

Chapter 4: **Nutritional water productivity of three traditional leafy vegetables in South Africa**

Nyathi MK, van Halsema GE, Beletse YG, Vincent L, Annandale JG (Journal of Agriculture Water Management)

Chapter 5: **Calibration and validation of AquaCrop model for selected traditional leafy vegetables**

Nyathi MK, van Halsema GE, Beletse YG, Vincent L, Annandale JG (Journal of Agriculture Water Management)

Chapter 6: Conclusion and summary

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b) Nutritional water productivity of spider plant (*Cleome gynandra* L.) as affected by nitrogen and water levels

By
T.S Nembudane

Degree: MSc. Agric (Agronomy)

ABSTRACT

This study investigated effects of water deficit levels and nitrogen application on physiological response, yield, water productivity and nutritional water productivity of drip-irrigated spider plant, *Cleome gynandra* L. (Capparaceae). Deficit irrigation was applied throughout the growing season. Field experiments were carried out under rainout shelter conditions for two consecutive seasons (2012/13 and 2013/14) at the Agricultural Research Council, Vegetable and Ornamental Plant Institute (ACR-VOPI) in Pretoria. A 3 (irrigation) × 4 (N fertilizer) factorial experiment was laid out in randomised complete block design (RCBD) with three replications. Results showed that water deficit decreased stomatal conductance (g_s), whereas plant photosynthetic efficiency increased. Irrigation treatment did not significantly influence g_s in the first growing season, but it differed significantly ($P \leq 0.05$) in the second season. The photosynthetic efficiency ratio (*Fv/Fm*) in spider plant was lower than reported values for healthy plants, but results showed an increase in this ratio as the growing season advanced. Significant differences in this ratio due to irrigation treatments were detected only in 2012/13 after the first crop harvest. Although leaf area index (LAI) was low earlier in the crop growing stage, it rapidly increased as the growing season advanced as measured at each harvest interval in both seasons. An increasing trend in LAI was observed under both irrigation and N treatments as crop harvest advanced. LAI values were high under treatments I3 and N150 in the first season, while in the second season, high values were recorded under treatments I1 and N150. The results of this study also revealed that spider plant yield (leaf fresh mass (LFM) and leaf dry mass (LDM) values) increased with an increase in N application. The highest yield LFM (8.9) and LDM (5 Mg ha^{-1}) was obtained from 150 kg N ha^{-1}, but did not differ significantly from the treatment with 100 kg N ha^{-1}. In the case of water application, no significant differences were detected on LFM and LDM in either season. The water productivity (WP) increased with a decrease in water application and an increase in N fertilisation. The WP in fresh leaf basis was highest at moderate (I2: 0.97 kg m^{-3}) and low (I3: 0.92 kg m^{-3}) irrigation treatments. Application of 150 kg N ha^{-1} gave the highest WP (1.10 kg m^{-3}) although it was not significantly different from application of 50 and 100 kg N ha^{-1} (0.90 and 0.96 kg m^{-3}). Water productivity in dry leaf basis was influenced by an interaction between irrigation and N treatments in the second growing season. Water productivity was low in all water treatments when N fertiliser was not applied. The N application significantly influenced Fe and Mn content, that application of 150 kg N ha^{-1} had the highest Fe and Mn content. Irrigation treatment significantly influenced Zn content in early crop stages. Irrigation coupled with N fertiliser resulted in higher nutritional water productivity (NWP) value when compared with irrigation coupled with limitation of N. Spider plant could supply 13.063 mg of beta-carotene per cubic meter of water when the crop was fertilised with 150 kg N ha^{-1}. Similarly, spider plant produced high mineral element content when N fertiliser was applied per cubic meter water. Application of 100 and 150 kg N ha^{-1} produced statistically comparable results. However, as inorganic fertiliser cost is important in smallholder agriculture, 100 kg N ha^{-1} would be ideal to obtain reasonable concentrations of mineral elements in spider plant.

Keywords: fertilizer, irrigation, nitrogen, nutritional water productivity, spider plant, water productivity.

c) AGRICULTURAL WATER PRODUCTIVITY

By
J Khoza
Degree: B-Tech in Agriculture

ABSTRACT

Growing water extractions combined with emerging demands for environment protection increase competition for scarce water resources worldwide, especially in arid and semiarid regions. Total food crop production still needs to increase to feed a growing world population, and this increase needs to be accomplished under increasing scarcity of water. This challenge has led to the notion that crop water productivity needs to be increased. The debate on how to increase WP is confounded by different definitions and scale levels of analysis. A single approach would not be able to tackle the forthcoming challenge of producing more food and fibre with limited or even reduced available water. Combining biological water-saving measures with engineering solutions (water saving irrigation method, deficit irrigation, proper deficit sequencing, modernization of irrigation system, etc.), and agronomic and soil manipulation (proper crop choice, increasing soil fertility, addition of organic matter, tillage and soil mulching, etc.) may solve the problem to a certain extent. Priority areas where substantive increases in water productivity are possible include: (i) areas where poverty is high and water productivity is low, (ii) areas of physical water scarcity where competition for water is high, and (iii) areas with little water resources development where high returns from a little extra water use can make a big difference. However, achieving these gains will be challenging at least, and will require strategies that consider complex biophysical and socioeconomic factors.

Key words: deficit irrigation, evapotranspiration, water productivity, water scarcity

d) EFFECT OF DIFFERENT WATER REGIMES ON YIELD RESPONSE OF SPIDER PLANT

By
IK Molopo
Degree: B-Tech in Agricultural Management

ABSTRACT

A study was conducted to determine the effect different water levels on yield response of spider plant. The experiment was a rainshelter field trial carried out at Agricultural Research Council-Vegetable and Ornamental Plant (ARC VOP) Roodeplaat between 2014 and 2015. Namely spider plant, pig weed, spinach and orange fleshed sweet potato were intercropped and subjected to three irrigation regimes (Irrigated to field capacity when 30%, 50% and 80% of plant available water was depleted) under a randomized complete block design replicated three times. Six weeks old traditional leafy vegetables were transplanted into a drip irrigated (non-leaking urinam dripper lines of 2.31 h^{-1}) field of an area of 288 m^2 divided into 40 plots which were 5.2 m^2.The following measurements were taken to determine the effect of different irrigation levels on the crop include stomatal conductance, leaf area meter (LAI), hydroprobe water readings, soil profile probe, plant height, stem diameter, root length, number of leaves and harvests. Spider plant was harvested three times after every three weeks by tipping of the shoots along with intact leaves. Analysis of the crops fresh mass its thickness and the number of harvests are helpful in concluding the effective optimum water regime based on PAW (Plant Available Water is depleted) to improve the crops quality, number of yields and nutritional water productivity. Results showed that there was a significant impact on yield as different water levels were applied.

Key words: irrigation regimes, stomatal conductance, traditional vegetable crops, yield

Appendix 2: Technology transfer

a) Conferences, symposiums and poster presentations

- NYATHI MK, VAN HALSEMA GE, BELETSE YG and DU PLOOY CP (2012) Yield response and water productivity of Spinacea oralecea. ASSAF conference proceedings conference, 23-25 November 2012, CSIR, Pretoria, South Africa.
- NYATHI MK, BELETSE YG and DU PLOOY CP (2013) Nutritional Water productivity of Traditional leafy vegetables: A Review presented at the Combined Conference 21-24 Jan 2013, University of KwaZulu-Natal, Westville Campus, Durban.
- RALIVHESA TC,NYATHI MK and BELETSE Y (2014) Effect of water and nitrogen regimes on selected mineral content of sweet potato (*Ipomoea batatas, Bophelo* var.) presented at the South African Society for Agricultural Technologists (SASAT) Congress, Kedar Country Retreat, Rustenburg 17-20 September 2013.
- NYATHI MK, BELETSE YG and DU PLOOY CP (2013) Water productivity of selected traditional leafy vegetables, a poster presented at the Food Security Conference, 3-5 December 2013, Johannesburg, South Africa.
- NYATHI MK, BELETSE YG, DU PLOOY CP, VAN HALSEMA GE and NEMBUDANE S (2013) Water productivity of Spider Plant (Cleome gynandra L.), A poster presented at The Global Food Security Conference, 29 September-03 October 2013, The Netherlands.
- NYATHI MK, BELETSE YG and FESSEHAZION MK (2014) Calibration of AquaCrop Model for Amaranth and Spider Flower, presented at the Combined Conference 20-23 Jan 2014, Rhodes University, Grahamstown.
- BELETSE YG, NYATHI MK, DU PLOOY CP, FESSEHAZION MK, VAN JAARSVELD P and FABER M (2014) Nutritional water productivity of four underutilized food crops in South Africa, Symposium on the Water Use and Nutritional value of Indigenous and Traditional South African Underutilized Food Crops for Improved Livelihoods, 18-20 February 2014.
- NYATHI MK, BELETSE YG and DU PLOOY CP (2014) Nutritional water productivity of orange fleshed sweet potato for selected micro-nutrients (β-carotene, Fe and Zn). 29th International Horticultural Conference, 17-22 August 2014, Brisbane, Australia.
- FESSEHAZION MK, BELETSE YG, NYATHI MK, DU PLOOY CP and TESFAMARIAM EH (2014) Simulating yield and water use of selected African Leafy vegetables. 29th International Horticultural Conference, 17-22 August 2014, Brisbane, Australia.
- NYATHI MK, BELETSE YG, DU PLOOY CP and VAN HALSEMA GE (2014) Effects of water and soil fertility stresses on nutritional yield of two traditional leafy vegetables. ASSAf conference, 14-16 October, 2014.
- NYATHI MK, BELETSE YG, DU PLOOY CP and VAN HALSEMA GE (2014) Effects of abiotic stresses and leaf harvesting on nutritional yield of sweet potato. 2nd National conference on global change, Eastern Cape, Port Elizabeth, 30 November-5 December, 2014.

- NYATHI MK, FESSEHAZION MK, MOLOPO IK, VAN HALSEMA GE and CP DUPLOOY (2016) Water productivity of traditional leafy vegetables, presented at the Combined Conference, 18-21 Jan 2016, University of Free State, Bloemfontein.
- NYATHI MK, FESSEHAZION MK, VAN HALSEMA GE and CP DUPLOOY (2016) Tackling hidden hunger with orange fleshed sweet potato leaves, a poster presented at the Combined Conference, 18-21 Jan 2016, University of Free State, Bloemfontein.
- NYATHI MK, FESSEHAZION MK, KHOZA J, VAN HALSEMA GE and CP DUPLOOY (2016) Nutritional yield of Amaranth and Spider flower, a poster presented at the young water professional conference, 18-21 Jan 2016, CSIR conference centre, Pretoria.
- NYATHI MK (2012) Irrigation and water use. Irrigation training to a group of farmers which was organized by the Agricultural Research Council, Vegetables and Ornamental Plant institute, Roodeplaat, Pretoria, 20-25 June, 2012.
- NYATHI MK (2012) Irrigation and water use. Irrigation training to a group of farmers which was organized by the Agricultural Research Council, Vegetables and Ornamental Plant institute, University of Zululand, KwaZulu-Natal, 5 July, 2012.
- NYATHI MK (2015) Nutritional water productivity of three traditional leafy vegetables. A seminar which was presented to farmers and scientists at the Agricultural Research Council, Vegetables and Ornamental Plant Institute, Roodeplaat, Pretoria, April 2015.

b) Scientific publications

The following papers are part of a PhD thesis at Wageningen University, Environmental Sciences, under the Water resource management group. Four publications are under way:

- NYATHI MK, BELETSE YG, VAN HALSEMA GE, ANNANDALE JG, VINCENT LF and STRUIK PC (2015) Targeting nutritional food security of resource poor households: the scope of cultivating traditional leafy vegetables. To be submitted to the Global Journal for Food Security.
  (Submitted to the Journal of food security. Status: Currently being reviewed)
- NYATHI MK, BELETSE YG, VAN HALSEMA GE, ANNANDALE JG and STRUIK PC (2016) Nutritional water productivity of traditional leafy vegetables.
  (To be submitted to the Agricultural Water Management Journal. Status: Drafted)
- NYATHI MK, BELETSE YG, VAN HALSEMA GE, ANNANDALE JG and STRUIK PC (2016) Calibration and validation of AquaCrop model for traditional leafy vegetables.
  (To be submitted to the Agricultural Water Management Journal. Status: To be drafted)
- NYATHI MK, BELETSE YG, VAN HALSEMA GE, ANNANDALE JG and STRUIK PC (2016) Market value chain of traditional leafy vegetables in South Africa: the case study of Dzindi irrigation scheme.
  (To be submitted to the Agricultural Water Management Journal. Status: To be drafted)

Appendix 3: Archiving of data

All collected data will be electronically archived at the Agricultural Research Council, Vegetables and Ornamental Plants (ARC-VOP). E-mail address of corresponding author: mnyathi@arc.agric.za