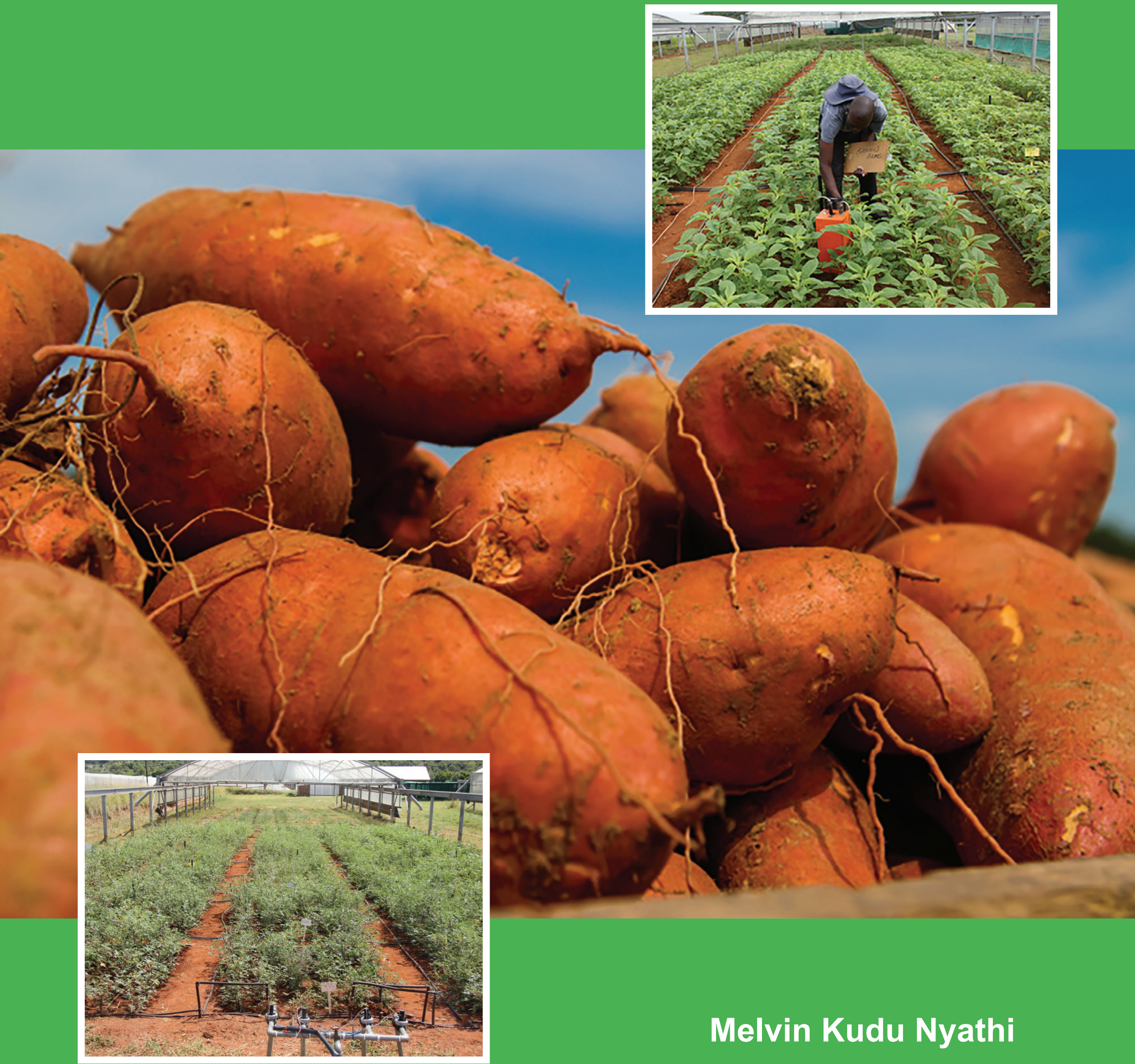
Assessment of nutritional water productivity and improvement strategies for traditional vegetables in South Africa



Melvin Kudu Nyathi

Propositions

1. Nutritional value of traditional vegetables is undervalued in sub-Saharan Africa. (this thesis).

2. Traditional vegetables are a catalyst to mitigate the detrimental effects of climate change against the nutritional food insecurity of rural resource-poor households. (this thesis).

3. Consuming ‘‘wild’’ food plants can supplement the diet with the required intake of micronutrients.

4. Lack of global thinking is a major weakness of crop modellers.

5. Growing Swiss chard under irrigation in sub-Saharan Africa is a waste of water.

6. Training a female farmer is like feeding the entire community.

Propositions belonging to the thesis, entitled ‘‘Assessment of nutritional water productivity and improvement strategies for traditional vegetables in South Africa’’

Melvin Kudu Nyathi
Wageningen, 3 September 2019

Assessment of nutritional water productivity and improvement strategies for traditional vegetables in South Africa

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Assessment of nutritional water productivity and improvement strategies for traditional vegetables in South Africa

Melvin Kudu Nyathi

Thesis

submitted in fulfilment of the requirements for the degree of doctor

at Wageningen University

By the authority of the Rector Magnificus

Prof. Dr A.P.J. Mol,

In the presence of the

Thesis Committee appointed by the Academic Board

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This thesis is dedicated to the following people:

1. My late grandmother, Josephina Ndzimandze

2. My late mother, Elizabeth Dlamini

3. My late father, Lawrence Nyathi

4. My two daughters, Noeleen Nyathi and Melvina Nyathi

5. Mother of my daughters, Bhekiwe Fakudze

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Chapter 1

Introduction

1.1 Background

In sub-Saharan Africa, food and nutrition security are pressing challenges, acknowledged by the sustainable development goals (goals 1, 2, and 3) on the eradication of poverty, zero hunger, and good health (Nendel et al., 2018). *"Food and nutrition security exist, when all people, at all times, have physical and economic access to sufficient, safe, and, nutritious food that meets their dietary needs and food preferences for an active and healthy life"* (FAO, 2012; 13). In the sub-Saharan African region, micronutrient deficiency stands at 23.8 %. This authenticates that the region has the highest prevalence of food and nutritional insecurity, affecting rural resource-poor households who derive their social-livelihoods directly or indirectly from agriculture (Graef et al., 2014; Mabhaudhi et al., 2016a). Thompson et al. (2010) iterated that the main components of food security are availability, accessibility, and utilisation. Availability relates to crop production, accessibility narrates to the ability of an individual or household to obtain food and utilisation is characterised by human beings deriving benefits in terms of nutritional value, social-cultural value, and food safety (Thompson et al., 2010). However, food systems[1] (Lartley et al.,2018) are already stressed in such a way that food availability and accessibility of rural resource-poor households are major concerns (Mabhaudhi et al., 2016b; Thompson et al., 2010). In addition, with continuing high population growth till the year 2050, agricultural production has to increase in order to meet the challenge of feeding approximately 9 billion people with fewer resources (land, water, and other inputs) and under the stress of climate change (Godfray et al., 2010). Agriculture can play a significant role by contributing to improved nutrition through increased food production for own consumption and the selling of surplus for income generation (Wiegers et al., 2011).

The current food system is skewed; policies, research agendas, and funding agencies acknowledge the need to increase crop productivity of mainstream crops, whereas there is varied biodiversity that can be used in combating food and nutrition insecurity that is yet underrepresented in the food system (Mabhaudhi et al., 2018). This is typical of the Green Revolution that promoted the use of high-yielding varieties, despite the consensus that it might not be able to meet nutritional goals (Mabhaudhi et al., 2017a). There is a need for a paradigm shift that will focus on delivering safer, more nutritious food (calories, proteins, fats, vitamins, and micronutrients) per unit of input resource (land area, fertiliser, water, and agrochemicals), in a sustainable way (Smith et al., 2013). The current food system should be inclusive of both the rich and the poor, including rural resource-poor households, in improving the food basket (Mabhaudhi et al., 2018). This can be achieved through the components of the smallholder value chain model. The model utilises a food-based approach to improve the nutritional food security of rural resource-poor households (Wiegers et al., 2011). The smallholder value chain model presents three pathways linking agriculture with food consumption and nutrition (Figure 1.1); (1) subsistence-oriented production for household consumption, (2) the sale of agricultural products to generate income, and (3) local procurement of nutritious food produced by smallholder farmers for use in food subsistence programs (Wiegers et al., 2011). The goal of the supply-side (Figure 1.1: dashed box on the right-hand side of the diagram) is to improve food availability at the household level and increase household income. The

[1] For food systems I follow the definition provided by Lartey et al. (2018) as: comprising all the elements (environment, people, inputs, processes, infrastructure, and institutions) and activities that relate to the production, processing, distribution, preparation, and consumption of food, and the output of these activities, including socio-economic and environmental outcomes.

demand-side (Figure 1.1: left side of the diagram) focuses on decisions made by rural resource-poor households regarding food purchase, allocation of resources to different household members, and knowledge of safe and nutritious food preparation (Wiegers et al., 2011).

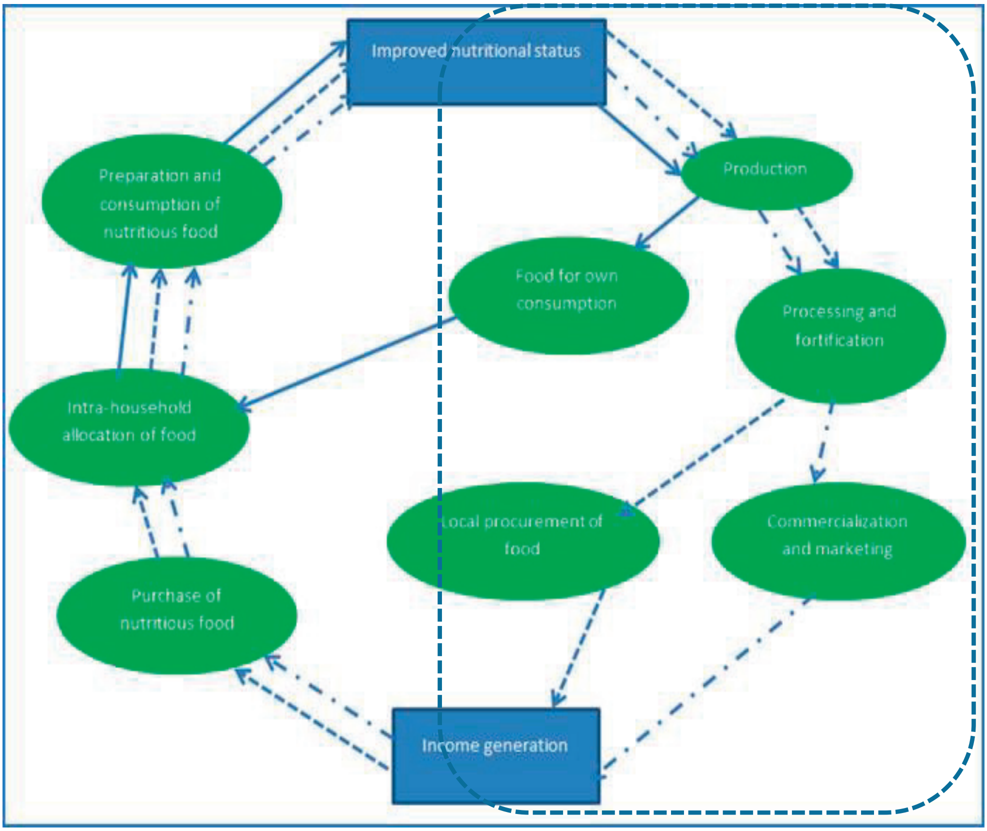

Figure 1.1 Components of the REACH smallholder value chain model (adapted from Wiegers et al., 2011). NOTE: the ovals (green in colour) represent the smallholder value chain components and the rectangles (blue in colour) represent the impacts to the small holders**.**


Direct pathway relating to improved nutrition to subsistence-oriented production for the household's own consumption


Indirect pathway relating improved nutrition to income generated from the sale of agricultural products


Indirect pathway relating to improved nutrition to income generated from local procurement of nutritious foods produced by smallholder farmers

Recently, the harvest plus project promoted bio-fortification [a process aimed at increasing the concentration of nutrients for edible portions of crop plants through plant breeding (Montalvo et al., 2016)] of essential micronutrients through breeding of staple crops such as maize (*Zea mays*), cassava (*Manihot esculenta*), sweet potato (*Ipomoea batatas*), and rice (*Oryza sativa*) (https://www.harvestplus.org/). However, these staple crops take a long period to mature when compared to traditional vegetables ("food plants that have been used over a hundred years'') (Table 1.1). Traditional vegetables grow naturally from the ‘‘wild’’ or next to mainstream crops. This prompted many authors (Afari-Sefa et al., 2012; Chivenge et al., 2015; Govender et al., 2017; Mabhaudhi et al., 2017a, b; Maseko et al., 2018; Mavengahama et al., 2013; Oelofse and Van Averbeke, 2012) to suggest that traditional vegetables are nutrient dense (iron, zinc, and β-carotene) and more productive [in terms of biomass (aboveground biomass plus stems and/ or storage organ, nutritional yield, and nutritional water productivity)] than alien vegetables. In addition, there are vegetables [traditional vegetables- cowpea (*Vigna unguiculata*), pumpkin (*Cucurbita pepo*), and sweet potato (*Ipomoea batatas* (L.) Lam.); alien vegetable- beetroot (*Beta vulgaris*)] that have the potential of being utilised as dual-purpose vegetables; green leafy vegetable and the storage organ. This list of dual-purpose vegetables includes sweet potato. Sweet potato is a major crop in sub-Saharan Africa, which is mostly produced by rural resource-poor households for subsistence use (Low et al., 2017; Motsa et al., 2015). Orange-fleshed sweet potato 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, b; Motsa et al., 2015). However, sweet potato aboveground edible biomass has been underutilised, except for feeding livestock. The aboveground edible biomass can be harvested several times for a maximum period of six months and are rich in iron, zinc, calcium, and β-carotene (β-carotene can be converted into vitamin A inside human bodies) (Islam, 2006). Therefore, orange-fleshed sweet potato should be investigated in sub-Saharan Africa for possible utilisation as a dual-purpose use food crop (green leafy vegetable and storage root for human consumption).

Table 1.1 Selected traditional vegetables used in sub-Saharan Africa

Scientific name	English name	Vernacular names	Seasonality
Amaranthus spp.	Amaranth	Imbuya/ vowa/ thebe	Summer
Bidens pilosa	Blackjack	Amalenjane/ uqadolo/mushidzhi	All year
Brassica rapa L.	Chinese cabbage	Mutshaina/ dabadaba	Winter
Corchorus spp.	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
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	Cowpea leaves	Dinawa/ indumba/ munawa	Summer

Traditional vegetables fit well with the smallholder value chain model (Figure 1.1) because they can be harvested frequently, in small quantities, and without the need for storage. However, knowledge on their yield response to water and fertiliser is limited; therefore, this study aims to understand how selected traditional vegetables (amaranth and spider flower), respond to inputs (water and fertiliser) and the potential role they can play in alleviating nutritional food insecurity of rural resource-poor households. It should be noted that traditional crops cannot replace mainstream crops, but are meant to improve the current food system through dietary diversity (Mabhaudhi et al., 2018).

1.2 Food system

The major components of a food system are food supply chains, food environments, and consumer behaviour. The *food supply chain* consists of different activities and actors; from food production to consumption. Therefore, decisions made by a group of actors can either increase the nutritional value of food or decrease it (Hawkes and Ruel, 2012). For example;

globally, there are six major crops that dominate what is grown; these are maize (*Zea mays*), rice (*Oryza sativa*), sugarcane (*Saccharum officinarum*), soybean (*Glycine max*), wheat (*Triticum aestivum*), and oil palm (Elaeis guineensis). Out of these six crops, maize, wheat, and rice represent half of the food supply in the world. To strengthen the current food systems against external shocks such as climate variability (Chivenge et al., 2015; Khoury et al., 2014; HLPE, 2017; Govender et al., 2017; Mabhudhi et al., 2016, 2017 a, b, 2019), more crops should be added, including traditional vegetables. This will improve dietary quality and diversity for the current production system and at different scales (household, community, and landscapes). In sub-Saharan Africa, predictions indicate that precipitation will decrease, whereas temperatures will increase over the coming decades (Dresselhaus and Hückelhoven, 2018; Ewert et al., 2015, Matthews et al, 2013). This threatens agricultural productivity. For example, a study by Dresselhaus and Hückelhoven (2018) showed that a combination of drought and heat stresses might reduce the growth and productivity of wheat by approximately 40 %. In addition, Matthews et al. (2013) argued that future climate changes will affect agriculture negatively in that; if existing crop varieties continue to be used, yields will decline dramatically due to less water availability, faster crop maturation, more erratic weather, and the invasion of new pests and diseases. However, changing climates might also bring new opportunities through shifting of crops to regions that cannot currently support them. In addition, farmers might adapt current food systems by cultivating crops that are currently under-utilised (Matthews et al., 2013).

The high level panel of experts (HLPE,2017: 28) has defined the *food environment* as the *‘’physical, economic, political and socio-cultural context in which consumers engage with the food system to make their decisions about acquiring, preparing, and consuming food*.’’ Healthy food environments produce highly nutritious food that can alleviate micronutrient deficiency and malnutrition. Generally, food environments are not healthy because they promote mainstream crops that play a major role in securing caloric food security at the national level (Mabhaudhi et al., 2017b). We acknowledge the crucial role played by mainstream crops in combating the energy-food security quest. However, these crops are deficient in essential micronutrients (iron and zinc) and β-carotene, which the body converts into vitamin A. To fulfil these nutritional requirements, the World Health Organisation encourages households to consume a minimum of 200 kg/capita/year of vegetables in order to live a healthy life (Afari-Sefa et al., 2012). Home gardens can play a major role in improving the intake of nutrient-dense vegetables, if combined with proper selection of crops that are highly nutritious. Vegetables are important in a diet because they supplement essential micronutrients and vitamins. Micronutrient deficiencies (known as ‘’hidden hunger") affect mostly rural resource-poor households and peri-urban households in sub-Saharan Africa (Nyathi et al., 2018a; Oelofse and Van Averbeke, 2012; Wenhold et al., 2012).

The current food system is under pressure to achieve equitable food distribution and to feed the growing population using resources already dedicated to agriculture (Mabhaudhi et al., 2018). Suggestions have been made (Chivenge et al., 2015; Mabhaudhi et al., 2016b, 2017 a, b; 2019; Oelofse and Van Averbeke, 2012, Wenhold et al., 2012) for the inclusion of traditional vegetables in the current food system for dietary diversity. However, current government policies acknowledge the need to achieve higher food productivity. These policies are silent on nutritional food security for all, including rural resource-poor households (Mabhaudhi et al., 2018). Therefore, policy-makers should set up a new agenda that could play a major role in incorporating traditional vegetables into the current food system.

The *food environment* also shapes *consumer behaviour*, which is influenced by several factors, including personal preferences, taste, convenience, values, traditions, culture and beliefs (HLPE, 2017). In many sub-Saharan African countries, rural resource-poor households might not consume traditional vegetables when there is a variety of other vegetables, because traditional vegetables carry the label of a ‘‘poor man’s crop’’. Yet, these vegetables are nutrient dense in micronutrients and vitamins (Oelofse and Van Averbeke, 2012). However, in times of food shortages, rural resource-poor households are likely to consume traditional leafy vegetables (Misselhorn and Hendriks, 2017). The HLPE (2017) recognises three types of the food system; these are the traditional food system, the mixed food systems, and the modern food systems:

Traditional food systems: this type of food system is characterised by very low dietary diversity because rural resource-poor households rely on locally produced food and tend to purchase processed products such as cooking oil and sugar. Under the traditional food system, diets of rural resource-poor households consist of maize and rice; micronutrient deficiency is very high, which leads to high rates of stunting and low cognitive development.

Mixed food system: Under this food system, people reside in peri-urban and urban areas with better income compared to the traditional food system. Food is accessed through local shops and supermarkets, which sell processed, packaged, and fresh food. Food is prepared at the household level or eaten outside at restaurants. In this system, there is access to sufficient calories and proteins. Therefore, incidences of stunting and delayed cognitive development are very low. However, micronutrient deficiency is still a major problem and cases of overweight and obesity are more predominant.

Modern food system: In this food system, people reside in urban areas and have higher incomes with a wide range of food choices. The well-developed infrastructure enables food to be transported from the point of production and delivered so that it is accessible to the high-income dwellers. Food is procured from supermarkets that offer more choices and better quality. In addition, options for meals prepared outside the household are plenty. Under this food system, people consume a balanced diet meal; therefore, incidences of micronutrient deficiency are minimal.

However, the current food system is under the threat of the loss of biodiversity and the reduction of land and water resources available for food production due to climate change (Ewert et al., 2015). Historical records indicate that global warming is causing changes in temperature and rainfall patterns and has increased the frequency and severity of extreme events (Ewert et al., 2015). For example, a study by Lobell and Gouirdji (2012) found that global warming (average temperatures over the growing season of major cereals increased by approximately 0.75 ºC between 1980 and 2011) decreased yields of maize and wheat by approximately 5 %, whereas an increase in carbon dioxide levels improved yields of C_3 crops by approximately 3 %. This shows that the current food system has to adapt to meet the challenge of improving nutritional food security (food production, food access, food utilisation, and food stability), especially for rural resource-poor households, under climate change (Ewert et al., 2015). Matthews et al. (2013) suggested four areas that current food system should adapt to: (i) the introduction of new crops; (ii) development of new varieties of existing crops; (iii) evolution of crop management practices; and (iv) dealing with climate uncertainty through the provision of information. Although good principles to adhere to, additional emphasis is needed to improve the food basket for sub-Saharan Africa by the ‘‘re-introduction’’ of traditional vegetables. According to claims in the literature, these vegetables are nutrient dense (iron, zinc, and β-carotene), drought tolerant, and they require minimum inputs in terms of water and fertiliser. Therefore, traditional vegetables are ideal crops for improving nutritional food security of rural resource-poor households, under climate change (Afari-Sefa et al., 2012; Chivenge et al., 2015; Govender et al., 2017; Mabhaudhi et al., 2017a and b; Maseko et al., 2018; Mavengahama et al., 2013; Nyathi et al., 2016, 2018 a, b, 2019a; Oelofse and Van Averbeke, 2012; Wenhold et al., 2012). However, these claims of nutrient denseness and high productivity of traditional vegetables need to be proven in a systematic way to establish their agronomic validity.

1.3 Crop modelling

The ‘‘re-introduction’’ of traditional vegetables calls for an understanding of how these vegetables will interact with the environment, in order to give out the desired outcome of producing highly nutritious food for rural resource-poor households (Matthews et al., 2013). Crop productivity is a function of cropping system management. Therefore, to understand the genotype by environment interaction of traditional vegetables, experiments need to be conducted throughout the country, which can be very expensive and cumbersome. Crop models can be used as key tools to contribute to research, decision support, and knowledge exchange on climate change and food security (Challinor et al., 2018; Matthews et al., 2013). Dynamic, process-based crop growth simulation models have been developed since the sixties to understand how crops respond to meteorological conditions, soil and management conditions, and crop genetic characteristics at varying spatial scales, including field, regional, and global scales (Ewert et al., 2015). Recently, several crop models have been developed, including the AquaCrop model (developed by the Food and Agriculture Organisation of the United Nations), the Soil Water Balance Model (SWB, by the University of Pretoria, South Africa), the Agricultural Production System Simulator model (APSIM, Australian crop model developed by various organisations), the World Food Studies model (WOFOST, developed by Wageningen University), and the Decision Support System for Agrotechnology Transfer (DSSAT, developed by the United States of America) (Nyathi et al., 2019a).

Progress has been made in testing crop models with field experiments under a wide range of crops and growing conditions. However, most crop models have been tested for maize, wheat, rice, and sorghum; neglecting vegetables, which play a major role in supplementing essential micronutrients and vitamins. This means that efforts to address nutritional food insecurity often lacks consideration (Mabhaudhi et al., 2018). For example, a study by Nyathi et al. (2018b) showed that the database for AquaCrop model caters for only two vegetables [*Solanum lycopersicum* (tomato) and *Beta vulgaris* (but as sugar beet not as a leafy vegetable)] that are not nutritious. The soil water balance crop model provides for a large number of alien vegetables [onion (*Allium cepa*), cabbage (*Brassica oleracea*), carrot (*Daucus carota*), beetroot (*Beta vulgaris*), lettuce (*Lactuca sativa*), Swiss chard (*Beta vulgaris*), eggplant (*Solanum melongena*), pumpkin (*Cucurbita pepo*), butternut (*Juglans cineria*), green pepper (*Capsicum annuum*), and tomato (*Solanum lycopersicum*)] with conservative parameters (Annandale et al., 1999). To construct sustainable food systems that is health-focused and inclusive of rural resource-poor households; more vegetables (including traditional vegetables) with conservative parameters should be added in model databases (Nyathi et al., 2018a). In this study, we selected the Food and Agriculture Organization AquaCrop model (www.fao.org/aquacrop), which simulates yield response of crops to water stress, particularly in locations where water is a limiting factor of crop production. The AquaCrop model can play a major role in assessing the potential of traditional vegetables for home consumption and their commercial viability. Since traditional vegetables are *"new crops"*, the AquaCrop model has not been calibrated and validated yet, using data from controlled experiments, for these selected traditional vegetables. Calibrated crop models can be used as a decision support tool for policymakers in making decisions for policy formulation, especially policies aligned to address nutritional food insecurity in sub-Saharan Africa (Matthews et al., 2013).

1.4 Nutritional water productivity

There is a strong linkage between water use in agriculture, food and nutrition security (Mabhaudhi et al., 2016a). The major factors that influence food security in sub-Saharan Africa are water scarcity, population growth, and nutrient deficiencies (iron, zinc, and vitamin A). This leads to increased pressure on production resources (water and fertiliser), resulting in lower productivity of crops. Therefore, agriculture is faced with a challenge of increasing productivity (producing more biomass per unit of water used) by adopting the slogan of *"more crop per drop"*; meaning increasing water productivity [yield or biomass (kg ha^{-1}) per unit of evapotranspiration (m^3 ha^{-1})] of crops by reducing the amount of water consumed by crops through actual evapotranspiration (Clemens and Molden, 2007). Van Halsema and Vincent (2012) averred that crop water productivity is governed by crop growth and production parameters rather than irrigation parameters. Therefore, water productivity is determined by (i) crop species (C_3 or C_4), (ii) nutrient deficiencies in the crop growth cycle, and (iii) to lesser extent irrigation practices. Some traditional vegetables are C_4 plant species [amaranth (*Amaranthus cruentus*) and spider flower (*Cleome gynandra*)]; therefore, they can improve water productivity of rural resource-poor households, as they are photosynthetically more water efficient than C_3 crops.

However, the agronomic knowledge of traditional vegetables is scarce, as most modern agronomy has been oriented towards commercial crops. There is a need to design field experiments aimed to understand the physiological behaviour of traditional vegetables under different water spectrum; ranging from rainfed to entirely fully irrigated conditions. The highest water productivity is attained at sub-optimal yield levels (slight water stress). However, in the process of altering yield to increase water productivity, we do not know what happens to the nutrient concentration of crops; for example, do nutrients concentration and yield increase or decrease (Figure 1.2)? This is a new research agenda where crop productivity research has to shift its focus from water productivity to nutritional water productivity [NWP = (Yield or biomass per actual evapotranspiration) × nutritional content of a product)]. The nutritional water productivity index links water use of crops, crop production, and nutritional requirements (Chibarabada et al., 2017; Nyathi et al., 2018b, 2019b; Renault and Wallender, 2000; Wenhold et al., 2012). A study conducted by Oelofse and Van Averbeke (2012) assessed nutritional water productivity of eight traditional vegetables using data sets (total edible aboveground biomass, total water applied, and nutrient concentration) sourced from various locations. Further research is needed to better understand the link between water, soil nutrients, management practices, biomass, and nutrients concentration of selected traditional vegetables. This research gap has been acknowledged by a scoping study on nutritional water productivity of food crops in South Africa (Wenhold et al., 2012). Therefore, research on nutritional water productivity of selected leafy vegetables (amaranth, spider flower, and Swiss chard) is a key step towards improving food and nutrition security of rural resource-poor households while conserving already limited freshwater resources. There is no other study we are aware of that evaluated nutritional water productivity of amaranth (*Amaranthus cruentus*), spider flower (*Cleome gynandra*), and Swiss chard (*Beta vulgaris*) using datasets (aboveground edible biomass, water use, and nutrient concentration) from the same location. This thesis is the first in assessing the nutritional water productivity of selected traditional vegetables.

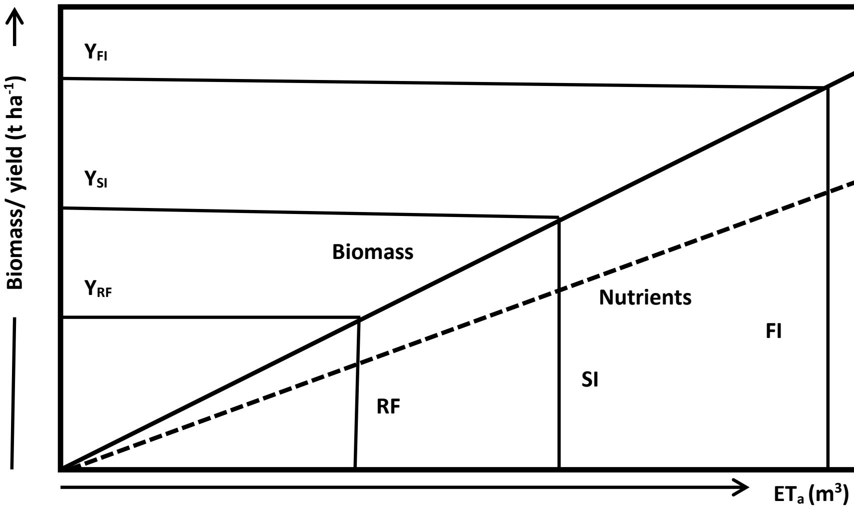

Figure 1.2 Relationship between water use and biomass/ or yield within different water levels. Where; RF= rainfed; SI= supplemental irrigation; FI= full irrigation; Y_{FI} = fully irrigated yield; Y_{SI} = supplemental irrigation yield; Y_{RF}= rainfed yield. Increasing water application from RF to FI will result in higher biomass whilst adding fertiliser from zero to optimum application will increase the slope of the line, causing it to move between the dashed and solid lines. However, the sensitivity of nutrients content and nutritional water productivity is unknown (adapted from Tittonell et.al, 2011)

1.6 Research objectives

The main objective of this thesis is to evaluate nutritional water productivity of traditional vegetables. Literature use anecdotal information to backup claims that traditional vegetables are nutrient dense[(iron, zinc, and β-carotene) and more productive than alien vegetables under water stressed conditions. If these claims are true, there is a need to ‘‘re-introduce’’ traditional vegetables into the current food system for dietary diversity; however, their yield response and nutrient concentration (iron, zinc, and β-carotene) to water stress have not been assessed. The research addresses the following research questions:

1. Are traditional vegetables superior to alien vegetables for selected plant parameters (aboveground biomass plus stems and/or storage organ, nutrient concentration, nutritional yield, and nutritional water productivity)?

2. Are traditional vegetables [spider flower (*Cleome gynandra*) and amaranth (*Amaranthus cruentus*)] superior to an alien vegetable [(Swiss chard (*Beta vulgaris*)] in terms of biomass (aboveground edible biomass plus stems), nutrient concentration, nutritional yield, and nutritional water productivity?

3. Can the AquaCrop model be calibrated and validated for repeatedly harvested vegetables such as amaranth, spider flower, and Swiss chard?

4. What is the effect of utilising orange-fleshed sweet potato (*Ipomoea batatas* var. Bophelo) as a dual-purpose food crop (green leafy vegetable and storage root for human consumption) on the storage root yield?

1.7 The structure of the this thesis

This thesis comprises of six chapters, including this introductory chapter. Chapter 2 addresses the first research question (RQ1); we used two independent databases [the water productivity (aboveground biomass plus stems and/ or storage organ/crop evapotranspiration) and nutrient concentration] to generate the nutritional water productivity database. Although this is not an ideal approach to generate the nutritional water productivity database using datasets [aboveground biomass plus stems and/ or storage organ, water use, and nutrient concentration (iron, zinc, and β-carotene)] sourced from various literature sources, it was the only available approach to come up with a first order estimate of ten alien vegetables and ten traditional vegetables. Traditional vegetables were superior in iron and zinc nutritional water productivities, whereas alien vegetables were rich in β-carotene nutritional water productivity. Chapter 3 tackles the second research question (RQ2) by assessing nutritional water productivity of two selected traditional leafy vegetables (amaranth and spider flower) using datasets (aboveground edible biomass, evapotranspiration, and nutrient concentration) collected from the same location. To further address question 2, nutritional water productivity of the selected traditional leafy vegetables was compared with the nutritional water productivity of Swiss chard. Key findings showed that Swiss chard was superior in iron and zinc nutritional water productivities, whereas amaranth was rich in β-carotene nutritional water productivity.

Chapter 4 addresses the third research question (RQ 3); the AquaCrop model was calibrated and validated for repeatedly harvested leafy vegetables (amaranth, spider flower, and Swiss chard) using datasets collected from the field experiments (Chapter 3). Crop modelling makes field experiment results to be more generic and applicable to various locations. Measured parameters were the aboveground biomass, canopy cover, soil water content, actual evapotranspiration, and water productivity. Findings showed that it is possible to calibrate and validate the AquaCrop model. However, AquaCrop version 4.0 is not capable of running sequential harvests in a single run; therefore, each harvest was calibrated and validated separately. Chapter 5 tackles research question 4 (RQ 4) by evaluating whether orange-fleshed sweet potato (*Ipomoea batatas* var. Bophelo) can be used as a dual-purpose food crop (green leafy vegetable and storage root for human consumption). The effect of vine harvest on selected plant parameters (storage root yield, leaf and storage root nutrient concentration, nutritional yield, and nutritional water productivity) was assessed. Key findings indicated that orange-fleshed sweet potato can be used a dual-purpose food for rural resource-poor households because the green leafy vegetable can be consumed during the growing season and at the end of the season, the storage root becomes available, which spreads food availability over a long period of time. However, for commercial farming, the dual use of orange-fleshed sweet potato is not an ideal practice because marketable storage root yield reduces by half. Chapter 6 presents the main findings of this thesis, which are discussed in the context of the research questions and the remaining research gaps are highlighted.

Chapter

2

Benchmarking nutritional water productivity of twenty vegetables - A review

This chapter is based on:

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Abstract

Traditional vegetables are piloted as champion species for sub-Saharan Africa, a region experiencing high levels of nutritional food insecurity and water scarcity. The important benefits of traditional vegetables over alien vegetables are; (i) their high nutrient density (iron, zinc, and β-carotene), (ii) their productivity under water stress, and (iii) their availability to rural resource-poor households. However, information on these benefits is anecdotal. The objectives of this study were to benchmark nutritional water productivity [NWP = (aboveground edible biomass and/ or storage organ biomass/actual evapotranspiration) × nutritional content of a product] of ten traditional vegetables and compare them with ten alien vegetables. We selected vegetables that are widely utilised by rural resource-poor households. A comprehensive literature search was conducted using common databases. Data [biomass (aboveground biomass and/ or storage organ), water use, and nutrient concentration] sourced from the literature were used to compute water productivity, nutritional yield (NY), and NWP of selected vegetables. Our results revealed that the water productivity of traditional vegetables was comparable to that of alien vegetables. In addition, traditional vegetables were superior in nutritional yield (Fe-NY and Zn-NY) and NWP (Fe-NWP and Zn-NWP) of micronutrients. Alien vegetables were rich in β-carotene-NY and β-carotene-NWP; this is contrary to the anecdotal information. We acknowledge the weakness of our approach; generating the NWP database using two independent datasets (crop water productivity and the nutrient concentration databases). However, this was the only pragmatic approach to establish first-order estimates of NWP for selected groups of vegetables. We propose that future research should be conducted to validate these results.

Keywords: Nutritional food security; traditional vegetables; water productivity; hidden hunger; micronutrients; vitamin A; water footprint

2.1 Introduction

Agriculture is faced with a threefold challenge; (i) meeting the demand for food to feed approximately 9 billion people in the coming decades, (ii) developing environmentally friendly and sustainable methods of production, and (iii) improving the nutritional food security of rural resource-poor households (Godfray et al., 2010). There are approximately 239 million people in sub-Saharan Africa suffering from micronutrient deficiency as a form of "hidden hunger" (Afari-Sefa et al., 2012). Hidden hunger is a chronic lack of iron, zinc, and vitamins; its effects may not be immediately apparent, but it may have severe consequences in the long term by inducing stunted growth, delayed cognitive development, and reduced immunity (Maberly et al., 1994). Afari-Sefa et al. (2012) noted that in sub-Saharan Africa, consumption of vegetables per capita was below the minimum of 200 kg person^{-1} year^{-1}. Vegetables are important in a diet because they supplement essential micronutrients (iron and zinc) and β-carotene, which the body converts into vitamin A.

Mabhaudhi et al. (2017a) iterated that vegetables could be classified as ''traditional'' or ''alien''. Traditional vegetables refer to species that were introduced in an area more than a hundred years ago, where they adapted to local conditions and they became part of the local culture. In contrast, alien vegetables are crops that have recently been imported to a certain geographical location and are produced commercially since recent times (Mabhaudhi et al., 2017a; Nyathi et al., 2018a; Oelofse and Van Averbeke, 2012). Several authors (Afari-Sefa et al., 2012; Chivenge et al., 2015; Govender et al., 2017; Mabhaudhi et al., 2017a, b; Maseko et al., 2018; Mavengahama et al., 2013; Oelofse and Van Averbeke, 2012) reached consensus on the important benefits of traditional vegetables when compared to alien vegetables. This includes their high nutrient density (iron, zinc, and β-carotene), their short crop cycle, the low use of agronomic inputs, their high productivity under water stress conditions, and their abundance in the ''wild'' (i.e., available for rural resource-poor households) or next to cereal crops as ''weeds" (Nyathi et al., 2018b). However, information on these benefits was anecdotal; assumptions were that traditional vegetables grow naturally in the ''wild'' or next to mainstream crops [*Zea mays* (maize), *Oryza sativa* (rice), *Triticum aestivum* (wheat), *Solanum tuberosum* (Irish potato)] without being supplied with fertiliser and water. This makes traditional vegetables champion species in areas experiencing high levels of nutritional food insecurity and water scarcity (Mabhaudhi et al., 2016b).

The water productivity index [WP = total biomass (aboveground dry biomass and/or storage organ)/actual evapotranspiration] was authenticated by several authors (Ali and Talukder, 2008; Geerts and Raes, 2009; Molden et al., 2010; Nyathi et al., 2016; Passioura and Angus, 2010; Renault and Wallender, 2000). This index can be used to assess food production per unit of water used. However, components of food security incorporate quantity (''more food produced per unit of water used'') and quality (''more nutrition per drop'') (Govender et al., 2017). Chibarabada et al. (2017) and Mabhaudhi et al. (2016b) realised that research on water use of crops, crop productivity, and nutrient concentration is being conducted in isolation. Agronomists and irrigation experts are interested in producing ''*more crop per unit of water used*'' (water productivity), whereas nutritionists research tends to focus on meeting the daily-recommended human nutrition requirements (Chibarabada et al., 2017; Mabhaudhi et al., 2016b; Oelofse and Van Averbeke, 2012; Odhav et al., 2007; Schönfeldt and Pretorius, 2011; Uusiku et al., 2010, Van Jaarsveld et al., 2014). This means that efforts to address food security of rural resource-poor households often lack consideration for their nutritional status.

Therefore, there is a need to link the two (Mabhaudhi et al., 2016a). Renault and Wallender (2000) proposed the nutritional water productivity index (NWP) [NWP = (aboveground dry edible biomass and/ or storage organ/actual evapotranspiration) × nutritional content of a product)], which links water use of crops, crop production, and nutritional requirements. Chibarabada et al. (2017) conducted a study that compared the nutritional water productivity of traditional legumes to the nutritional water productivity of alien legumes. To the best of our knowledge, there is no study, which evaluated nutritional water productivity of traditional vegetables and compared them with alien vegetables.

The main aim of the study is to benchmark the nutritional water productivities of ten traditional vegetables [*Amaranthus spp.* (amaranth), *Bidens pilosa* (blackjack), *Brassica carinata* (kale), *Brassica rapa*, (Chinese cabbage), *Cleome gynandra* (spider flower), *Corchorus spp.* (jute mallow), *Cucurbita maxima* (pumpkin leaves), *Ipomoea batatas* (sweet potato leaves), *Solanum nigrum* (black nightshade), and *Vigna unguiculata* (cowpea leaves)] and ten alien vegetables [*Allium cepa* (onion), *Beta vulgaris* (beetroot), *Beta vulgaris* (Swiss chard), *Brassica oleracea* (cabbage), *Brassica oleracea* var*.* *italica* (broccoli), *Cucumis sativus* (cucumber), *Daucus carota* (carrot), *Juglans cineria* (butternut), *Lactuca sativa* (lettuce), and *Solanum lycopersicum* (tomato)]. We selected vegetables that are widely utilised by rural resource-poor households in sub-Saharan Africa (Hendriks et al., 2016; Maseko et al., 2018; Nyathi et al., 2016; Oelofse and Van Averbeke et al., 2012). Thereafter, we computed their water productivity, nutritional yield, and nutritional water productivity. The research questions of this study were: (1) Are traditional vegetables more nutrient dense than alien vegetables for iron, zinc, and β-carotene (β-carotene can be converted to vitamin A inside human bodies)? (2) Are traditional vegetables more productive than alien vegetables in terms of biomass [aboveground biomass (aboveground edible biomass plus stems and/or storage organ)], nutritional yield, and nutritional water productivity? (3) What are the research gaps that future research needs to address for traditional vegetables?

2.2 Materials and methods

The database for this study comprised of peer-reviewed journal articles, books, research project reports, and conference proceedings that were produced between 2000 and 2019. Databases such as the United States Department of Agriculture Food Composition (https://ndb.nal.usda.gov/ndb/) and the Food and Agricultural Composition/In Foods (http://www.fao.org/infoods/infoods/tables-and-databases/faoinfoods-databases/en/) were also considered. We conducted a comprehensive literature search using databases such as Google Scholar, Scopus, CAB Abstracts, and Web of Science. The following keywords were included in the search: (i) ‘‘species scientific name or common name; water productivity, water footprint, water use efficiency, deficit irrigation, water requirements, evapotranspiration, water stress, biomass, yield response, and productivity.’’ (ii) ‘‘species scientific name or common name; nutrient content, nutrient concentration, micronutrients, mineral content (iron, zinc, and β-carotene), and nutritional water productivity.’’ We retrieved approximately 420 peer-reviewed articles; ≈ 50 % were from sub-Saharan Africa, ≈ 30 % from Asia, ≈ 10 % from North and South America, and ≈ 10 % from Europe. Articles were further screened and only those meeting the following criteria were selected: (i) experiments were conducted under field conditions or rain shelters (pot experiments were excluded), (ii) treatments included water-stressed conditions and well-watered conditions, (iii) measured plant parameters included biomass or yield and water used (evapotranspiration and/ or water applied), (iv) articles reported vegetable yield per unit area of land (kg ha^{-1}, t ha^{-1}, and g m^{-2}), and (v) nutrient concentrations were reported in nutrient concentration per 100 g (mg per 100 g or retinol activity equivalent per 100 g). After screening, we selected 53 articles that were included in the review. Data sourced from the literature were used to calculate water productivity, nutritional yield, and nutritional water productivity (Eqs. 1, 2, and 3). Note that water footprint [evapotranspiration (ET)/ biomass (aboveground biomass and/ or storage organ)] is the inverse of water productivity [biomass (aboveground biomass and/ or storage organ)/ET]. In this study, we converted the water footprints values of selected alien vegetables to water productivity. For example, Mekonnen and Hoekstra (2011) found that the total water footprint (green plus blue water footprints) of spinach is 132 m^3 ton^{-1}, thus its water productivity [(1 ton × 1000 kg/ton)/132 m^3] is 7.58 kg m^{-3}.

WP = [biomass (t DM ha^{-1}) / ET] × 100 (Eq. 1)

NY = biomass (t DM ha^{-1})] × HI × NC × 10 (Eq. 2)

NWP = [aboveground edible biomass (t DM ha^{-1}) / ET)] × NC (Eq. 3)

where biomass is the aboveground biomass (aboveground edible biomass plus stems) and/ or storage organ; WP (kg m^{-3}) is the water productivity, ET (mm/ season) is evapotranspiration; NY (g DM ha^{-1}) is iron, zinc, and β-carotene nutritional yields; HI is the harvest index (unitless); NC (mg DM 100 g^{-1}) is nutrient concentration (iron, zinc, and β-carotene); and NWP (mg m^{-3}) is the nutritional water productivity index. β-carotene concentration was converted into vitamin A concentration [(µg RAE (retinol activity equivalents)] based on Trumbo et al. (2003) (1µg RAE = 1µg retinol = 12 µg of β-carotene). The daily-recommended nutrient intakes (DRNI) for iron, zinc, and β-carotene [infants (1-3 years); children (4-19 years); male adults (19-65 years); female adults (19-65 years)] were sourced from Uusiku et al. (2010). Percentage contribution to the daily recommended-nutrient intake was calculated according to Kruger et al. (2015) (Eq. 4). The nutrient content (iron, zinc, and vitamin A) for boiled vegetables were computed from the raw values using the United States Department of Agriculture nutrient retention factors (USDA, 2007) (Table 2A.1). We further assumed that around 45 % is lost due to limited bioavailability inside human bodies (Amagloh et al., 2017; Gupta et al., 2006). In addition, we calculated the amount of water required to meet human nutritional requirements per person (Box 2.1) using Eq. 5.

% contribution to DRNI = [Iron, zinc, or vitamin A concentration (mg 100g^{-1}) / Iron, zinc, or vitamin A concentration (mg day^{-1})] × 100 Eq. 4)

Water required (litres $person^{-1}$ day^{-1}) = [TNR / NWP (mg m^{-3}) / 6 people] × 1000 (Eq. 5)

where TNR (mg day^{-1}) is total nutrients required [iron (mg day^{-1}), zinc (mg day^{-1}), and vitamin A (µg RAE day^{-1})] by a family of six people.

Box 2.1 Iron, zinc, and vitamin A requirements for a family of six people

Vitamin A requirements for a household of six [(one adult male = 600 µg RAE day^{-1}; one adult female = 500 µg RAE day^{-1}; two 1-3 year infants (2 × 400 µg = 800 µg RAE day^{-1}); two 4-18 year children (2 × 600 µg = 1200 µg RAE day^{-1}); ***total = 3100 µg RAE day^{-1}***)]. Iron requirements for a household of six [(one adult male = 13.7 mg day^{-1}; one adult female = 29.7 mg day^{-1}; two 1-3 year infants (2 × 5.8 mg = 11.6 mg day^{-1}); 4-18 year children (2 × 32.7 mg = 65 mg day^{-1}); ***total = 120 mg day^{-1}***)]. Zinc requirements for a household of six [(one adult male = 14 mg day^{-1}; one adult female = 9.8 mg day^{-1}; two 1-3 year infants (2 × 8.3 mg = 16.6 mg day^{-1}); 4-18 year children (2 × 14.4 mg = 28.8 mg day^{-1}); ***total = 69.2 mg day^{-1}***)].

2.3 Results

2.3.1 Total dry biomass, water use, and water productivity of twenty vegetables

Table 2.1 presents dry biomass (aboveground biomass and/or storage organ) for twenty vegetables. The mean values for traditional vegetables ranged from 0.5 to 5.9 t ha^{-1}; the lowest aboveground edible biomass was obtained from pumpkin (0.5 t ha^{-1}), the median biomass (aboveground edible biomass plus stems) from amaranth (3.6 t ha^{-1}) and jute mallow (3.6 t ha^{-1}), and the highest biomass (aboveground edible biomass plus stems) from sweet potato (5.9 t ha^{-1}). Chinese cabbage and black nightshade exhibited the lowest seasonal water use (180 mm), whereas sweet potato displayed the highest seasonal water use (505 mm). Water productivity values for traditional vegetables ranged from 0.21 to 2.09 kg m^{-3}; the lowest water productivity value was obtained from pumpkin (0.21 kg m^{-3}) and the highest water productivity values were obtained from Chinese cabbage (2.09 kg m^{-3}) and spider flower (2.05 kg m^{-3}). We could not compute water productivity for blackjack and kale because information on biomass (aboveground edible biomass plus stems) and water use was missing in the literature investigated.

For alien vegetables, biomass (aboveground biomass and/or storage organ) ranged from 2.6 to 9.0 t ha^{-1}; the lowest biomass (aboveground biomass and/ or storage organ) was obtained from beetroot (2.6 t ha^{-1}), median values from Swiss chard (4.0 t ha^{-1}) and carrot (4.2 t ha^{-1}), and the highest from cabbage (9.0 t ha^{-1}) (Table 2.1). Our results illustrate that alien vegetables are more productive than traditional vegetables per unit area of land. The lowest seasonal water use for alien vegetables was 234 mm (tomato), median seasonal values were 340 mm (beetroot) and 360 mm (butternut), and the highest seasonal water use was 537 mm (onion). Water productivity values for alien vegetables ranged from 0.76 to 2.45 kg m^{-3}; the lowest water productivity was obtained from beetroot, whereas the highest water productivity was observed from cabbage. Generally, the grand mean results show that water productivity values for traditional vegetables (grand mean = 1.29 kg m^{-3}) and alien vegetables (1.37 kg m^{-3}) are comparable.

2.3.2 Nutrient concentrations, nutritional yield, and potential contribution to human nutrition

The nutrient concentrations of ten traditional vegetables are presented in Table 2.2. The mean iron content varied from 9 to 47 mg 100 g^{-1}; pumpkin aboveground edible biomass exhibited the lowest iron concentration and black nightshade displayed the highest iron concentration. Zinc concentration ranged from 2 to 29 mg 100 g^{-1}; the lowest zinc concentration was attained from sweet potato aboveground edible biomass, whereas the highest zinc concentration was obtained from cowpea aboveground edible biomass. Kale showed the lowest vitamin A concentration (241 µg RAE 100 g^{-1}) and amaranth (1556 µg RAE 100 g^{-1}) displayed the highest vitamin A concentration. Table 2.3 presents nutrient concentrations values of ten alien vegetables. The results of this study highlighted that alien vegetables are lower in iron and zinc compared to traditional vegetables. The mean values ranged from 4 to 43 mg 100 g^{-1} for iron; for zinc, the mean values ranged from 2 to 16 mg 100 g^{-1}. For vitamin A, alien vegetables were superior (grand mean ≈ 2121 µg RAE 100 g^{-1}) over traditional vegetables (grand mean ≈ 884 µg RAE 100 g^{-1}). It is crucial to note that onion contains no vitamin A (0 µg RAE 100 g^{-1}).

Table 2.1 Dry biomass, water use, and water productivity (WP) of twenty vegetables

Vegetables	Biomass ($t\ ha^{-1}$)			HI[a]	Water use (mm)			WP	References
Traditional vegetables	**Min.**	**Max.**	**Mean**		**Min.**	**Max.**	**Mean**	**$kg\ m^{-3}$**	
Amaranthus spp. (amaranth)	0.5	6.6	3.6	0.68	50	520	285	1.25	Nyathi et al. (2018b); Oelofse and Van Averbeke et al. (2012); Wenhold et al. (2012)
Bidens pilosa (blackjack)	NV[b]	NV	NV	NV	NV	NV	NV	NV	
Brassica carinata (kale)	NV	NV	NV	NV	NV	NV	NV	NV	
Brassica rapa (Chinese cabbage)	0.5	7	3.8	0.71	37	322	180	2.09	Oelofse and Van Averbeke (2012); Wenhold et al. (2012)
Cleome spp. (spider flower)	0.6	9.8	5.2	0.40	50	457	254	2.05	Nyathi et al. (2018b); Oelofse and Van Averbeke et al. (2012)
Corchorus spp. (jute mallow)	0.4	6.7	3.6	0.63	78	462	270	1.31	Oppong-Danso et al. (2015); Maseko et al. (2015); Oelofse and Van Averbeke (2012); Wenhold et al. (2012)
Cucurbita pepo (pumpkin leaves)	0.3	0.7	0.5	0.85	86	389	238	0.21	Oelofse and Van Averbeke et al. (2012)
Ipomoea batatas (sweet potato leaves)	0.7	11	5.9	0.50	160	850	505	1.16	Gomes and Carr (2003a); Laurie et al. (2018); An et al. (2003); Motsa et al. (2015); Nyathi et al. (2018b)
Solanum nigrum (black night shade)	0.4	4.2	2.3	0.36	37	322	180	1.28	Oelofse and Van Averbeke (2012); Wenhold et al. (2012)
Vigna unguiculata (cowpea leaves)	0.5	5.1	2.8	0.73	117	462	290	0.97	Chimonyo et al. (2016); Oelofse and Van Averbeke (2012)
Mean	**0.5**	**6.4**	**3.4**	**0.61**	**77**	**473**	**275**	**1.29**	
Alien vegetables									
Allium cepa (onion)	3.1	5.4	4.3	0.84	180	893	537	0.79	Enciso et al. (2009); Igbadun et al. (2012); Kumar et al. (2007); López -Urrea et al. (2009)
Beta vulgaris (beetroot)	2.0	3.2	2.6	0.71	383	383	340	0.76	Wenhold et al. (2012)
Beta vulgaris (Swiss chard)	1.5	6.4	4.0	0.86	129	625	377	1.05	Nyathi et al. (2018b); Wenhold et al. (2012)
Brassica oleracea (cabbage)	7.5	10.4	9.0	0.61	182	549	366	2.45	Imtiyaz et al. (2000); Nurhidayati et al. (2016); Paranhos et al. (2016); Seidel et al. (2017); Wenhold et al. (2012)
Brassica oleracea var. *italica* (broccoli)	1.7	9.6	5.6	0.25	187	440	314	1.79	Erdem et al. (2010); Wenhold et al. (2012)
Cucumis sativus (cucumber)	1.1	6.5	3.8	0.70	150	672	411	0.91	Wan et al. (2010); Wang et al. (2009); Yaghi et al. (2013)
Daucus carota (carrot)	2.0	6.4	4.2	0.79	112	390	251	1.67	Imtiyaz et al. (2000); Wenhold et al. (2012)
Juglans cineria (butternut)	2.4	4.5	3.5	0.45	350	370	360	0.96	Wenhold et al. (2012)
Lactuca sativa (lettuce)	0.6	4.9	2.7	0.54	122	477	300	0.91	Bozkurt et al. (2009); D'Haene et al. (2018)
Solanum lycopersicum (tomato)	2.4	8.7	5.6	0.65	137	330	234	2.38	Yang et al. (2017); Zhang et al. (2017); Wenhold et al. (2012)
Mean	**2.4**	**6.6**	**4.5**	**0.64**	**193**	**513**	**349**	**1.37**	

[a]HI- harvest index

Table 2.2 Nutrient concentration (on dry mass basis) of iron, zinc, and vitamin A and fats for ten traditional vegetables

Traditional vegetables	Moisture	Iron (mg $100g^{-1}$)			Zinc (mg $100g^{-1}$)			Vitamin A (µg RAE 100 g^{-1})			Fats (g)	References
		Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean		
Amaranthus spp. (amaranth)	0.82	1.6	47	24	1.1	56	29	146	2983	1565	0.31	Njume et al. (2014); Nyathi et al. (2018b); Odhav et al. (2007); Schönfeldt and Pretorius (2011); Uusiku et al. (2010); Van Jaarsveld et al. (2014)
Bidens pilosa (blackjack)	0.85	1.3	40	21	6.1	22	14	983	983	983	0.50	Schönfeldt and Pretorius (2011); Uusiku et al. (2010); Wenhold et al. (2012)
*Brassica carinata (*kale*)*	0.85	6.0	22	14	0.0	0.0	0.0	241	241	241	0.31	Kawashima et al. (2003); USDA (2018)
Brassica rapa (Chinese cabbage*)*	0.95	4.0	70	37	2.8	6.0	4.4	357	1907	1132	0.20	Njume et al. (2014); USDA (2018)
Cleome spp. (spider flower)	0.76	2.6	78	40	4.0	8.4	6.2	40	1808	924	0.57	Njume et al. (2014); Nyathi et al. (2018b); Schönfeldt and Pretorius (2011); Uusiku et al. (2010); Van Jaarsveld et al. (2014)
Corchorus spp. (jute mallow)	0.80	2.0	78	40	2.5	4.0	3.3	40	1645	843	0.18	Abukutsa-Onyango et al. (2010); Njume et al. (2014); Traore et al. (2017); Schönfeldt and Pretorius (2011); Van Jaarsveld et al. (2014)
Cucurbita pepo (pumpkin leaves)	0.93	2.2	16	9.1	2.9	13	8.0	194	325	260	0.17	Schönfeldt and Pretorius (2011); USDA (2018); Uusiku et al. (2010); Van Jaarsveld et al. (2014)
Ipomoea batatas (sweet potato leaves)	0.79	5.0	69	37	1.4	3.2	2.3	103	945	524	0.08	Nyathi et al. (2019b); USDA et al. (2018); Wenhold et al. (2012)
Solanum nigrum (black night shade)	0.83	8.5	85	47	5.0	23	14	240	2482	1361	0.50	Abukutsa-Onyango et al. (2010); Njume et al. (2014); Uusuku et al. (2010); Van Jaarsveld et al. (2014)
Vigna unguiculata (cowpea leaves)	0.86	2.0	81	42	1.6	125	63	540	1485	1013	0.43	Belane and Dakora (2011); Njume et al. (2014); Schönfeldt and Pretorius (2011); Uusiku et al. (2010); Wenhold et al. (2012)
Mean	**0.84**	**3.5**	**59**	**31**	**2.7**	**26**	**14**	**288**	**1480**	**884**	**0.33**	

Table 2.3 Nutrient concentration (on dry mass basis) of iron, zinc, vitamin A, and fats for ten alien vegetable crops

Alien vegetables	Moisture	Iron (mg 100g^{-1})			Zinc (mg 100g^{-1})			Vitamin A (µg RAE 100 g^{-1})			Fats	References
		Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean		
Allium cepa (onion)	0.84	1.3	11	6	0.6	9.6	5.1	NV[a]	NV	NV	0.10	FAO (2018); Wenhold et al. (2012); USDA (2018)
Beta vulgaris (beetroot)	0.92	5.8	25	16	2.0	6.4	4.2	25	25	25	0.20	FAO (2018); Mamatha et al. (2011); Sasa et al. (2012)
Beta vulgaris (Swiss chard)	0.90	18.0	54	36	3.0	6.3	4.7	1417	4680	3049	0.15	Bozodkalfa et al. (2011); Kawashima et al. (2003); Nyathi et al. (2018b); Wenhold et al. (2012); USDA (2018)
Brassica oleracea (cabbage)	0.92	1.8	33	18	1.9	4.4	3.1	50	70	60	0.20	FAO (2018); Kawashima et al. (2003); USDA (2018); Xiao et al. (2016)
Brassica oleracea var. *italica* (broccoli)	0.89	6.5	8.0	7.2	3.2	3.6	3.4	4	54	29	0.35	Reif et al.. (2013); USDA (2018); Xiao et al. (2016); Mamatha et al. (2011)
Cucumis sativus (cucumber)	0.95	4.6	15	10	3.4	8.6	6.0	50	50	50	0.11	FAO (2018); Maboko et al. (2017); USDA (2018)
Daucus carota (carrot)	0.89	2.7	7.7	5.2	2.2	29	16	1663	8350	5007	0.24	FAO (2018); Singh et al. (2001); USDA (2018); Wenhold et al. (2012)
Juglans cineria (butternut)	0.85	2.7	4.7	3.7	1.0	2.7	1.9	853	3547	8750	0.10	USDA (2018); Wenhold et al. (2012); Zacchari and Galietta (2015)
Lactuca sativa (lettuce)	0.95	10.0	76	43	3.6	11.5	7.6	480	7400	3940	0.19	FAO (2018); Kawashima et al. (2003); Reif et al. (2013); USDA (2018)
Solanum lycopersicum (tomato)	0.94	3.7	8.5	6.1	1.2	3.3	2.3	244	356	300	0.20	Borgoguone et al. (2013); Erba et al. (2013); FAO (2018); Pinela et al. (2012); USDA (2018)
Mean	**0.91**	**5.7**	**24**	**15**	**2.2**	**8.5**	**5.4**	**479**	**2453**	**2121**	**0.18**	

[a]NV- no value

The estimated percentage nutrient contribution of twenty vegetables for four age groups is presented in Table 2.4. Assessments showed that 100 g of boiled spider flower could potentially provide ≈ 87 % of iron, whereas amaranth could potentially provide ≈ 32 % of zinc and ≈ 47 % of vitamin A to the daily-recommended nutrient intake for infants. For children aged between 4 to 19 years, traditional vegetables could potentially contribute a lesser percentage to the daily-recommended nutrient intake because of the higher demand (Box 2.1). For vitamin A, it was interesting to note that butternut could potentially provide more than the daily-recommended nutrient intake for all age groups. We calculated the amount of nutrients that can be harvested per unit area of land (nutritional yield, NY) for traditional and alien vegetables (Table 2.5). The grand means displayed more micronutrients (≈ 2-fold) could be harvested from traditional vegetables compared to alien vegetables and more β-carotene (≈ 3-fold) could be harvested from alien vegetables compared to traditional vegetables. For traditional vegetables, the highest Fe-NY (1082 g ha^{-1}), Zn-NY (1294 g ha^{-1}), and β-carotene-NY (453 g ha^{-1}) were obtained from sweet potato aboveground edible biomass, cowpea aboveground edible biomass, and amaranth, respectively. For alien vegetables, the highest Fe-NY (1223 g ha^{-1}), Zn-NY (515 g ha^{-1}), and β-carotene-NY (1984 g ha^{-1}) were achieved from Swiss chard and butternut, respectively.

Table 2.4 Estimated percentage nutrient contribution of twenty vegetables for four groups based on 100 g fresh boiled product intake per person per day

	Iron				Zinc				Vitamin A			
	Infants	Children	Adult Male	Adult female	Infants	Children	Adult Male	Adult female	Infants	Children	Adult Male	Adult female
Vegetables	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**
Traditional vegetables												
Amaranthus spp. (amaranth)	39	7	17	8	32	19	19	27	47	31	31	37
Bidens pilosa (blackjack)	28	5	12	5	13	8	8	11	25	16	16	20
Brassica carinata (kale)	19	3	8	4	0	0	0	0	6	4	4	5
Brassica rapa (Chinese cabbage)	17	3	7	3	1	1	1	1	9	6	6	8
Cleome spp.(spider flower)	87	15	37	17	9	5	6	8	37	25	25	29
Corchorus spp. (jute mallow)	72	13	31	14	4	2	2	3	28	19	19	22
Cucurbita pepo (pumpkin leaves)	6	1	2	1	4	2	2	3	3	2	2	2
Ipomoea batatas (sweet potato leaves)	70	12	30	14	3	2	2	3	18	12	12	15
Solanum nigrum (black night shade)	72	13	30	14	15	9	9	13	38	26	26	31
Vigna unguiculata (cowpea leaves)	52	9	22	10	56	32	33	47	24	16	16	19
	46	**8**	**20**	**9**	**14**	**8**	**8**	**12**	**17**	**12**	**12**	**14**
Alien vegetables												
Allium cepa (onion)	5	1	2	1	3	2	2	2	NV[a]	NV	NV	NV
Beta vulgaris (beetroot)	6	1	2	1	1	1	1	1	NV	NV	NV	NV
Beta vulgaris (Swiss chard)	32	6	14	6	3	2	2	2	51	34	34	41
Brassica oleracea (cabbage)	13	2	5	2	2	1	1	1	1	1	1	1
Brassica oleracea var. italica (broccoli)	7	1	3	1	2	1	1	2	1	0	0	0
Cucumis sativus (cucumber)	5	1	2	1	2	1	1	2	0	0	0	0
Daucus carota (carrot)	3	0	1	1	6	3	3	5	67	45	45	54
Juglans cineria (butternut)	3	0	1	1	1	1	1	1	161	107	107	129
Lactuca sativa (lettuce)	20	4	9	4	3	1	1	2	34	23	23	28
Solanum lycopersicum (tomato)	3	1	1	1	1	1	1	1	3	2	2	2
	10	**2**	**4**	**2**	**2**	**1**	**1**	**2**	**32**	**21**	**21**	**25**

[a]NV- no value

Table 2.5 Nutritional yield and nutritional water productivity of twenty vegetables

Vegetables	Nutritional yield			Nutritional water productivity		
	Iron	Zinc	β-carotene	Iron	Zinc	Vitamin A
Traditional vegetables	g ha^{-1}	g ha^{-1}	g ha^{-1}	mg m^{-3}	mg m^{-3}	µg RAE m^{-3}
Amaranthus spp. (amaranth)	587	689	453	303	356	19488
Bidens pilosa (blackjack)	NV[a]	NV	NV	NV	NV	NV
Brassica carinata (kale)	NV	NV	NV	NV	NV	NV
Brassica rapa (Chinese cabbage)	985	117	362	773	92	23649
Cleome spp. (spider flower)	838	129	231	827	127	18954
Corchorus spp. (jute mallow)	895	73	226	526	43	11077
Cucurbita pepo (pumpkin leaves)	38	34	13	19	17	546
Ipomoea batatas (sweet potato leaves)	1082	67	184	429	27	6070
Solanum nigrum (black night shade)	387	116	135	599	179	17439
Vigna unguiculata (cowpea leaves)	848	1294	248	401	612	9793
Mean	**708**	**315**	**232**	**485**	**182**	**13377**
Alien vegetables						
Allium cepa (onion)	218	182	NV	48	40	NV
Beta vulgaris (beetroot)	287	78	6	119	32	191
Beta vulgaris (Swiss chard)	1223	158	1243	377	49	31941
Brassica oleracea (cabbage)	959	171	39	430	77	1469
Brassica oleracea var. italica (broccoli)	102	48	5	130	61	516
Cucumis sativus (cucumber)	257	158	16	89	55	456
Daucus carota (carrot)	172	515	1984	87	260	83375
Juglans cineria (butternut)	57	29	1630	35	18	83854
Lactuca sativa (lettuce)	633	112	700	392	69	36045
Solanum lycopersicum (tomato)	220	81	130	145	54	7150
Mean	**413**	**153**	**639**	**185**	**71**	**27222**

[a]NV- no value

2.3.3 Nutritional water productivity

The grand mean results indicated that nutritional water productivity values for traditional vegetables were 485 mg m^{-3} for iron, 182 mg m^{-3} for zinc, and 13377 µg RAE m^{-3} for vitamin A (Table 2.5). The lowest nutritional water productivity values for iron (19 mg m^{-3}), zinc (17 mg m^{-3}), and vitamin A (546 mg m^{-3}) were observed from pumpkin aboveground edible biomass, respectively. The highest nutritional water productivity for iron was observed from spider flower (827 mg m^{-3}); for zinc (612 mg m^{-3}); it was attained from cowpea aboveground edible biomass and for vitamin A (23649 µg RAE m^{-3}) from Chinese cabbage. Generally, our results revealed that traditional vegetables were more productive than alien vegetables (grand means for iron = 185 mg m^{-3} and for zinc = 71 mg m^{-3}) per unit of water used to produce micronutrients, whereas alien vegetables were more productive per unit of water used to produce vitamin A (grand mean = 27222 µg RAE m^{-3}). For alien vegetables, the lowest nutritional water productivity for iron, zinc, and vitamin A was obtained from carrot (87 mg m^{-3}), butternut (18 mg m^{-3}), and beetroot (191 µg RAE m^{-3}), respectively. The highest nutritional water productivity values were 430 mg m^{-3} for iron (cabbage), 260 mg m^{-3} for zinc (carrot), and 83854 µg RAE m^{-3} for vitamin A (butternut). Our results showed that spider flower required the least amount of water to meet iron (202 litres $person^{-1}$ day^{-1}) and vitamin A (162 litres $person^{-1}$ day^{-1}) requirements, whereas cowpea aboveground edible biomass required the least amount of water to meet zinc requirements (269 litres $person^{-1}$ day^{-1}) (Table 2.6). For alien vegetables, our results revealed that more water would be required to meet human nutrition requirements for micronutrients. Swiss chard indicated that 1060 litres $person^{-1}$ day^{-1} would be required to meet iron requirements, carrot showed that 808 litres $person^{-1}$ day^{-1} would be required to meet zinc requirements, and butternut illustrated that 59 litres $person^{-1}$ day^{-1} would be required to meet vitamin A requirements.

Table 2.6 The amount of water needed to meet human nutritional requirements (iron, zinc and vitamin) for selected vegetables

	Iron	**Zinc**	**Vitamin A**
Traditional vegetables	**litres $person^{-1}$ day^{-1}**	**litres $person^{-1}$ day^{-1}**	**litres $person^{-1}$ day^{-1}**
Amaranthus spp. (amaranth)	734	360	210
Bidens pilosa (blackjack)	NV[a]	NV	NV
Brassica carinata (kale)	NV	NV	NV
Brassica rapa (Chinese cabbage)	1035	5019	624
Cleome spp. (spider flower)	202	756	162
Corchorus spp. (jute mallow)	380	2699	333
Cucurbita pepo (pumpkin leaves)	29992	19689	19301
Ipomoea batatas (sweet potato leaves)	444	4123	579
Solanum nigrum (black night shade)	393	756	249
Vigna unguiculata (cowpea leaves)	712	269	538
Mean	**4237**	**4209**	**2750**
Alien vegetables			
Allium cepa (onion)	5169	3572	0[b]
Beta vulgaris (beetroot)	4205	8977	48260
Beta vulgaris (Swiss chard)	1060	4735	231
Brassica oleracea (cabbage)	1162	3762	6280
Brassica oleracea var. italica (broccoli)	2805	3427	13008
Cucumis sativus (cucumber)	8947	8427	32358
Daucus carota (carrot)	4187	808	80
Juglans cineria (butternut)	7582	8674	59
Lactuca sativa (lettuce)	2043	6675	410
Solanum lycopersicum (tomato)	4597	7169	1721
Mean	**4176**	**5623**	**11378**

[a]NV-mean that there is no value; [b]0- mean that the amount of water needed to meet nutritional requirements for vitamin A is 0 for onion because it contains no vitamin A

2.4 Discussion

Although nutritional water productivity data can provide useful information in an agricultural context, in relation to human nutritional requirements, water use of crops, and crop productivity, nutritional water productivity data of traditional vegetables is minimal. Ordinarily, literature (Chivenge et al., 2015; Maseko et al., 2018; Mavengahama et al., 2013) use anecdotal information to back up claims that traditional vegetables are more productive [in terms of biomass (aboveground biomass, and/ or storage organ) and water productivity] and nutrient dense (iron, zinc, and β-carotene) than alien vegetables. Therefore, this study sought to evaluate these claims using datasets [biomass (aboveground biomass and/or storage organ), nutrient concentration, and evapotranspiration] sourced from literature. We assessed nutritional water productivity of ten traditional vegetables with ten alien vegetables. Our expectations were that selected traditional vegetables were superior to alien vegetables in terms of biomass (aboveground biomass and/or storage organ). However, the results of this study revealed that alien vegetables were more productive than traditional vegetables in terms of biomass (aboveground biomass and/or storage organ). We suspect that reported yield values for traditional vegetables occurred under sub-optimal conditions and reported yield values for alien vegetables occurred under optimal conditions. Over the years, alien vegetables have been improved through plant breeding and were selected for high performance under well-endowed growing conditions. Agricultural production for most rural resource-poor households occurs under rain-fed conditions (Maseko et al., 2018); therefore, achieving yield potential is limited by water availability, assuming that the crop is well managed (sowing date, cultivar date, plant density, nutrient management, and crop protection) (Van Ittersum et al., 2013).

In future decades, water scarcity will intensify, especially for sub-Saharan Africa; therefore, the water productivity index [WP- a ratio of biomass (aboveground biomass and/ or storage organ) per crop evapotranspiration] would be a critical benchmark for food production (Van Ittersum et al., 2013). This index is synonymous to water use efficiency; however, Van Halsema and Linden (2012) argued that these two terms are not similar, the difference being the denominator. Water use efficiency is the ratio of biomass (aboveground biomass and/or storage organ) per total water applied. Our results show that traditional vegetables use slightly less water (grand mean = 473 mm/season) than alien vegetables (grand mean = 513 mm/ season), which agrees with other studies (Chibarabada et al., 2017; Nyathi et al., 2018b; Oelofse and Van Averbeke, 2012). In addition, the results of this study illustrated that water productivity of both vegetables (traditional vegetables = 1.29 kg m^{-3} and alien vegetables = 1.37 kg m^{-3}) was comparable. This was contrary to previous studies (Nyathi et al., 2016; Nyathi et al., 2018b), which reported that the water productivity of traditional vegetables was higher than that of alien vegetables. These contradictory findings by our study might have been caused by assessing water productivity using datasets from various locations, whereas studies by Nyathi et al. (2016) and Nyathi et al. (2018b) assessed water productivity using datasets from the same location.

Unkovich et al. (2018) emphasised the need to use the beneficial use of water (transpiration rather than evapotranspiration) when assessing water productivity of crops. Studies conducted by Nyathi et al. (2018a and b) assessed water productivity of selected traditional vegetables (amaranth and spider flower) and an alien vegetable (Swiss chard). Their initial results showed that water productivity of traditional vegetables and an alien vegetable were similar when evapotranspiration was used as the denominator. However, when transpiration was used as the denominator, water productivity of traditional vegetables was higher than the water productivity of the alien vegetable; this illustrates the need to use transpiration instead of evapotranspiration. In addition, assessing water productivity of vegetables (beetroot, cowpea, pumpkin, and sweet potato) that have both different types of edible plant parts (leaves and the storage organ) is a challenge. Some studies evaluated water productivity using only one plant part; for example, a study by Oelofse and Van Averbeke (2012) evaluated water productivity of pumpkin aboveground edible biomass, which excluded the storage organ. This is a bit unfortunate because the aboveground biomass may be partitioned into both plant parts and would favour the storage organ over the aboveground edible biomass; therefore, it is crucial to use total biomass (aboveground biomass and the storage organ) when assessing the water productivity of these vegetables. These vegetables have the potential of being used for dual purpose (dark green leafy vegetable and the storage organ for human consumption) for improved food and nutrition security. In addition, we converted the water footprint values of selected alien vegetables to water productivity values (Table 2A.2); at a glance, these values are higher compared to the values of this study. Probably the water footprint values from Le Roux et al. (2016) and Mekonnen and Hoekstra (2011) were calculated on a fresh mass basis. Therefore, alien vegetables might have high water footprint if a fresh mass was used, but if a dry mass was used, water footprints of these vegetables could be relatively low (Le Roux et al., 2016). Le Roux et al. (2016) found that the water footprints of maize and wheat were higher than those of vegetables if expressed in terms of fresh mass; however, when expressed in terms of dry mass, the water footprints of maize and wheat were similar to those of vegetables. Information on water footprints for selected traditional vegetables was missing from literature surveyed.

From research conducted by nutritionists on the nutrient concentration of crops, daily consumption targets to meet human nutrition requirements can be derived (Uusiku et al., 2010; Van Jaarsveld et al., 2014; Schönfeldt and Pretorius, 2011). Our results showed that traditional vegetables were superior to alien vegetables in iron (≈ 52 %) and zinc (≈ 64 %), whereas alien vegetables were superior to traditional vegetables in vitamin A (≈ 58 %) concentration. This concurs with several studies which have been conducted on the nutrient concentration of selected vegetables (Schönfeldt and Pretorius, 2011; USDA, 2018; Uusiku et al., 2010; Van Jaarsveld et al., 2014; Wenhold et al., 2012). However, the reported nutritional values show a quite high degree of variability. We pose a question; why are nutritional values of vegetables not conservative? Uusiku et al. (2010) attributed the variation to genotype, environment, management, and different seasons. Several studies (Afolayan and Jimoh, 2009; Odhav et al., 2007; Uusiku et al., 2010; Van Jaarsveld et al., 2014; Schönfeldt and Pretorius, 2011) conducted by nutritionists did not evaluate the effect of environmental factors (climatic conditions, severe drought conditions, soil fertility, and management) on nutrient concentrations of vegetables. The goal of nutritionists is to compute the portion (per 100 g) of iron, zinc, and β-carotene that should be consumed to meet daily consumption targets for human nutrition. Aerts and Chapin (1999) found that nitrogen deficiency in crops such as lettuce, carrot, Swiss chard, and maize reduced β-carotene concentration. Another study conducted by Cole et al. (2016) found that fertiliser application increased iron and zinc in tomato plant tissues. In addition, Nyathi et al. (2018b) revealed that severe water stress increased iron and zinc nutrient concentration, whereas β-carotene concentration showed sensitivity towards severe water-stressed conditions. These studies highlight that environmental factors play a major role in the nutrient concentration of crops. There is not much collaboration amongst nutritionists, agronomists, and irrigation experts (Mabhaudhi et al., 2016a). However, evaluating nutrient concentration without considering yield is not an ideal practice, because of both account for the nutrient yield per unit area of land, a useful term that was suggested by Bumgarner et al. (2012).

The mean results revealed that traditional vegetables have higher iron and zinc nutritional yields, while alien vegetables were superior in β-carotene nutritional yield. This study provided new insight into the importance of using nutritional yield as a parameter for assessing the nutritional superiority of selected vegetables. For the assessments of the number of children aged between 4 to 18 years that one could feed for a period of 90 days from one hectare, for iron and zinc requirements; traditional vegetables showed that it could provide for more children (iron-grand mean = 40; zinc-grand mean = 15 children) compared to alien vegetables (iron-grand mean = 15 children; zinc-grand mean = 6 children) (Table 2A.3). Practically, this suggests that these children would need to consume huge amounts of boiled alien vegetables to meet their daily iron and zinc requirements. Sweet potato aboveground edible biomass (96 children) showed the highest number of children that it could potentially supply with iron and cowpea leaves (70 children) showed the highest number of children that it could potentially supply with zinc. For vitamin A, alien vegetables (69 children) could potentially supply more children compared to traditional vegetables (grand mean = 32 children). Butternut illustrated the highest number (264 children) of children that it could potentially supply with vitamin A. Limited information exists on nutritional yield of alien and traditional vegetables; Nyathi et al. (2018b) conducted a study that evaluated nutritional yields of nutrients (iron, zinc, and β-carotene) for amaranth, spider flower, and Swiss chard. They reported nutritional yield values that were within the range of the current study. For example, our study reported iron nutrition yield of 587 g ha^{-1} for amaranth, whereas Nyathi et al. (2018b) reported iron nutritional yield values for amaranth ranging from 362 to 1361 g ha^{-1}.

Nutritional water productivity (NWP) is an index that links crop production, water use in agriculture, and nutrient concentration (Chibarabada et al., 2017; Mabhaudhi et al., 2016b). It was interesting to note that traditional vegetables were more productive than alien vegetables in Fe-NWP and Zn-NWP. Spider flower was the most productive vegetable to produce iron per unit of water used, whereas cowpea (aboveground edible biomass) was the most productive vegetable to produce zinc per unit of water used (Table 2.5). Alien vegetables were more productive (≈ 2-fold) in β-carotene-NWP compared to traditional vegetables; butternut was the most productive vegetable to produce vitamin A per unit of water used (Table 2.5). This highlights the need for crop diversification in order to maximise the amount of nutrients produced per unit of water used to meet human nutrition requirements. Practically, NWP values can be used to compute the total amount of water required (litres $person^{-1}$ day^{-1}) to meet human nutrition requirements (iron, zinc, and vitamin A) (Table 2.6). For example, the current population of South Africa is estimated at 56.5 million people and it is expected to reach 65 million people by the year 2030 (Stats SA, 2018). Therefore, a diet of spider flower used as a side dish would require 11417424 kiloliters day^{-1} [(202 L day^{-1} × 56,521,900 people)/1000 L/kL] to meet iron requirements for children aged between 4 to 18 years in 2018. In 2030, the same diet would require 13130000 kL day^{-1} [(202 L day^{-1} × 65,000,000 people)/1000 L/kL] to meet iron requirements for the same age group, an additional 1712576 kL day^{-1}. Information on NWP of vegetables is inadequate; conducted studies (Mabhaudhi et al., 2017b; Nyathi et al., 2018b; Mdemu et al., 2009; Renault and Wallender, 2000) reported NWP values (iron, zinc, and β-carotene) for limited vegetables (amaranth, spider flower, Swiss chard, cowpea, tomato, and onion). Our study is the first to benchmark NWP for a number of vegetables (Table 2.5).

2.5 Summary and future research

Water use values of selected vegetables were sourced from literature and used to generate the water productivity database. The challenge with this approach is that some studies did not indicate whether water use was total water applied or evapotranspiration. This has placed a severe limitation on water productivity values reported by this study. Another complexity was that the estimates of nutritional water productivity values (Fe-NWP, Zn-NWP, and β-carotene-NWP) of this study came from two independent datasets; a crop water productivity database and the nutrient concentration database, both with some level of uncertainty. Our major concern was the reliability of using these two independent datasets to generate a third database (NWP). We agree that this approach is not ideal, but it was the only pragmatic approach to come up with first order estimates of nutritional water productivity for traditional vegetables and alien vegetables. Regardless of the complexities reported by this paper, key findings showed that traditional vegetables are low in β-carotene concentration and dense in iron and zinc. This contradicts information from literature, which reported traditional vegetables as ‘‘miracle crops’’ (nutrient dense in all micronutrients and vitamins), using anecdotal information. Our study is the first in assessing nutritional water productivity of ten traditional vegetables and compare them with ten alien vegetables. We propose that future research and validation of these results should consider the following:

- The results of this study highlighted that nutrient concentration of vegetables is not conservative because of several factors [plant variety among species, environment (soil type and pH), harvesting method, climatic conditions, different seasons, soil fertility, and water availability]. However, it was not clear which of these factors affect nutrient concentration of vegetables. Therefore, future research should assess the major factors crucial for determining the nutrient concentration of vegetables.

- Yield response of traditional vegetables to irrigation and fertiliser is unknown. We propose that field experiments for a wide range of traditional vegetables should be conducted to assess their yield response to inputs (water and fertility stresses) and should develop ‘‘new variables’’ (aboveground edible biomass, nutrient concentration, nutritional yield, evapotranspiration, water productivity, and nutritional water productivity) using datasets collected from the same experiments (Table 2.7). These ‘‘newly developed variables’’ will improve the agronomic knowledge of traditional vegetables. In addition, data collected from field experiments can be used to calibrate and validate crop growth models [AquaCrop, the soil water balance, and Agricultural Production System Simulator (APSIM)] for upscaling the results.

Table 2.7 New variables for traditional vegetables research

Parameter	Definition	Justification
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.
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.
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
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.
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.

- In countries such as Kenya and Tanzania, traditional vegetables have been commercialised through various awareness campaigns (local radio stations, TV stations, trade fairs, exhibitions, in-store promotions, outdoor promotions, nutritional walks, and product sampling) (Mwangi and Kimathi, 2006). This shows that there is a possibility of commercializing traditional vegetables in other sub-Saharan African countries. Therefore, future efforts to commercialise traditional vegetables should consider using massive awareness campaigns as in Kenya and Tanzania. In addition, these studies should consider assessing other factors [personal food preferences, attitude, aspirations, and identity (middle-class)] that influence the acceptability and consumption of traditional vegetables in other sub-Saharan African countries (Mavengahama et al., 2013).

- The aboveground edible biomass of traditional vegetables can be higher in nutrient concentration (iron, zinc, and β-carotene) compared with alien vegetables. However, nutrients might not be bioavailable because of anti-nutrients such as oxalate, hydrocyanic acid, tannins, and polyphenols (Mavengahama et al., 2013). Moreover, the bioavailability of nutrients might change depending on the method of food preparation, i.e. boiling, steaming, or frying (Schönfeldt and Pretorius, 2011). We propose that food scientists in collaboration with chefs should find the best method of preparing traditional vegetables such that micronutrients and vitamins are bioavailable for human consumption.

- Traditional vegetables are highly perishable within a few hours of being harvested. In 2015, the South Africa's Agricultural Research Council in collaboration with Nestle launched a new line of Maggi noodles containing amaranth (http://www.nestle.com/media/news/nestle-south-africa-maggi-noodles-morogo-launch). To improve the shelf life of traditional vegetables and reduce post-harvest losses, we propose that more of such products should be developed from traditional vegetables, in collaboration with nutraceutical companies in sub-Saharan Africa.

- In sub-Saharan Africa, vegetables such as beetroot, cowpea, pumpkin, and sweet potato have the potential of being utilised as dual-purpose vegetables; green leafy vegetable and the storage organ. The aboveground edible biomass can be an additional source of green leafy vegetable during the summer season and after the end of the growing season, the storage organ can be consumed. This spreads food availability over a longer period, hence an improvement in the nutritional food security of rural resource-poor households (Nyathi et al., 2019a). We propose that a study should be conducted to evaluate the effect of leaf harvesting on yield and nutrient concentration of storage organs.

- If water becomes scarce, water footprints information can inform farmers to plant less water-intensive crops (Le Roux et al., 2016). The literature surveyed for this study showed that information on the water footprint of traditional vegetables is minimal. We propose that future research should consider evaluating the water footprints of many traditional vegetables using data collected from the same location.

Appendix 2A

Table 2A.1 Nutrient concentration of twenty raw (fresh mass basis) and twenty boiled vegetables for iron, zinc, and vitamin A

	Raw (fresh mass)			Boiled			Availability after human consumption		
	Iron	Zinc	Vitamin A	Iron	Zinc	Vitamin A	Iron	Zinc	Vitamin A
Traditional vegetables	**mg 100g^{-1}**	**mg 100g^{-1}**	**RAE 100g^{-1}**	**mg 100g^{-1}**	**mg 100g^{-1}**	**µg RAE 100g^{-1}**	**mg 100g^{-1}**	**mg 100g^{-1}**	**RAE 100g^{-1}**
Amaranthus spp. (amaranth)[g]	4.37	5.14	282	4.16	4.88	268	2.29	2.69	187
Bidens pilosa (blackjack)[g]	3.10	2.11	147	2.94	2.00	140	1.62	1.10	98
Brassica carinata (Kale)[g]	2.10	0.00	36	2.00	0.00	34	1.10	0.00	24
Brassica rapa (Chinese cabbage)[g]	1.85	0.22	57	1.76	0.21	54	0.97	0.11	38
Cleome spp.(spider flower)[g]	9.67	1.49	222	9.19	1.41	211	5.05	0.78	147
Corchorus spp. (jute mallow)[g]	8.00	0.65	169	7.60	0.62	160	4.18	0.34	112
Cucurbita pepo (pumpkin leaves)[g]	0.63	0.56	18	0.60	0.53	17	0.33	0.29	12
Ipomoea batatas (sweet potato leaves)[g]	7.77	0.48	110	7.38	0.46	105	4.06	0.25	73
Solanum nigrum (black night shade)[g]	7.95	2.38	231	7.55	2.26	220	4.15	1.24	154
Vigna unguiculata (cowpea leaves)[g]	5.81	8.86	142	5.52	8.42	135	3.04	4.63	94
Mean	**5.13**	**2.19**	**141**	**2.56**	**1.09**	**99**	**1.41**	**0.60**	**69**
Alien vegetables									
Allium cepa (onion)[r]	0.98	0.82	0.00	0.49	0.41	0.00	0.27	0.22	NV[a]
Beta vulgaris (beetroot)[r]	1.24	0.34	2.00	0.62	0.17	1.40	0.34	0.09	0.98
Beta vulgaris (Swiss chard)[g]	3.60	0.47	305	3.42	0.44	290	1.88	0.24	203
Brassica oleracea (cabbage)[g]	1.41	0.25	4.80	1.33	0.24	4.56	0.73	0.13	3.19
Brassica oleracea var. italica (broccoli)[g]	0.79	0.38	3.16	0.76	0.36	3.00	0.42	0.20	2.10
Cucumis sativus (cucumber)*	0.49	0.30	2.50	0.49	0.30	2.50	0.27	0.17	1.75
Daucus carota (carrot)[r]	0.57	1.71	551	0.29	0.86	386	0.16	0.47	270
Juglans cineria (butternut)[r]	0.55	0.28	1313	0.28	0.14	919	0.15	0.08	643
Lactuca sativa (lettuce)*	2.14	0.38	197	2.14	0.38	197	1.18	0.21	138
Solanum lycopersicum (tomato)	0.37	0.14	18	0.37	0.14	17	0.20	0.07	12.0
Mean	**1.21**	**0.50**	**240**	**0.61**	**0.25**	**168**	**0.33**	**0.14**	**117**

[a]NV- no value; [g]dark green vegetables; [r]storage root vegetables; *vegetables which are eaten raw (i.e. cucumber and lettuce). Nutrient retention factors used to compute raw nutrient values to boiled values were as follows: dark green vegetables- iron = 0.95, zinc = 0.95, and vitamin A = 0.95; storage root vegetables-iron =0.95, zinc = 0.95, and vitamin A = 0.90; tomatoes- iron =1.00, zinc = 1.00, and vitamin A = 0.95; vegetables eaten raw- iron, zinc, and vitamin A = 1.00

Table 2A.2 Water footprint and water productivity of alien vegetables (Adapted from le Roux et al., 2016; Mekonnen and Hoekstra, 2011)

Alien vegetables	**Water footprint (m^3 ton^{-1})**			**Water productivity (kg m^{-3})**		
	Green	**Blue**	**Total**	**Green**	**Blue**	**Total**
Allium cepa (onion)	192	88	280	5.21	11	3.57
Beta vulgaris (beetroot)	92	18	110	10.8	56	9.07
Beta vulgaris (Swiss chard)	118	14	132	8.47	71	7.58
Brassica oleracea (cabbage)	119	20	140	8.38	50	7.17
Brassica oleracea var. italica (broccoli)	202	41	243	4.95	24	4.12
Cucumis sativus (cucumber)	206	42	248	4.85	24	4.03
Daucus carota (carrot)	87	22	109	11.5	46	9.20
Juglans cineria (butternut)	228	24	252	4.39	42	3.97
Lactuca sativa (lettuce)	95	20	116	10.5	49	8.64
Solanum lycopersicum (tomato)	108	63	171	9.26	16	5.85
Mean	**145**	**35**	**180**	**7.83**	**39**	**6.32**

Table 2A.3 Number of people that one hectare of selected traditional vegetables and selected alien vegetables could possibly feed (fresh edible portion) for iron, zinc, and β-carotene nutritional requirements for ninety days

Vegetables	Number of people		
	Iron	Zinc	β-carotene
Traditional vegetables			
Amaranthus spp. (amaranth)	44	48	88
Bidens pilosa (blackjack)	NV[a]	NV	NV
Brassica carinata (Kale)	NV	NV	NV
Brassica rapa (Chinese cabbage)	21	2	20
Cleome spp. (spider flower)	85	12	60
Corchorus spp. (jute mallow)	75	6	49
Cucurbita pepo (Pumpkin leaves)	1	1	1
Ipomoea batatas (Sweet potato leaves)	96	5	42
Solanum nigrum (Black night shade)	28	8	25
Vigna unguiculata (Cowpea leaves)	50	70	38
Mean	**40**	**17**	**32**
Alien vegetables			
Allium cepa (onion)	15	11	0
Beta vulgaris (beetroot)	10	2	NV
Beta vulgaris (Swiss chard)	51	6	134
Brassica oleracea (cabbage)	32	5	3
Brassica oleracea var. italica (broccoli)	5	2	1
Cucumis sativus (cucumber)	5	3	1
Daucus carota (carrot)	8	22	236
Juglans cineria (butternut)	4	2	264
Lactuca sativa (lettuce)	13	2	38
Solanum lycopersicum (tomato)	6	2	8
Mean	**15**	**6**	**69**

[a]NV- no value

Underlined values mean the highest values

Chapter

3

Nutritional water productivity of selected leafy vegetables

This chapter is based on:

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Abstract

The major challenge affecting rural resource-poor households (RRPHs) in South Africa is deficiencies in micronutrients (iron and zinc) and vitamin A. Traditional leafy vegetables (TLVs) are dense in iron, zinc, and β-carotene concentrations. Therefore, they are deemed suitable to improve the dietary diversity of RRPHs. The main objective of this study was to assess the effect of irrigation regimes on nutritional water productivity (NWP) of selected leafy vegetables [*Amaranthus cruentus* (amaranth) and *Cleome gynandra* (spider flower), both TLVs, and *Beta vulgaris* (Swiss chard)]. Experiments were conducted under a rain shelter at the ARC-VOP, Pretoria, South Africa, during two consecutive seasons (2013/14 and 2014/15). Leafy vegetables were subjected to three irrigation regimes [well-watered (I_{30}), moderate water stress (I_{50}), and severe water stress (I_{80})]. Data collected [(aboveground biomass (AGB), aboveground edible biomass (AGEB), actual evapotranspiration, and nutrient concentrations (iron, zinc and β-carotene)] were used to calculate NWP of leafy vegetables. Swiss chard exhibited a higher portion of AGEB compared to TLVs due to its larger harvest index (0.57-0.92). Selected TLVs displayed superiority in terms of nutrient richness compared to Swiss chard, under I_{50}. Results indicated that TLVs could provide more than the daily-recommended nutrient intake (DRNI) for vitamin A to all age groups. For iron, spider flower could supply more than the DRNI to infants between 1 and 3 years of age, whereas for zinc, it could supply approximately 11 % to this age group. However, higher micronutrient and β-carotene concentrations did not translate to superior nutritional yield (NY). Swiss chard showed higher Fe-NY and Zn-NY, whereas TLVs were rich in β-carotene-NY. Similarly, Swiss chard demonstrated the highest Fe-NWP (1090 mg m^{-3}) and Zn-NWP (125 mg m^{-3}), whereas amaranth was larger in β-carotene-NWP (1799 mg m^{-3}), under moderate water stress. These results show that there may be an opportunity to improve NWP under drought conditions. There is a need for future studies that will assess NWP for a wider range of leafy vegetables. These studies should be conducted in different locations and explore the effect of management factors (fertiliser, water stress, planting density and planting date), and soil type on NWP of micronutrients and β-carotene.

Keywords: Deficit irrigation; Hidden hunger; African leafy vegetables; Micronutrient deficiency; Irrigation regimes; Indigenous leafy vegetables

3.1 Introduction

In South Africa, nearly fourteen million rural resource-poor households (RRPHs) have diets deficient in essential micronutrients (iron and zinc) and vitamin A (Oelofse and Van Averbeke, 2012). Thirty-four per cent of RRPHs rely on agriculture; therefore, this remains the main vehicle that can address food and nutrition insecurity (Mabhaudhi et al., 2016a). Govender et al. (2017) defined food and nutrition insecurity as the inability to access adequate quantities of nutritious foods required for optimal growth and development. Hendriks et al. (2016) found that in South Africa, one in four RRPHs experienced food and nutrition insecurity, which became severe in winter months (May-October) due to lack of water for irrigation. A typical diet of many RRPHs consisted of maize meal with sugar, and where income permitted, RRPHs consumed a relish of onions and tomato or cabbage once per day. Another study conducted by Wenhold et al. (2012) found that 50% of RRPHs consumed a diet including fewer than four food groups per day. This highlights that food and nutrition insecurity is persistent in rural areas of South Africa. Over the past decades, some progress has been made in addressing issues around food insecurity. However, most attention has been given to promote mainstream crops [Zea mays (maize), *Oryza sativa* (rice), *Triticum aestivum* (wheat), *Solanum tuberosum* (Irish potato), *Arachis hypogaea* (groundnut), and *Phaseolus vulgaris* (beans)] and selected vegetables [*Brassica oleracea* (cabbage), *Daucus carota* (carrot), *Allium cepa* (onion), *Lactuca sativa* (lettuce) and *Spinacea oleracea* (spinach)] to address food and nutrition security, underwater scarcity (Chibarabada et al., 2017; Mabhaudhi et al., 2016a, b). Minimal attention has been given towards addressing nutritional goals, especially for RRPHs.

We recognise the crucial role played by mainstream crops in providing proteins and calories. However, mainstream crops are deficient in essential micronutrients (iron and zinc) and β-carotene. Deficiency of micronutrients and vitamin A in human diets causes ‘‘hidden hunger’’; a condition whose effects may not be immediately apparent, but may have severe consequences by inducing stunted growth, delayed cognitive development, and reduced immunity (Mabhaudhi et al., 2016a). To broaden the food basket of rural poor South Africans, the Water Research Commission has directed considerable funding towards research on traditional leafy vegetables (TLVs); i.e. vegetables that have adapted in a certain geographic location, where they have become part of local culture and indigenised (Mabhaudhi et al., 2017b). Popularity of TLVs is attributed to their high nutrient concentration (iron, zinc, and β-carotene), their short crop cycle, the low use of agronomic inputs (water and fertiliser), their drought tolerance, and their abundance (available for RRPHs) in the ‘‘wild’’ or next to cereal crops as “weeds” (Chibarabada et al., 2017; Chivenge et al., 2015; Maseko et al., 2017; Mavengahama et al., 2013; Nyathi et al., 2016; Oelofse and Van Averbeke, 2012). It is important to note TLVs cannot replace mainstream crops in the diets of RRPHs; however, TLVs can contribute significantly to dietary diversity and agro-biodiversity (Chibarabada et al., 2017).

Chibarabada et al. (2017) noted that there is a gap between water use in agriculture, crop production, and nutritional requirements. From research conducted by nutritionists on nutrient concentrations of crops, daily consumption targets to meet human nutritional requirements can be derived (Uusiku et al., 2010; Van Jaarsveld et al., 2014; Schönfeldt and Pretorius, 2011). Agronomic and irrigation research tends to focus on producing as much crop with minimum water as possible (i.e. improving crop water productivity) (Chibarabada et al., 2017; Mabhaudhi et al., 2016 a, b; Nhamo et al., 2016; Renault and Wallender, 2000). These three aspects (water use in agriculture, crop production, and nutritional requirements) cannot be assessed in isolation, because they interlink (Mabhaudhi et al., 2016b). Mabhaudhi et al. (2016a) averred that *"to meaningfully address food and nutrition security, there is a need for an index that combines aspects of water use, crop production, human nutrition, and food access*." They proposed the nutritional water productivity index (NWP) [NWP = (Yield or biomass/actual evapotranspiration) × nutritional content of a product)], which was coined by Renault and Wallender (2000). We fully support the suggestion of using the NWP index for assessing the relationship between water use, food production, and nutrition. However, this index can only be optimised for RRPHs if suitable crops that are highly nutritious (rich in iron, zinc, and β-carotene) are available to RRPHs, and data on their production requirements, consumption, and nutritional values are available to be incorporated in NWP assessments.

Information on NWP of TLVs is minimal. A scoping study conducted by Wenhold et al. (2012) benchmarked NWP of selected vegetables [(amaranth (*Amaranthus cruentus*), Chinese cabbage (*Brassica rapa*), spider flower (*Cleome gynandra*), Swiss chard (*Beta vulgaris*), cowpea (*Vigna unguiculata*), jute (*Corchorus spp.*), bitter watermelon (*Citrullus lanatus*), blackjack (*Bidens pilosa*), pumpkin leaves (*Cucurbita maxima*), sweet potato leaves (*Ipomoea batatas*), and kale (*Brassica oleracea var. sabellica*)] using datasets (yield or biomass, evapotranspiration, and nutrient concentration) derived from different literature sources. These parameters not only differ among crops, they also vary among different locations for the same crop due to climatic conditions, soil fertility, and water availability. This is a severe limitation to this data, as crop comparisons for these agronomic and nutritional factors are only valid when they are grown under the same conditions (Uusiku et al., 2010). The main aim of the study was to assess the effect of irrigation regimes on NWP of amaranth, spider flower, and Swiss chard using datasets (yield or biomass, evapotranspiration, and nutrient content) from the same location. The two TLVs (amaranth and spider flower) were selected because they are nutrient dense (high mass concentrations of iron, zinc, and β-carotene), and they are utilised by RRPHs as a relish in South Africa (Mavengahama et al., 2013). In this study, we compared NWP of selected TLVs with that of Swiss chard (*var. Fordhook Giant*). We selected Swiss chard because it is an alien leafy vegetable that is highly nutritious (contains high levels of Fe, Zn and β-carotene), has been commercialised many decades ago, and is widely consumed in sub-Saharan Africa as a relish with maize porridge (Mavengahama et al., 2013). For these selected TLVs and Swiss chard, we imposed three water stress levels and measured selected plant parameters [leaf area index, stomatal conductance, light interception, radiation use efficiency, biomass (above ground growth and above ground edible biomass), nutritional yield, and water productivity]. Our hypotheses were that: (1) TLVs are more tolerant to water stress than Swiss chard; (2) TLVs are more nutrient dense (iron, zinc, and β-carotene) than Swiss chard; and (3) TLVs are more productive than Swiss chard in terms of aboveground biomass, NY, and NWP under severe water stress.

3.2 Materials and methods

3.2.1 Experimental site description, set up, and crop management

Experiments were conducted under a rainshelter, at the Agricultural Research Council-Vegetables and Ornamental Plants (ARC-VOP), located in Roodeplaat, Pretoria (25° 59'' S; 28° 35'' E; 1168 m a.s.l.), in the Gauteng Province of South Africa, during the 2013/14 and 2014/15 summer seasons (November – May). The rainshelter has a rain sensor that activates an electric motor during a rainfall event and the shelter closes and covers the experimental field. Therefore, the experiment experiences normal field conditions, except when it is raining (Mabhaudhi et al., 2014). Nyathi et al. (2018a) presented the long-term climatic data (rainfall, maximum and minimum temperatures), detailed meteorological conditions [maximum and minimum temperatures (°C), total radiation (MJ m^{-2}), reference evapotranspiration (mm day^{-1}), wind speed (m s^{-1}), and vapour pressure deficit (kPa)] during the growing seasons, and soil type of the experimental site, which was classified as a sandy loam using the USDA soil classification system (https://hrsl.ba.ars.usda.gov/soilwater/Index.htm). The field capacity of the soil was 168 mm m^{-1} and the permanent wilting point was 37 mm m^{-1}. Table 3.1 illustrates the chemical properties of the experimental site. A 3 × 3 factorial design was used; three leafy vegetables (amaranth, spider flower and Swiss chard) and three irrigation regimes [I_{30} (well-watered), I_{50} (moderate water stress), and I_{80} (severe water stress)]. I_{30}, I_{50}, and I_{80} represent the different irrigation regimes in terms of irrigating the soil back to field capacity after 30%, 50%, and 80% of plant available water was depleted, respectively. We used a randomised complete block design with three replications. The ARC-VOP gene bank provided amaranth and spider flower seeds, whereas Swiss chard seedlings were procured. Seeds for amaranth and spider flower were sown in seedling trays and covered with vermiculite, which was used as a medium for seed germination. After 8 weeks, seedlings were planted at an inter-row and intra row spacing of 0.3 m x 0.3 m (111,111 plants ha^{-1}). Residual soil P (127 mg kg^{-1}) and K (132 mg kg^{-1}) values were very high due to previous experiments conducted under the rainshelter. Therefore, only N was applied in the form of limestone ammonium nitrate (28% N) at a recommended rate of 150 kg N ha^{-1}; of which 50 kg N ha^{-1} was applied at planting and the remaining 100 kg N ha^{-1} was applied as top-dressing, at increments of 25 kg N ha^{-1} after each harvest, during the growing period (Nyathi et al., 2018a).

Table 3.1 Chemical soil properties for the experimental site

	Chemical properties						
	Fe	**Zn**	**N-NO_3**	**N-NH_4**	**pH(H_2O)**	**K**	**P-Bray 1**
Depth (cm)	**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	15.5	7.9	7.3	192	78
30-60	52.3	4.3	3.3	4.7	7.3	86	16
2014/15							
0-30	13.7	5.1	26.5	3.5	6.0	156	76

3.2.2 Irrigation management

The rain-shelter was divided into 27 small plots (4.6 m^2) to accommodate all the treatments and replications. Compensating non-leaking (CNL) Urinam drip emitters with a discharge rate of 2.3 l h^{-1} were used to irrigate each plot separately, and were spaced at 0.3 m × 0.3 m. The CNL drip system operates similar to a pressure compensated drip emitter, but has the advantage of having a non-leakage device that prevents water from draining out of the drip emitter once the system is shut off and the pressure drops below 20 kPa. This system ensures uniform water application within each plot. Aluminium access tubes were installed in the middle of each plot to a depth of 1 m. Soil water content was measured twice a week at fixed depth increments of 0.2 m using a neutron water meter (CPN, 503 DR Hydroprobe, USA) calibrated for the site using measurements from a wet and dry profile. The effective water extraction depth over the season was determined based on the soil water depletion pattern using the neutron probe data and was taken as 0.6 m. The soil water balance was determined using equation 1 (Table 3.2). Seedlings of selected leafy vegetables were irrigated with the same amount of water for the first 14 days to establish the crops; thereafter, irrigation regimes commenced (Nyathi et al., 2018a).

Table 3.2 Equations used to calculate the selected parameters

Equation	Description	Number
$ET = I \pm \Delta W$	Where ET (mm) is the actual evapotranspiration, I is the irrigation amount (mm**),** and ΔW is the change in soil water content (mm). In the case of the rain-shelter experiment, rainfall equals zero mm. There was no deep percolation because the rain-shelter kept rain out and irrigation was always to restore the top 0.6 m of the profile to field capacity.	(1)
$HI = \frac{AGEB}{AGB}$	HI is the harvest index (unit-less); AGEB is the above ground edible biomass (g m^{-2}); AGB is the total above ground biomass (g m^{-2}).	(2)
$ET_n = \sum (\frac{ET}{ET0})$	Where ET_n is the normalised evapotranspiration (unit-less); ET (mm); ET_0 is reference evapotranspiration (mm day^{-1}).	(3)
$WP_n = \frac{AGB}{ETn}$	Where WP_n is normalised water productivity (g m^{-2}); AGB (g m^{-2}); ET_n (unit less).	(4)
$FI = [1 - exp^{(-LAI \times k)}]$	Where FI is fractional interception (unit-less); LAI is the leaf area index; *k* is the light extinction coefficient (unit-less).	(5)
$LI = FI \times R_s$	Where LI is light intercepted (MJ m^{-2}); R_s is total radiation (MJ m^{-2}).	(6)
$I: ET_0 = (\sum irrigation) / ET_0$	I: ET_0 (unit less) is the irrigation (mm/ season) to ET_0 (mm/season) ratio.	(7)
$RUE = \frac{AGB}{\sum LI}$	Where RUE is radiation use efficiency (g MJ^{-1}); AGB (g m^{-2}); LI (MJ m^{-2}).	(8)
$NY = (AGEB \times NC) \times 10$	Where NY is nutritional yield (g ha^{-1}); AGEB (g m^{-2}); NC is nutritional content (mg g^{-1}).	(9)
$NWP_n = WP_n \times NC$	Where NWP_n is normalised nutritional water productivity (mg m^{-2}); WP_n (g m^{-2}); NC (mg g^{-1}).	(10)
$NWP = (\frac{AGEB}{ET}) \times NC \times 10$	Where NWP is nutritional water productivity (mg m^{-3}); AGEB (g m^{-2}); ET (mm); NC is in mg $100g^{-1}$.	(11)

3.2.3 Data collection

Leaf area index was measured at two-week intervals during the growing seasons using the LAI-2000 canopy analyser (Licor, Lincoln, NE, United States of America). Stomatal conductance was measured only for the 2013/14 season, due to equipment breakdown. Measurements were taken at 10, 25, 35, 45, 55, and 75 days after planting using the SC-1 leaf porometer (Decagon Devices, Pullman, WA, United States of America) (Nyathi et al., 2018a). Leaves of amaranth were harvested four times, whereas for spider flower and Swiss chard, they were harvested five times during the growing seasons. To avoid border effects, only data from the middle rows were utilised (1.8 m^2). Fresh mass was determined by weighing freshly harvested aboveground biomass (AGB = leaves plus stems) and aboveground edible biomass (AGEB = AGB × harvest index). Thereafter, samples were oven dried at 75 ^oC for 3-4 days and the dry biomass was measured. Selected plant parameters [harvest index, normalised evapotranspiration, normalised water productivity, fractional interception of photosynthetically active radiation (PAR), irrigation to reference evapotranspiration ratio (I: ET_0), radiation use efficiency (RUE), nutritional yield (NY), normalised nutritional water productivity (NWP_n), and nutritional water productivity (NWP)] were calculated using equations 2-11 (Table 3.2). Water productivity was normalised for climatic conditions because of seasonal variations in vapour pressure deficit (2013/14 and 2014/15 seasons) that affect evapotranspiration. Canopy extension coefficient (*k*) values for PAR were obtained from Archontoulis et al. (2011).

3.2.4 Nutrient analysis

Fresh samples of amaranth, spider flower, and Swiss chard leaves were weighed (500 g) and thoroughly washed with distilled water to remove debris. The stalks were removed from the leaves. Thereafter, samples were enclosed in transparent plastic polythene bags and sent immediately to NviroTek Laboratories for iron and zinc mass concentration analysis using a method suggested by the Association of Official Analytical Chemists (AOAC) (1990). Leaf samples were oven-dried at 80 ^{o}C for 24 hours and their water contents calculated. Samples were ground in a Wiley mill with No. 20 stainless steel sieve. Thereafter, they were stored in airtight containers. Details of the reagents and extraction method used for determining iron and zinc nutrient concentration are explained in AOAC (1990). These elements were determined with an inductively coupled plasma atomic emission spectrometer. Duplicate samples were analysed for β-carotene content at ARC-VOP biotechnology laboratory. Fresh mass was determined; thereafter samples were frozen and stored at - 80 ^{o}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 analysed using an HPLC-DAD (Shimadzu, Kyoto, Japan) at 450 nm wavelength. A 5-point standard curve that bracketed the concentration of the samples was constructed for quantitative analysis of β-carotene.

3.2.5 Potential contribution to human nutrition

β-carotene concentration was converted into Vitamin A [(µg RAEs (retinol activity equivalents)] based on Trumbo et al. (2003) (1µg RAE = 1µg retinol = 12 µg of β-carotene). Daily recommended nutrient intakes (DRNI) for iron, zinc, and β-carotene [infants (1-3 years); children (4-19 years); male adult (19-65 years); female adult (19-65 years)] were sourced from Uusiku et al. (2010). Percentage contribution to DRNI was calculated [nutrient concentrations (iron, zinc, and β-carotene, mg 100 g^{-1}) divided by nutrient requirements in mg day^{-1} (Box 3.1) × 100]. The potential contribution of 1 ha for a family of six (one adult female; one adult male; two 1-3 year infants; two 4-9 year old children) was calculated using nutritional yield data [iron, zinc, and β-carotene NYs (g ha^{-1}) × 10 (mg day^{-1} ha^{-1}) divided by DRNI (mg day^{-1} $people^{-1}$)]. We assumed that 30% of β-carotene is lost during cooking (boiling) as mentioned by Laurie et al. (2012a) and Van Jaarsveld et al. (2006). For iron and zinc, around 50 % is lost due to cooking (boiling ≈ 5 %) and bioavailability (≈ 45 %) inside human bodies (Amagloh et al., 2017; Gupta et al., 2006).

Box 3.1 Iron, zinc, and vitamin A requirements for a family of six people

Vitamin A requirements for a household of six [(one adult male = 600 µg RAE day^{-1}; one adult female = 500 µg RAE day^{-1}; two 1-3 year infants (2 × 400 µg = 800 µg RAE day^{-1}); two 4-18 year children (2 × 600 µg = 1200 µg RAE day^{-1}); ***total = 3100 µg RAE day^{-1}***)]. Iron requirements for a household of six [(one adult male = 13.7 mg day^{-1}; one adult female = 29.7 mg day^{-1}; two 1-3 year infants (2 × 5.8 mg = 11.6 mg day^{-1}); 4-18 year children (2 × 32.7 mg = 65 mg day^{-1}); ***total = 120 mg day^{-1}***)]. Zinc requirements for a household of six [(one adult male = 14 mg day^{-1}; one adult female = 9.8 mg day^{-1}; two 1-3 year infants (2 × 8.3 mg = 16.6 mg day^{-1}); 4-18 year children (2 × 14.4 mg = 28.8 mg day^{-1}); ***total = 69.2 mg day^{-1}***)].

3.2.6 Statistical analysis

Analysis of variance was performed with GenStat (version 14, VSN, UK) to determine the main and interaction effects of all factors on the studied variables (aboveground biomass, above ground edible biomass, harvest index, normalised evapotranspiration, actual evapotranspiration, water productivity, normalised water productivity, light intercepted, radiation use efficiency, nutrient concentrations, nutritional yield, nutritional water productivity, and normalised nutritional water productivity). Checks for normality and homogeneity of variance were carried out using Shapiro Wilk's and Bartlett's tests. Means separation for the analyses of variance was done using Fischer's unprotected least significance difference test at a 5% significance level. Previously conducted experiments [sorghum (*Sorghum bicolor*), sunflower (*Helianthus annuus*), wheat, and chickpea (*Cicer arietinum*)] revealed that the relationship between aboveground biomass (AGB, g m^{-2}) and water consumed (crop evapotranspiration, mm) is highly linear, whereby the slope of the line represents water productivity (Steduto et al., 2007). This concept has been used in the AquaCrop model, which simulates yield response to water (Foster et al., 2017; Hsiao et al., 2009; Raes et al., 2009; Steduto et al., 2009; Vanuytrecht et al., 2014). Other studies (Bastiaanssen and Steduto, 2017; Campos et al., 2018; López-López et al., 2018; Trout and De Jonge, 2017) confirmed that indeed the relationship between water use and biomass is linear. We followed the Steduto et al. (2007) concept to compare the relationship between normalised water use ($\sum ET / \sum ET_0$) and aboveground biomass for amaranth, spider flower, and Swiss chard.

3.3 Results

3.3.1 Soil water content and irrigation to reference evapotranspiration ratio

Figure 3.1 presents the soil water content (SWC) of the experiment on selected leafy vegetables (amaranth, spider flower, and Swiss chard). The results revealed that SWC was different across seasons, irrigation regimes, and leafy vegetables. The time to initiation of water stress differed between the 2013/14 season (amaranth and spider flower = 18 DAT; Swiss chard = 14 DAT) and the 2014/15 season (amaranth and spider flower = 10 DAT; Swiss chard = 14 DAT). The observed trend across irrigation regimes showed that the well-watered treatment (I_{30}) maintained higher SWC compared to the moderate water stress (I_{50}), and the severe water stress (I_{80}) treatments for both seasons, indicating that the treatments were successfully applied. For the 2014/15 season, there was a clear distinction between SWC for all water treatments (I_{30}, I_{50}, and I_{80}). The observed differences were associated with irrigation frequency and the length of growing period. Irrigation to reference evapotranspiration ratio (I: ET0) provides an indication of the level of water stress experienced by selected leafy vegetables (Figure 3.2a). A low ratio means severe water stress, whereas a ratio closer to 1 depicts little or no water stress. During the 2013/14 season, I: ET_0 ranged from 0.40 to 0.77 for amaranth, 0.46 to 0.87 for spider flower, and 0.43 to 0.86 for Swiss chard. For the 2014/15 season, I: ET_0 ranged from 0.29 to 0.77 for amaranth, 0.34 to 0.74 for spider flower, and 0.16 to 0.71 for Swiss chard.

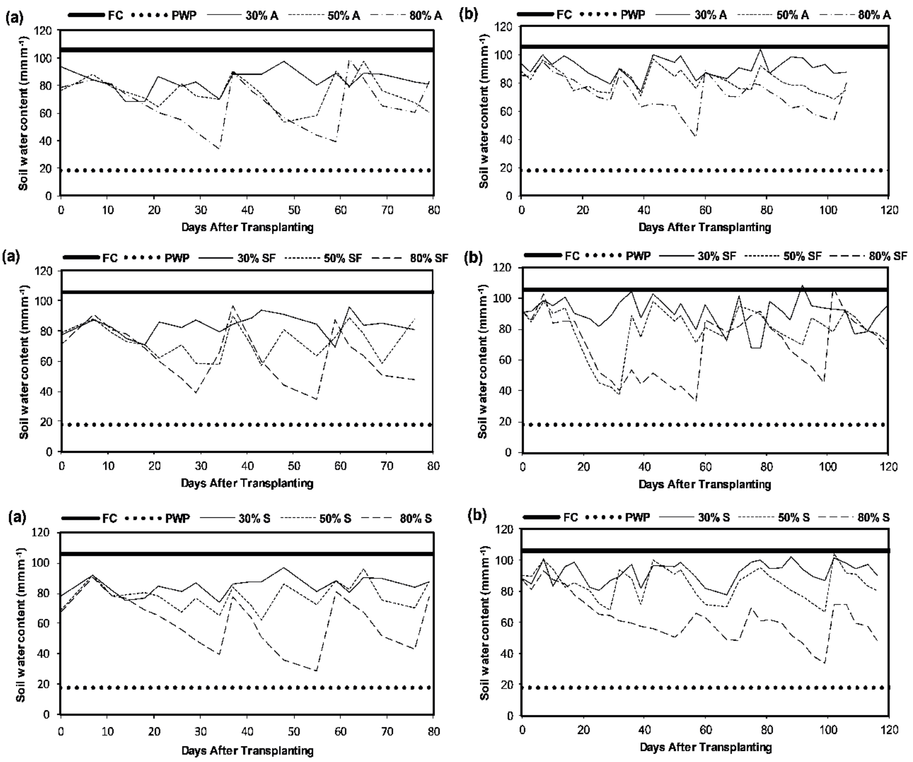

Figure 3.1 Soil water content for amaranth (A), spider flower (SF), and Swiss chard (S). FC - Field capacity and PWP- permanent wilting point; **a** and **b** are the 2013/14 and 2014/15 seasons, respectively. 30% (well-watered), 50% (moderate water stress), and 80% (severe water stress) are the three irrigation water regimes.

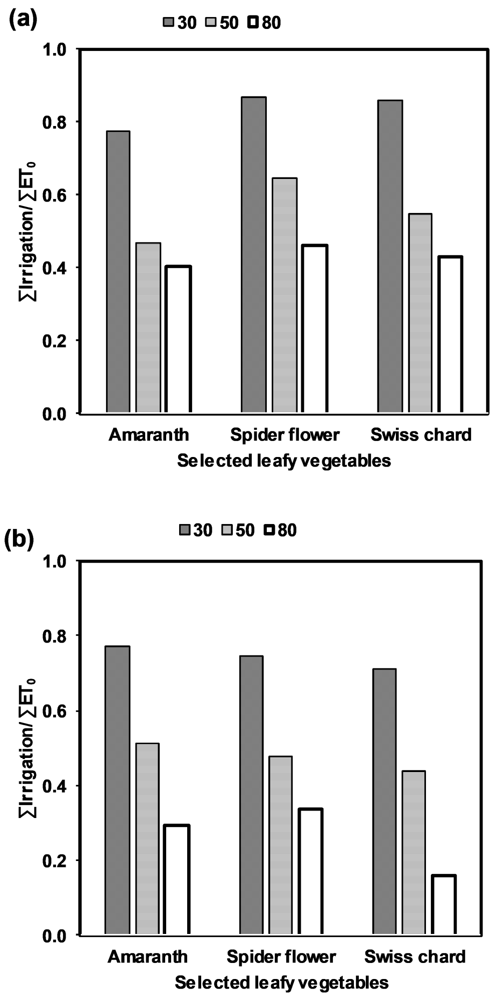

Figure 3.2 Irrigation to reference evapotranspiration ratio (∑irrigation/ $\sum ET_0$) for Amaranth, spider flower, and Swiss chard; **a** and **b** are the 2013/14 and 2014/15 seasons, respectively. 30% (well-watered), 50% (moderate water stress), and 80% (severe water stress) are the three irrigation water regimes.

3.3.2 Plant parameters

Leaf area index

Irrigation regimes affected ($P < 0.001$) leaf area index (LAI) during the growing seasons. Selected leafy vegetables responded differently; based on the well-watered treatment for the 2013/14 season, maximum LAI was 3.6 m^2 m^{-2} for amaranth, 3.9 m^2 m^{-2} for spider flower, and 3.4 m^2 m^{-2} for Swiss chard (Figure 3A.1). The 2014/15 results showed that maximum LAI was reduced by 16% for amaranth and 25% for Swiss chard, whereas for spider flower, maximum LAI increased by 19%. Increasing water stress reduced LAI significantly ($P < 0.05$). During the

2013/14 season, the trend for mean LAI was I_{30} (amaranth = 2.3 m^2 m^{-2} spider flower = 3.0 m^2 m^{-2}; Swiss chard = 2.2 m^2 m^{-2}) which was greater than I_{50} (amaranth = 1.9 m^2 m^{-2} , spider flower = 2.4 m^2 m^{-2}; Swiss chard = 1.8 m^2 m^{-2}) which was greater again than I_{80} (amaranth = 1.6 m^2 m^{-2} , spider flower = 1.9 m^2 m^{-2}; Swiss chard = 1.5m^2 m^{-2}). For the 2014/15 season, mean LAI for the I_{80} was lower by approximately 22% for amaranth, 12% for spider flower, and 31% for Swiss chard, relative to their respective well-watered treatments in the 2013/14 season. This corresponds with the lower I: ET_0 (amaranth = 0.29; spider flower = 0.34; Swiss chard = 0.16) for the 2014/15 season (Figure 3.2b).

Actual evapotranspiration and stomatal conductance

Significant differences (P = 0.01) were observed between the interaction of irrigation regimes and seasons for actual evapotranspiration (ET) (Table 3.3); ET ranged from 163 to 323 mm for amaranth, 183 to 457 mm for spider flower, and 129 to 315 mm for Swiss chard (2013/14 and 2014/15). Under well-watered conditions, spider flower consumed more water than amaranth and Swiss chard [spider flower (457 mm) < amaranth (323 mm) < Swiss chard (315 mm)]. Increased water stress significantly (P = 0.001) reduced ET by approximately 50% for amaranth and 60% for spider flower and Swiss chard, relative to their well-watered controls. Irrigation regimes affected ($P < 0.05$) stomatal conductance (g_s, mmol m^{-2} s^{-2}) of leafy vegetables. The results showed that higher ET resulted in an increase in mean g_s of amaranth (142 mmol m^{-2} s^{-2}), spider flower (141 mmol m^{-2} s^{-2}), and Swiss chard (181 mmol m^{-2} s^{-2}). Under well-watered conditions, mean g_s of amaranth (- 38 %) and spider flower (- 39 %) was lower than that of Swiss chard (181 mmol m^{-2} s^{-2}). Similarly, under severe water stress, g_s of amaranth (-12 mmol m^{-2} s^{-2}) and spider flower (-23 mmol m^{-2} s^{-2}) were lower compared to Swiss chard (113 mmol m^{-2} s^{-2}) (Figure 3.3).

Table 3.3 The effect of three irrigation water regimes on biomass and related parameters of selected leafy vegetables during 2013/14 and 2014/15

Leafy vegetables		**AGB**[a]	**AGBE**[b]	**HI**[c]	**ET_n**[d]	**ET**[e]	**LI**[f]	**RUE**[g]
Amaranth		**$g\ m^{-2}$**	**$g\ m^{-2}$**			**mm**	**$MJ\ m^{-2}$**	**$g\ MJ^{-1}$**
IWR[h] **x Season**								
I_{30}	one	613^{a}	297^{b}	0.48^{ab}	13.6^{b}	289^{ab}	1560^{b}	1.61^{a}
I_{50}	one	433^{b}	268^{b}	0.63^{ab}	9.7^{c}	190^{cd}	1432^{b}	1.25^{b}
I_{80}	one	343^{bc}	158^{c}	0.46^{b}	6.1^{d}	150^{d}	1246^{c}	1.19^{b}
I_{30}	Two	658^{a}	387^{a}	0.62^{ab}	19.6^{a}	323^{a}	1712^{a}	1.65^{a}
I_{50}	Two	423^{b}	292^{b}	0.69^{a}	14.4^{b}	240^{bc}	1480^{b}	1.22^{b}
I_{80}	Two	311^{c}	151^{c}	0.48^{ab}	9.3^{c}	163^{d}	1269^{c}	1.09^{b}
Spider flower								
IWR x Season								
I_{30}	one	658^{b}	272^{b}	0.41^{bc}	17.5^{bc}	324^{b}	1541^{c}	2.05^{a}
I_{50}	one	544^{bc}	249^{b}	0.46^{ab}	12.9^{d}	243^{d}	1416^{d}	1.86^{ab}
I_{80}	one	440^{c}	228^{b}	0.52^{a}	9.7^{e}	183^{e}	1200^{e}	1.76^{b}
I_{30}	Two	977^{a}	325^{a}	0.34^{c}	25.9^{a}	457^{a}	2718^{a}	1.84^{ab}
I_{50}	Two	682^{b}	271^{b}	0.40^{bc}	18.3^{b}	293^{bc}	2479^{ab}	1.42^{c}
I_{80}	Two	543^{bc}	108^{c}	0.20^{d}	15.3^{cd}	252^{cd}	2176^{b}	1.30^{c}
Swiss chard								
IWR x Season								
I_{30}	one	639^{a}	416^{bc}	0.65^{bc}	16.4^{a}	315^{a}	1572^{a}	2.05^{a}
I_{50}	one	536^{b}	365^{cd}	0.68^{b}	11.4^{b}	214^{bc}	1426^{b}	1.88^{ab}
I_{80}	one	467^{cd}	338^{d}	0.73^{b}	8.2^{c}	176^{cd}	1190^{c}	1.96^{ab}
I_{30}	Two	614^{a}	564^{a}	0.92^{a}	18.6^{a}	276^{ab}	1598^{a}	1.93^{ab}
I_{50}	Two	505^{bc}	432^{b}	0.86^{a}	12.7^{b}	147^{cd}	1377^{b}	1.77^{6}
I_{80}	Two	420^{d}	241^{e}	0.57^{c}	6.7^{c}	129^{d}	1149^{c}	1.75^{b}

Column values followed by the same symbol are not statistically different at $p \leq 0.05$. [a]AGB- above ground biomass; [b]AGEB-above ground edible biomass; [c]HI- harvest index; [d]ET_n-normalised evapotranspiration; [e]ET- actual evapotranspiration; [f]LI- light intercepted; [g]RUE- radiation use efficiency (RUE has been calculated as $\sum RUE_{h1} + RUE_{h2} + \ldots\ldots RUE_{hn}$, where H_1 is harvesting period one and H_n is the final harvest); [h]IWR- irrigation water regimes; I_{30}, I_{50}, and I_{80} are the well-watered, moderate water stress, and severe water stress IWR, respectively. Standard deviation of the means are presented in Table 3A.1.

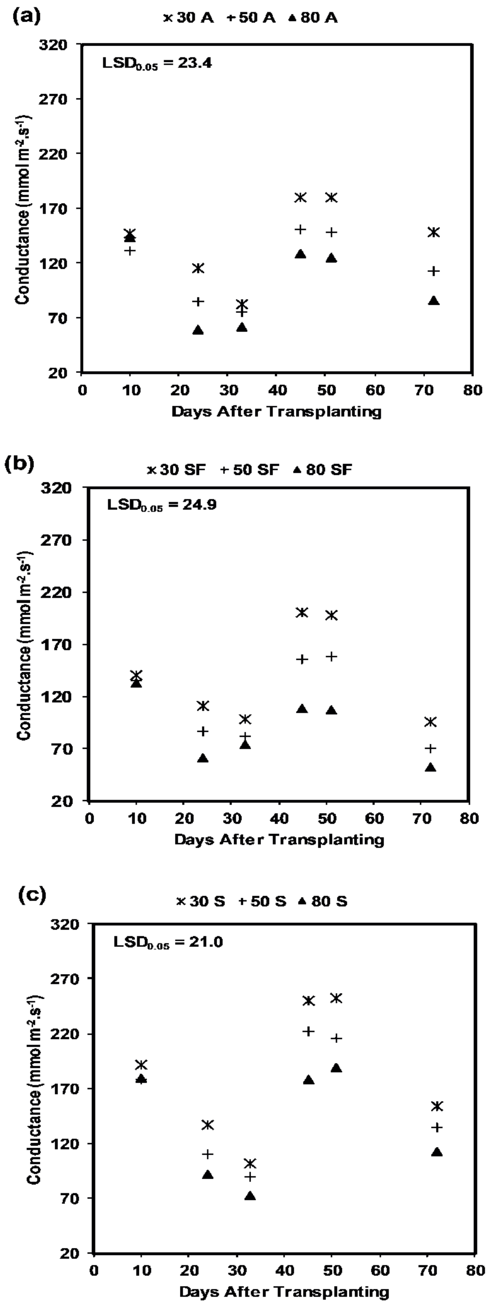

Figure 3.3 The effect of three irrigation water regimes [30% (well-watered), 50% (moderate water stress), and 80% (severe water stress)] on stomatal conductance for **a** amaranth (A), **b** spider flower (SF), and **c** Swiss chard (S) for the 2013/14 season

Light intercepted, radiation use efficiency, aboveground biomass, and aboveground edible biomass

Light interception (LI) of leafy vegetables was significantly ($P = 0.004$) affected by irrigation regimes. Over both seasons and water stress treatments, LI ranged from 1246 to 1712 MJ m^{-2} for amaranth, 1200 to 2718 MJ m^{-2} for spider flower, and 1149 to 1598 MJ m^{-2} for Swiss chard (Table 3.3). Under severe water stress, LI was reduced by ≈ 27 % for amaranth, 56 % for spider flower, and 28 % for Swiss chard, relative to their respective well-watered treatments. Our results demonstrated that there was seasonal variation ($P \leq 0.001$) for LI; for the 2014/15 season, spider flower intercepted nearly twice as much radiation compared to the previous season. Although there was no significant difference ($P = 0.23$) between irrigation regimes and seasons, radiation use efficiency (RUE) values decreased with increased water stress. The values ranged from 1.09 to 1.65 g MJ^{-1} for amaranth, 1.30 to 2.05 g MJ^{-1} for spider flower, and 1.75 to 2.05 g MJ^{-1} for Swiss chard. Under well-watered conditions, spider flower and Swiss chard exhibited similar RUE (2.05 g MJ^{-1}), whereas amaranth was much lower (1.65 g MJ^{-1}).

Total aboveground biomass (∑AGB for several harvests) for amaranth was significantly ($P < 0.05$) affected by the interaction between irrigation regimes and seasons (Table 3.3). amaranth AGB was higher (+ 7 %) during the 2014/15 season in comparison to the 2013/14 season. The observed trend for amaranth AGB (2013/14 and 2014/15 seasons) was I_{30} (613 and 658 g m^{-2}) was greater than I_{50} (433 and 423 g m^{-2}) which in turn was still greater than I_{80} (343 and 311 g m^{-2}). Irrigation regimes and seasons significantly ($P < 0.05$) affected AGB for spider flower; the 2014/15 season illustrated an increase of ≈ 32 % for I_{30}, 20 % for I_{50}, and 19 % for the I_{80} treatment, in comparison to the 2013/14 season (Table 3.3). Similarly, total AGB for Swiss chard was significantly ($P < 0.05$) affected by irrigation regimes and seasons. The AGB ranged from 467 to 639 g m^{-2}, whereas for the 2014/15 season, AGB ranged from 420 to 614 g m^{-2}. A trend was maintained whereby Swiss chard AGB was reduced by increased water stress for both seasons [(I_{30} (639 and 614 g m^{-2}) > I_{50} (536 and 505 g m^{-2}) > I_{80} (467 and 420 g m^{-2})] (Table 3.3). This is explained by the higher I: ET0 ratio (0.43) during the 2013/14 in comparison to 0.19 in 2014/15. There was a significant ($P < 0.05$) interaction between irrigation regimes and seasons on the above ground edible biomass (AGEB) (Table 3.3). Amaranth AGEB ranged from 158 to 297 g m^{-2} for the 2013/14 season. During the 2014/15 season, AGEB for amaranth ranged from 151 to 387 g m^{-2}. This shows that under well-watered conditions, amaranth AGEB increased by ≈ 23%, whereas under severe water stress, AGEB decreased by ≈ 18%, relative to AGB for the 2013/14 season. Spider flower was significantly ($P < 0.05$) affected by irrigation regimes and seasons. The AGEB ranged from 108 to 325 g m^{-2} for both seasons. Under the well-watered treatment (2013/14), spider flower exhibited larger AGEB (≈ 23 %) in comparison to the 2014/15 season. Increased water stress reduced AGEB for spider flower for both seasons. Similarly, the AGEB for Swiss chard was affected ($P < 0.05$) by irrigation regimes and seasons. During the 2014/15 season, AGEB was larger by 26 % for the I_{30}, 16 % for the I_{50}, and - 40 % for the I_{80} water regime, relative to those of the previous season. Observed trends showed that increased water stress reduced AGEB for Swiss chard for both seasons. For the I_{80}, the 2014/15 season showed lower AGEB (- 40 %) in comparison to the 2013/14 season. There was no significant ($P = 0.22$) interaction between irrigation regimes and seasons for amaranth harvest index (HI); however, there was a significant ($P < 0.05$) effect for spider flower and Swiss chard HI (Table 3.3). The mean values ranged from 0.46 to 0.69 for amaranth, 0.20 to 0.52 for spider flower, and 0.57 to 0.92 for

Swiss chard. Harvest index results coincide with the AGEB results; amaranth (151-387 g m^{-2}) and spider flower (108-325 g m^{-2}) AGEB were inferior to Swiss chard (241-564 g m^{-2}).

3.3.3 Micronutrients, β-carotene and nutritional yield

Table 3.4 presents the moisture content and nutrient concentrations of iron, zinc, and β-carotene. The 2013/14 season results revealed that there was a significant (P = 0.02) interaction effect of irrigation regimes and leafy vegetables for moisture content. Mean values ranged from 0.74 to 0.91; Swiss chard indicated higher moisture content (0.90-0.91) compared to amaranth (0.79-0.82) and spider flower (0.74-0.79). In contrast, the 2014/15 moisture content results indicated that there was no significant (P = 0.87) effect between irrigation regimes and leafy vegetables. However, the observed trend (moisture content for Swiss chard > amaranth > spider flower) was consistent with the 2013/14 results. The interaction of irrigation regimes and leafy vegetables had an effect on iron (P ≤ 0.001), zinc (P = 0.03) and β-carotene (P = 0.01) concentrations (2013/14). Iron ranged from 45.2 to 46.6 mg $100g^{-1}$ for amaranth, 49.5 to 58.6 mg $100g^{-1}$ for spider flower, and 30.9 to 56.7 mg $100g^{-1}$ for Swiss chard. The severe water stress did not affect iron concentrations for amaranth and spider flower, whereas for Swiss chard, the iron concentration was decreased by ≈ 46 % under severe water stress, relative to well-watered conditions. Zinc ranged from 4.07 (Swiss chard, I_{80}) to 8.38 mg $100g^{-1}$ (spider flower, I_{80}). Under the I_{80}, zinc increased by 8 % for amaranth and 12 % for spider flower, whereas for Swiss chard, it decreased by 36 %, relative to the well-watered conditions. For the well-watered treatment, β-carotene for amaranth was three-fold higher than for spider flower and four-fold higher than Swiss chard. Leafy vegetables responded differently to water stress; β-carotene for amaranth (≈ +1 %) and Swiss chard (≈ +21 %) increased under the I_{80}, whereas β-carotene for spider flower increased up to the I_{50}, relative to the well-watered conditions. During the 2014/15 season, irrigation regimes and leafy vegetables interaction affected iron (P = 0.005), zinc (P = 0.003), and β-carotene (P ≤ 0.001) concentrations. Generally, iron, zinc, and β-carotene were lower compared to the 2013/14 season. Under the I_{80} treatment, iron for amaranth was reduced (- 20 %), whereas iron for spider flower (+ 52 %) increased, relative to the I_{30} treatment. A similar trend was observed for zinc (amaranth < - 32 %; spider flower > + 19 %). Under well-watered conditions, β-carotene for amaranth was higher compared to spider flower (+ 17 %) and Swiss chard (+ 87 %). Severe water stress significantly (P ≤ 0.001) reduced β-carotene (amaranth ≈ - 61 %, spider flower ≈ -19 %, and Swiss chard ≈ +29 %) for selected leafy vegetables. Swiss chard displayed contradicting results between seasons; in 2013/14, severe water stress reduced iron and zinc concentrations, whereas the opposite was observed in 2014/15.

Table 3.4 The effect of three water stress levels on nutritional content (dry mass basis) and nutritional yield (dry mass basis) of iron, zinc, and β-carotene during the 2013/14 and 2014/15 seasons

Leafy vegetables	IWR[a]	Moisture %	Fe[b] mg $100g^{-1}$	Zn[c] mg $100g^{-1}$	β[d] mg $100g^{-1}$	Fe-NY[e] g ha^{-1}	Zn-NY g ha^{-1}	β-NY g ha^{-1}
2013/14								
Amaranth	I_{30}	0.82[bc]	46.6[c]	5.86[bcd]	145[a]	1361[bc]	174[abc]	4285[a]
Amaranth	I_{50}	0.79[bcd]	45.8[c]	5.86[bcd]	137[a]	1283[c]	157[bc]	3563[a]
Amaranth	I_{80}	0.84[ab]	45.2[c]	6.30[abcd]	147[a]	743[d]	102[c]	2299[b]
Spider flower	I_{30}	0.79[bcd]	49.5[bc]	7.47[abc]	49[bc]	1350[bc]	203[ab]	1330[bc]
Spider flower	I_{50}	0.76[cd]	58.6[a]	7.60[ab]	73[b]	1461[bc]	190[abc]	1823[bc]
Spider flower	I_{80}	0.74[d]	55.5[ab]	8.38[a]	40[c]	1266[cd]	190[abc]	915[c]
Swiss chard	I_{30}	0.91[a]	56.7[ab]	6.28[abcd]	37[c]	2351[a]	262[a]	1557[bc]
Swiss chard	I_{50}	0.91[a]	50.1[bc]	5.28[cd]	34[c]	1829[ab]	192[abc]	1254[bc]
Swiss chard	I_{80}	0.90[a]	30.9[d]	4.07[d]	45[bc]	1046[cd]	137[bc]	1526[bc]
2014/15								
Amaranth	I_{30}	0.84[ab]	30.4[de]	6.85[a]	141[a]	1182[bcd]	262[ab]	5509[a]
Amaranth	I_{50}	0.84[ab]	34.8[cde]	4.75[b]	138[a]	1016[bcd]	139[d]	4039[ab]
Amaranth	I_{80}	0.84[ab]	24.1[e]	4.64[b]	55[d]	362[d]	70[e]	840[d]
Spider flower	I_{30}	0.77[c]	51.1[bcd]	5.57[ab]	117[b]	1692[bc]	178[cd]	3820[b]
Spider flower	I_{50}	0.79[bc]	59.1[ab]	6.04[ab]	104[c]	1602[bc]	162[d]	2566[bc]
Spider flower	I_{80}	0.77[bc]	77.9[a]	6.87[a]	94[bc]	842[cd]	75[e]	1123[cd]
Swiss chard	I_{30}	0.90[a]	52.0[bc]	5.24[ab]	17[e]	2904[a]	295[a]	1005[cd]
Swiss chard	I_{50}	0.90[a]	44.1[bcde]	5.37[ab]	19[e]	1905[b]	232[bc]	827[d]
Swiss chard	I_{80}	0.89[a]	53.5[bc]	5.88[ab]	22[e]	1286[bc]	142[d]	548[d]

Column values followed by the same symbol are not statistically different at $p \leq 0.05$. [a]IWR- irrigation water regimes; [b]Fe- Iron, [c]Zn- Zinc, and [d]β- β-carotene concentrations; [e]Fe-NY- Fe nutritional yield (NY). I_{30}, I_{50}, and I_{80} are the well-watered, moderate water stress, and severe water stress irrigation water regimes, respectively. Standard deviation of the means are presented in Table 3A.2.

During the 2013/14 season, iron nutritional yield (Fe-NY) and β-carotene NY (β-NY) were affected ($P < 0.05$) by the interaction between irrigation regimes and leafy vegetables. Iron NY ranged from 743 to 1361 g ha^{-1} for amaranth, 1266 to 1461 g ha^{-1} for spider flower, and 1064 to 2351 g ha^{-1} for Swiss chard (Table 3.4). Under well-watered conditions, Swiss chard (2351 g ha^{-1}) showed higher Fe-NY than spider flower (1350 g ha^{-1}), and amaranth (1361 g ha^{-1}). Although there was no effect ($P = 0.09$) between irrigation regimes and leafy vegetables for zinc NY (Zn-NY), without water stress Swiss chard (262 g ha^{-1}) maintained higher values compared to spider flower (203 g ha^{-1}) and amaranth (174 g ha^{-1}). β-carotene-NY for amaranth was considerably higher (3-fold) than for spider flower and Swiss chard, under well-water conditions. For the 2014/15 season, Zn-NY and β-carotene-NY were significantly ($P < 0.05$) affected by irrigation regimes and leafy vegetables. In contrast, there was no interaction effect ($P = 0.09$) for Fe-NY. Under well-watered conditions, Fe-NY for amaranth was lower (- 13 g ha^{-1}), whereas Fe-NY for spider flower and Swiss chard were higher (+ 25 % and + 23 %) in comparison to the 2013/14 season. Zinc-NY ranged from 70 (amaranth, I_{80}) to 295 g ha^{-1} (Swiss chard, I_{30}). Under the well-watered treatment, β-carotene-NY was improved for amaranth (≈ +28 %) and spider flower (≈ +87 %); for Swiss chard, β-carotene-NY was reduced by ≈ 35 %, in comparison to the 2013/14 season. The severe water stress mean values for both seasons indicated that Fe-NY was reduced significantly ($P \leq 0.001$) (amaranth and Swiss chard < 56 %, spider flower < by 31 %) relative to the well-watered treatment. Similar trends were observed for Zn-NY (amaranth < 61 %; spider flower < 30 %; Swiss chard < 50 %) and β-carotene-NY (amaranth < 68 %; spider flower < 69 %; Swiss chard < 19 %) (2014/15).

3.3.4 Normalised water productivity, water productivity and nutritional water productivity

There was a significant ($P \leq 0.001$) regression between normalised water use ($\sum ET/\sum ET_0$) and AGB. The R^2 was 0.85 for amaranth, 0.94 for spider flower, and 0.80 for Swiss chard (Figure 3.4). The average normalised water productivities (WP_n) across all irrigation regimes and seasons was very similar for all crops studied, 35 g m^{-2} for amaranth, 36 g m^{-2} for spider flower, and 34 g m^{-2} for Swiss chard. Normalised NWP (NWP_n) showed that there was no effect ($P > 0.05$) between irrigation regimes and leafy vegetables (2013/14 season) for Fe-NWP_n, Zn-NWP_n and β-carotene-NWP_n. For the 2014/15 season, Fe-NWP_n was not affected ($P = 0.08$) by irrigation regimes and leafy vegetables. During the same season, irrigation regimes and leafy vegetables affected Zn-NWP_n ($P = 0.02$), and β-NWP_n ($P \leq 0.01$) (Table 3.5). For both seasons, leafy vegetables and water regimes did not affect water productivity (WP) significantly ($P > 0.05$); WP values ranged from 21 to 23 kg ha^{-1} mm^{-1} for amaranth, 20 to 24 kg ha^{-1} mm^{-1} for spider flower, and 20 to 26 kg ha^{-1} mm^{-1} for Swiss chard (2013/14 season) (Table 3.5). For the 2014/15 season, WP values ranged from 18 to 20 kg ha^{-1} mm^{-1} for amaranth, 21 to 23 kg ha^{-1} mm^{-1} for spider flower, and 22 to 36 kg ha^{-1} mm^{-1} for Swiss chard. For both seasons, Swiss chard displayed the highest WP compared to spider flower and amaranth.

There was a seasonal variation in nutritional water productivities (NWP) of leafy vegetables. For the 2013/14 season, Fe-NWP was affected ($P = 0.01$), whereas Zn-NWP ($P = 0.07$) and β-carotene-NWP ($P = 0.10$) were not affected by irrigation regimes and leafy vegetables. In contrast to the previous season, the 2014/15 results showed that Fe-NWP ($P = 0.82$) was not affected by irrigation regimes and leafy vegetables; whereas, Zn-NWP ($P = 0.01$) and β-NWP ($P \leq 0.001$) were affected by this interaction (Table 3.5). Generally, our results illustrated that $NWP_{Fe,\ Zn\ and\ \beta\text{-carotene}}$ improved with moderate water stress. The mean results for both seasons presented an interesting perspective; under moderate water stress, Swiss chard exhibited the highest Fe-NWP (1090 mg m^{-3}) and Zn-NWP (125 mg m^{-3}) compared to spider flower and amaranth. However, under severe water stress, spider flower exhibited the highest Fe-NWP (513 mg m^{-3}) and Zn-NWP (67 mg m^{-3}) in comparison to amaranth and Swiss chard. Amaranth had the highest β-carotene-NWP under both water stress levels (moderate and severe water stress).

Table 3.5 The effect of three irrigation water regimes on normalised nutritional water productivity (NWP_n) and nutritional water productivity (NWP) of iron, zinc, and β-carotene during the 2013/14 and 2014/15 seasons

Leafy vegetables	IWR[a]	WP_n[b]	Fe-NWP_n[c]	Zn-NWP_n[d]	β-NWP_n[e]	WP[f]	Fe-NWP[g]	Zn-NWP[h]	β-NWP[i]
2013/14		$g\ m^{-2}$	$mg\ m^{-2}$	$mg\ m^{-2}$	$mg\ m^{-2}$	$kg\ ha^{-1}\ mm^{-1}$	$mg\ m^{-3}$	$mg\ m^{-3}$	$mg\ m^{-3}$
Amaranth	I_{30}	14^{b}	10^{cd}	1.3^{bc}	31^{b}	21^{d}	470^{cd}	60^{c}	1479^{b}
Amaranth	I_{50}	10^{d}	13^{abc}	1.6^{abc}	37^{ab}	23^{bcd}	680^{b}	83^{abc}	1886^{a}
Amaranth	I_{80}	6^{e}	12^{bc}	1.7^{abc}	37^{a}	23^{bcd}	494^{cd}	68^{bc}	1531^{b}
Spider flower	I_{30}	18^{a}	8^{d}	1.2^{c}	8^{e}	20^{d}	416^{d}	63^{c}	413^{e}
Spider flower	I_{50}	13^{b}	11^{bc}	1.5^{abc}	14^{cd}	22^{cd}	602^{bc}	78^{bc}	747^{cd}
Spider flower	I_{80}	10^{d}	13^{abc}	2.0^{a}	9^{de}	24^{abc}	691^{ab}	104^{a}	499^{de}
Swiss chard	I_{30}	16^{a}	14^{ab}	1.6^{abc}	9^{de}	20^{d}	749^{ab}	83^{abc}	496^{de}
Swiss chard	I_{50}	11^{c}	16^{a}	1.7^{ab}	11^{de}	26^{a}	858^{a}	90^{ab}	588^{cde}
Swiss chard	I_{80}	8^{d}	13^{bc}	1.7^{abc}	19^{c}	25^{ab}	595^{bc}	78^{abc}	867^{c}
2014/15									
Amaranth	I_{30}	20^{b}	6^{cd}	1.3^{cd}	28^{a}	20^{b}	368^{cd}	81^{c}	1711^{a}
Amaranth	I_{50}	14^{cd}	7^{cd}	1.0^{de}	28^{a}	19^{b}	423^{cd}	58^{cd}	1712^{a}
Amaranth	I_{80}	9^{ef}	4^{d}	0.8^{e}	9^{bcd}	18^{b}	226^{d}	44^{de}	518^{bc}
Spider flower	I_{30}	26^{a}	6^{cd}	0.7^{e}	15^{b}	21^{b}	368^{cd}	39^{de}	833^{b}
Spider flower	I_{50}	18^{bc}	9^{c}	0.9^{de}	14^{bc}	23^{b}	543^{c}	55^{de}	872^{b}
Spider flower	I_{80}	15^{bcd}	6^{cd}	0.5^{e}	7^{d}	22^{b}	336^{cd}	30^{e}	447^{c}
Swiss chard	I_{30}	19^{bc}	16^{ab}	1.6^{bc}	6^{d}	22^{b}	1043^{ab}	108^{b}	365^{c}
Swiss chard	I_{50}	13^{de}	15^{b}	1.8^{ab}	6^{d}	36^{a}	1323^{a}	160^{a}	580^{bc}
Swiss chard	I_{80}	7^{f}	20^{a}	2.2^{a}	9^{cd}	34^{a}	1042^{b}	115^{b}	445^{c}

Column values followed by the same symbol are not statistically different at $p \leq 0.05$. [a]IWR- irrigation water regimes; [b]WP_n-normalised water productivity (WP); normalised nutritional water productivity (NWP_n) for [c]Fe (iron), [d]Zn (zinc), and [e]β (β-carotene); [f]WP-water productivity; nutritional water productivity (NWP) for [g]Fe, [h]Zn, and [i]β. I_{30}, I_{50}, and I_{80} are the well-watered, moderate water stress, and severe water stress irrigation water regimes, respectively. Standard deviation of the means are presented in Table 3A.3.

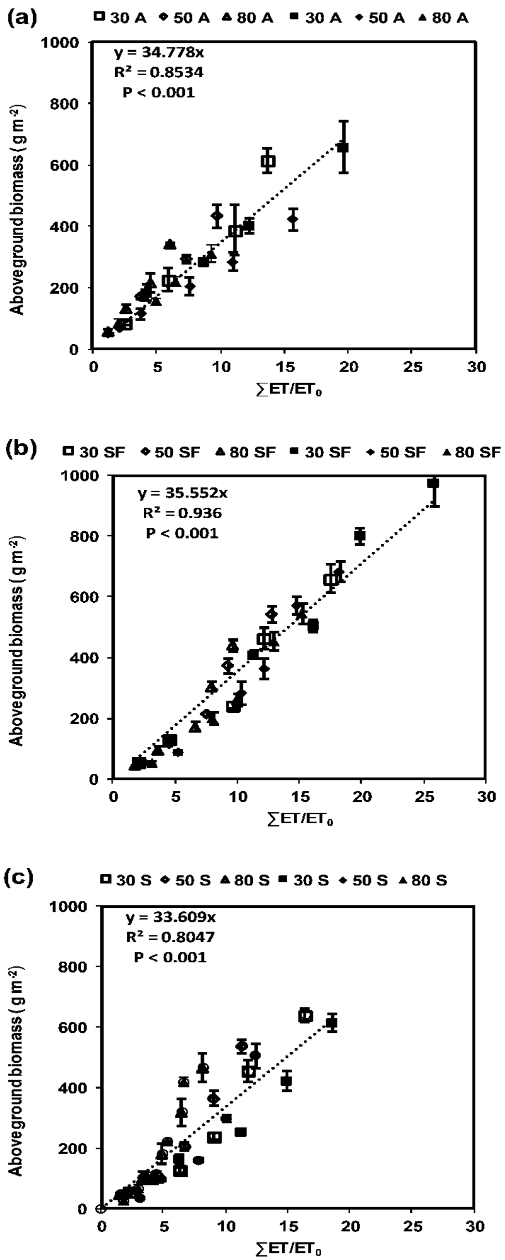

Figure 3.4 The relationship between normalised water use $\sum(ET/ET_0)$ and above ground dry biomass for **a** amaranth (A), **b** spider flower (SF), and **c** Swiss chard (S). The empty symbols represent the 2013/14 season, whereas the filled in symbols represent the 2014/15 season. 30% (well-watered), 50% (moderate water stress), and 80% (severe water stress) are the three irrigation water regimes. Error bars represent the standard deviation of the means

3.4. Discussion

This study assessed nutritional water productivity (NWP) of selected leafy vegetables (amaranth, spider flower and Swiss chard). Previously conducted studies (Mdemu et al., 2009; Renault and Wallender, 2000; Wenhold et al., 2012) have evaluated NWP of vegetables using datasets sourced from literature. The weakness of this approach is that meteorological conditions, evapotranspiration, irrigation and soil fertility management, vary across different locations (Zwart and Bastiaanssen, 2004). In addition, these studies focused on NWP for calories, protein and fat. Micronutrients (iron and zinc) and vitamin A, which are the root causes of micronutrient deficiency ('hidden hunger''), were not considered. Chibarabada et al. (2017) assessed NWP (fat content, protein, calcium, zinc, and iron) of grain legumes [groundnuts, Bambara groundnut (*Vigna subterranean*), dry bean, and cowpea] in Kwazulu Natal, using data sets from the same location. As far as can be ascertained, our study is the first attempt to assess NWP (Fe-NWP, Zn-NWP and β-carotene-NWP) of selected leafy vegetables using datasets [above ground biomass, evapotranspiration and nutrient concentration (Fe, Zn, and β-carotene)] from the same experiment. Therefore, the findings of this research serve as a benchmark. In this study, water stress reduced total aboveground biomass (∑ AGB for several harvests). Mean values for both seasons show that reductions were larger under severe water stress, relative to well-watered conditions. Similar results were observed in severely stressed bottle gourd (*Lagenaria siceraria*), sorghum, cowpea, and *Colocasia esculenta* (taro) (Chimonyo et al., 2016; Mabhaudhi et al., 2013; Mashilo et al., 2018). The response of total AGB for selected leafy vegetables to water stress was consistent with measured plant parameters [leaf area index (LAI), actual evapotranspiration (ET), stomatal conductance, light intercepted (LI), and radiation use efficiency (RUE)]. The observed trend indicated that as the level of water stress increased (Figures 3.1 and 3.2) measured plant parameters decreased significantly (Table 3.3 and Figure 3A.1). Under severe water stress, mean RUE for both seasons showed that Swiss chard is more efficient in converting intercepted radiation into dry matter (Table 3.3). We expected C_4 plants (amaranth and spider flower) to be more productive than the C_3 plant (Swiss chard), as suggested by Renault and Wallender (2000), Van Halsema and Vincent (2012), and Wenhold et al. (2012). Quite surprisingly, our results revealed the opposite (Table 3.3). Perhaps the differing chemical composition of the crops studied could shed light on this unexpected result. It is likely that more energy was required to produce total AGB (lignified stems and leaves) for amaranth and Spider flower, compared to Swiss chard. Mavengahama et al. (2013) highlighted that resource-poor households consume the softest portion (soft stems and leaves) of leafy vegetables. It is crucial to consider the effect of water stress on above ground edible biomass. This study showed that under drought conditions, AGEB was lower by ≈ 55 % for amaranth, ≈ 44 % for spider flower and ≈ 41 % for Swiss chard, compared to the well-watered irrigation regime (Table 3.3). The AGB and AGEB results of this study propose that amaranth and spider flower's reported drought tolerance is perhaps somewhat overestimated in the literature (Afari-Sefa et al. 2012; Aliber and Hart, 2009; Chivinge et al., 2015; Mabhaudhi et al., 2016a, b; Chibarabada et al., 2017; Maseko et al., 2018). Information from these studies was based on anecdotal evidence; with the assumption that TLVs grow naturally next to mainstream crops. We show that TLVs will benefit from irrigation, and most likely fertiliser, as is the case for commercially cultivated crops. Our study tested the performance of selected TLVs under three drought levels and found they are comparable with Swiss chard under drought conditions.

Several reported studies (Afolayan and Jimoh, 2009; Odhav et al., 2007; Uusiku et al., 2010; Van Jaarsveld et al., 2014; Schönfeldt and Pretorius, 2011) did not evaluate the effect of environmental factors (meteorological conditions, soil fertility, severe drought conditions and management) on nutrient concentrations of leafy vegetables. Our results show that micronutrient concentrations (iron and zinc) and β-carotene, differed among selected leafy vegetables, across irrigation regimes, and seasons. Firstly, during the 2013/14 season, water stress did not affect iron concentration. In contrast, iron concentration for the 2014/15 season was reduced (- 21 %) due to severe water stress. Secondly, the 2014/15 season values were low compared to the previous season. This suggests that nutrient concentrations of leafy vegetables are not that conservative, as alluded by Uusiku et al. (2010). We suspect that different meteorological conditions and irrigation management caused the variation in nutrient concentrations (Figures 3.1 and 3.2). It was remarkable that severe water stress increased iron and zinc concentrations for amaranth and spider flower, whereas for Swiss chard, iron (- 46 %) and zinc (- 35 %) concentrations were reduced. β-carotene concentration showed sensitivity towards severe water stress levels. Our selected TLVs displayed superiority in terms of nutrient richness compared to Swiss chard (Figure 3A.2). This authenticates our hypothesis that TLVs are nutrient dense compared to Swiss chard (Table 3.4). In this study, nutrient concentrations (fresh mass basis) values for amaranth and spider flower, ranged from 5.5 to 16 mg 100 g^{-1} for iron, 0.9 to 1.9 mg 100 g^{-1} for zinc, and 934 to 1483 µg RAE, over different irrigation treatments (Table 3A.4). A study conducted by Chibarabada et al. (2017) assessed the nutrient concentrations of grain legumes under three irrigation regimes. Their findings showed that cowpea and dry bean contained around five times the zinc of selected leafy vegetables; whereas, grain legumes exhibited iron concentration lower than this study. Our results indicate that amaranth and spider flower can provide more than the daily-recommended nutrient intake (DRNI) for vitamin A to all age groups, under severe drought conditions. For iron, spider flower could provide more than the DRNI to infants between 1 and 3 years old, whereas for zinc, spider flower can provide ≈ 11 % of the DRNI to the same age group (Table 3A.4). We contend that evaluating nutrient concentrations without considering yields, is a bit unfortunate, as together they can indicate the nutrient yield per unit area of cropped land (g ha^{-1}), a useful term proposed by Bumgarner et al. (2012).

This study revealed that severe water stress decreased NY of iron, zinc and β-carotene across selected leafy vegetables. The mean values for both seasons illustrated that spider flower was more tolerant to severe drought conditions than amaranth and Swiss chard. Spider flower Fe-NY and Zn-NY were reduced by ≈ 30 % with severe stress, whereas for amaranth and Swiss chard, this reduction was ≈ 50 %. For β-carotene-NY, Swiss chard was tolerant (- 19 %) compared to spider flower (- 60 %) and amaranth (- 68 %), under severe drought conditions (Table 3.4). Generally, Swiss chard shows high Fe-NY and Zn-NY, whereas the TLVs exhibited higher β-carotene-NY (Figure 3A.2). The NY findings are not consistent with nutrient concentration results, which showed that selected TLVs are more nutrient dense than Swiss chard. The advantage of Swiss chard over selected TLVs is its higher proportion of AGEB, which increases its NY values. This study brought new insight into the importance of considering NY as a parameter for assessing nutrient richness of crops. Assessments displayed that spider flower can potentially supply a large number of people (RRPHs) with the required amount of micronutrients and vitamin A (iron = 11 people, zinc = 2 people, and β-carotene = 47 people) in comparison to amaranth (iron = 4 people; zinc = 1 person; β-carotene = 47 people), and Swiss chard (iron = 5 people; zinc = 1 person; β-carotene = 20 people), under severe drought conditions. Limited information exists on NY of selected leafy vegetables; Wen Luoh et al. (2014) conducted a study assessing NYs of three TLVs [amaranth (*Amaranthus spp.*), (Ethiopian kale (*Brassica carinata*) African nightshade (*Solanum spp*)] under controlled conditions. The merit of our study is that we evaluated NYs of selected leafy vegetables under variously controlled water regime.

The goal of WP is to improve yield under limited water supply (‘‘more crop per drop of water’’). Our results displayed that WP of leafy vegetables improved under severe water stress in both seasons (Table 3.5). This agrees with other studies which indicate that WP of sorghum (Chimonyo et al., 2016), taro (Mabhaudhi et al., 2013), and maize (Wu et al., 2015) improve under water-stress. Steduto et al. (2007) emphasised the need to normalise AGB water productivity (WP_n) because of variation in evaporative demand caused by different climatic conditions. Our results illustrated that WP_n of selected leafy vegetables is conserved because there was no significant difference between irrigation regimes and seasons. Astonishingly, mean WP_n of C_4 leafy vegetables (amaranth and spider flower) was similar to a C_3 leafy vegetable (Swiss chard). In this study, stomatal conductance (g_s, mmol m^2 s^{-2}) of selected C_4 leafy vegetables was lower than that of a C_3 leafy vegetable under severe water stress. Initially, this suggests that with limited water supply, C_4 plants are more efficient than C_3 crops at minimising their water loss (Ali and Talukder, 2008; Renault and Wallender, 2000; Van Halsema and Vincent, 2012; Wenhold et al., 2012). The similarity between WP_{C4} and WP_{C3} is ascribed to the methodology used to compute WP [the numerator is mass produced (yield or AGB) and the denominator is ET]. Steduto et al. (2007) suggested normalising WP for different climates using T_r as the denominator. A study conducted by Nyathi et al. (2018a) evaluated WP of selected leafy vegetables using the AquaCrop model, which separated T_r from ET. Their findings confirmed that amaranth and spider flower are more productive compared to Swiss chard. This insight highlights the importance of assessing WP using the productive use of water (T_r). Renault and Wallender (2000) emphasised the need for a transition from WP to nutritional water productivity (NWP).

Nutritional water productivity is a novel concept that links crop production, water use in agriculture, and nutrient concentration. The main findings of this study showed that Fe-NWP, Zn-NWP and β-NWP varied among leafy vegetables, across irrigation regimes, and seasons (Table 3.5). Generally, the results revealed that these NWP’s improved with moderate water stress. Either severe water stress reduced NWP, or it remained constant, with some variation between seasons. For example, during the 2013/14 season, Fe-NWP improved by ≈ 5 % for amaranth and ≈ 19 % for spider flower, whereas for Swiss chard, it was reduced by ≈ 21 %. In contrast, in 2014/15, Fe-NWP was reduced by ≈ 39 % for amaranth, whereas for spider flower and Swiss chard, it remained the same. Under severe water stress, NWP of micronutrients and β-carotene were higher compared to the well-watered treatment. Generally, Swiss chard was the most productive leafy vegetable for Fe-NWP and Zn-NWP, whereas amaranth was superior with β-carotene-NWP, under severe water-stressed conditions (Figure 3A.2). This highlights the need for crop diversification in order to maximise the amount of micronutrients produced per unit of water used. A study conducted by Chibarabada et al. (2017) reported Fe-NWP (ranged from 5.3 to 79 mg m^{-3}) and Zn-NWP (ranged from 3.7 to 38.6 mg m^{-3}) values that are lower than found in this study. This suggests that selected leafy vegetables are more productive than grain legumes (Table 3.5). The possible explanation is the length of growing period; leafy vegetables take ≈ 3 months; therefore, they utilise less water (147-457 mm) compared to grain legumes. Our study computed the total amount of water required per day to meet total nutrient requirements [∑

water required for nutrients (iron + zinc + β-carotene)] for a family of six people (Box 3.1). The moderate water stress was the best because it displayed the minimum amount of water required (Figure 3A.3). Amazingly, selected TLVs (amaranth = 3544 litres day^{-1}; spider flower = 5057 litres day^{-1}) required less water compared to Swiss chard (5992 litres day^{-1}). This contradicts the NWP results, which suggested that Swiss chard was more productive, compared to selected TLVs. The possible reason could be converting nutrient concentration from dry mass to fresh mass basis. Under severe drought conditions, the observed trend was that Swiss chard is more productive than amaranth in terms of total water required (Figure 3A.3). This study presented new insights that there is some scope to alleviate micronutrient deficiency under drought conditions.

3.5 Conclusions and future research

In this study, severe water stress reduced aboveground biomass (AGB) for selected traditional leafy vegetables (TLVs) and Swiss chard, relative to the well-watered treatment. This implies that not all TLVs are tolerant to water stress compared to Swiss chard; productivity data from literature is based on anecdotal evidence. Under severe water stress, Swiss chard produced more edible biomass (AGEB) over selected TLVs. This highlights that under drought conditions, less AGEB will be available for rural resource-poor households (RRPHs). Traditional leafy vegetables exhibited higher micronutrient (iron and zinc) and β-carotene concentrations. Amaranth and spider flower can provide more than the daily-recommended nutrient intake (DRNI) for vitamin A to all age groups. However, higher nutrient concentrations did not translate to higher nutritional yield (NY). Findings displayed that Swiss chard was rich in Fe-NY and Zn-NY, whereas TLVs were superior in β-carotene-NY. This highlights the importance of using NY as a parameter for assessing nutrient denseness of crops. Under moderate water stress, selected TLVs (amaranth = 3544 litres day^{-1}; spider flower = 5057 litres day^{-1}) required less water to meet total human nutritional requirements for a family of six, compared to Swiss chard (5992 litres day^{-1}). There is a possibility of alleviating micronutrient deficiency of RRPHs under drought conditions. The results of this study are a first in quantifying nutritional productivity under controlled water regime; we propose that future research and validation of our results should consider the following:

- This study assessed NWP of three selected leafy vegetables under well-controlled conditions. Future studies are needed to assess NWP (iron, zinc and β-carotene) of many TLVs and alien vegetables. These studies should be conducted in different locations (climates and soils), explore the effect of management factors (fertiliser, water stress, planting density and planting date), on NWP. Such studies should consider using GIS and remote sensing as a tool to scale up NWP results throughout Southern Africa. In this study, conversion of raw nutrient concentrations (iron, zinc and β-carotene) into cooked (boiled) values used conversion factors from other studies.

- Future studies on NWP should consider assessing the effect of various cooking methods (i.e. boiling, frying, steaming, and grilling) on nutrient concentrations of leafy vegetables. This calls for a multidisciplinary team (soil scientists, agronomists, irrigation scientists, and food scientists) when assessing NWP. In addition, factors affecting the bioavailability of iron and zinc of TLVs should be assessed.

- Key findings of our study are that micronutrients and β-carotene concentrations are not conservative. Future research should assess the factors affecting the stability of micronutrients and β-carotene concentrations. This can provide the basis for modelling the NWP of crops.

Appendix 3A

Table 3A.1 Standard deviations of the means for biomass and other related parameters of selected leafy vegetables during 2013/14 (one) and 2014/15 (two) seasons

Leafy vegetables		AGB[a]	AGEB[b]	HI[c]	ET_n[d]	ET[e]	LI[f]	RUE[g]
Amaranth		**$g\ m^{-2}$**	**$g\ m^{-2}$**			**mm**	**$MJ\ m^{-2}$**	**$g\ MJ^{-1}$**
IWR[h] x Season								
I_{30}	One	32	53	0.07	0.19	2.5	38	0.09
I_{50}	One	29	61	0.19	0.33	5.9	70	0.13
I_{80}	One	5	38	0.11	0.40	4.6	41	0.06
I_{30}	Two	93	53	0.19	0.70	8.8	36	0.19
I_{50}	Two	28	12	0.04	0.67	26	96	0.05
I_{80}	Two	18	19	0.03	0.50	17	78	0.08
Spider flower								
IWR x Season								
I_{30}	One	38	11	0.02	0.09	7.5	15	0.13
I_{50}	One	22	5	0.02	0.50	7.0	11	0.10
I_{80}	One	17	15	0.03	1.03	1.0	43	0.13
I_{30}	Two	66	49	0.07	0.92	12	43	0.12
I_{50}	Two	27	37	0.06	1.41	23	41	0.01
I_{80}	Two	27	5	0.01	0.82	14	70	0.04
Swiss chard								
IWR x Season								
I_{30}	One	44	9	0.06	0.23	4.6	16	0.14
I_{50}	One	18	17	0.01	0.20	2.9	15	0.04
I_{80}	One	39	2	0.06	3.39	3.4	15	0.18
I_{30}	Two	24	23	0.06	2.82	20	66	0.16
I_{50}	Two	32	6	0.07	0.82	23	46	0.16
I_{80}	Two	11	7	0.01	1.19	22	92	0.09

[a]AGB- above ground biomass; [b]AGEB-above ground edible biomass; [c]HI- harvest index; [d]ET_n-normalised evapotranspiration; [e]ET- actual evapotranspiration; [f]LI- light intercepted; [g]RUE- radiation use efficiency (RUE has been calculated as $\sum RUE_{h1} + RUE_{h2} + \ldots\ldots RUE_{hn}$, where H_1 is harvesting period one and H_n is the final harvest); [h]IWR- irrigation water regimes; I_{30}, I_{50}, and I_{80} are the well-watered, moderate water stress, and severe water stress IWR, respectively.

Table 3A.2 Standard deviations of the means for nutritional content (dry mass basis) and nutritional yield (dry mass basis) of iron, zinc, and β-carotene during the 2013/14 and 2014/15 seasons

Leafy vegetables	**IWR**[a]	**Moisture**	**Fe**[b]	**Zn**[c]	**β**[d]	**Fe-NY**[e]	**Zn-NY**	**β-NY**
2013/14		%	mg $100g^{-1}$	mg $100g^{-1}$	mg $100g^{-1}$	g ha^{-1}	g ha^{-1}	g ha^{-1}
Amaranth	I_{30}	0.02	4	0.43	15	323	33	697
Amaranth	I_{50}	0.02	6	0.03	16	455	37	388
Amaranth	I_{80}	0.02	7	1.04	8	276	37	449
Spider flower	I_{30}	0.03	5	0.45	9	178	11	205
Spider flower	I_{50}	0.00	4	0.78	9	108	20	216
Spider flower	I_{80}	0.01	3	0.64	8	129	16	233
Swiss chard	I_{30}	0.00	9	0.87	4	329	40	140
Swiss chard	I_{50}	0.01	7	0.57	3	288	20	138
Swiss chard	I_{80}	0.00	9	0.10	3	299	4	93
2014/15								
Amaranth	I_{30}	0.01	1	0.99	8	192	27	1075
Amaranth	I_{50}	0.01	4	0.31	11	116	7	266
Amaranth	I_{80}	0.02	2	0.41	4	47	12	174
Spider flower	I_{30}	0.03	7	0.72	11	489	8	746
Spider flower	I_{50}	0.04	9	0.64	11	324	15	442
Spider flower	I_{80}	0.01	10	0.55	7	119	9	14
Swiss chard	I_{30}	0.01	12	0.30	3	568	15	119
Swiss chard	I_{50}	0.01	3	0.41	3	122	19	147
Swiss chard	I_{80}	0.00	6	0.16	1	135	7	26

[a]IWR- irrigation water regimes; [b]Fe- Iron, [c]Zn- Zinc, and [d]β- β-carotene concentrations; [e]Fe-NY- Fe nutritional yield (NY). I_{30}, I_{50}, and I_{80} are the well-watered, moderate water stress, and severe water stress irrigation water regimes, respectively

Table 3A.3 Standard deviations of the mean for normalised nutritional water productivity and nutritional water productivity of iron, zinc, and β-carotene during the 2013/14 and 2014/15 seasons

Crop	IWR[a]	WP_n[b]	Fe-NWP_n[c]	Zn-NWP_n[d]	β-NWP_n[e]	WP[f]	Fe-NWP[g]	Zn-NWP[h]	β-NWP[i]
2013/14		$g\ m^{-2}$	$mg\ m^{-2}$	$mg\ m^{-2}$	$mg\ m^{-2}$	$kg\ ha^{-1}\ mm^{-1}$	$mg\ m^{-3}$	$mg\ m^{-3}$	$mg\ m^{-3}$
Amaranth	I_{30}	0.19	2.07	0.13	4.10	2	111	11	230
Amaranth	I_{50}	0.33	0.92	0.24	12.3	4	245	20	240
Amaranth	I_{80}	0.40	4.36	0.66	9.86	4	184	25	299
Spider flower	I_{30}	0.09	2.42	0.00	3.66	2	47	3	71
Spider flower	I_{50}	0.50	1.44	0.33	3.76	0	57	6	66
Spider flower	I_{80}	0.11	1.57	0.35	4.22	2	67	9	126
Swiss chard	I_{30}	0.23	5.06	0.39	2.52	3	113	13	51
Swiss chard	I_{50}	0.20	2.99	0.20	1.89	2	139	10	71
Swiss chard	I_{80}	0.23	4.42	0.20	2.02	5	175	3	63
2014/15									
Amaranth	I_{30}	0.70	1.16	0.55	3.05	4	65	10	352
Amaranth	I_{50}	0.67	1.35	0.10	2.26	1	23	3	277
Amaranth	I_{80}	0.50	0.99	0.21	2.35	2	41	9	105
Spider flower	I_{30}	0.92	0.72	0.48	5.08	4	97	1	145
Spider flower	I_{50}	1.41	4.50	0.38	6.11	3	83	5	102
Spider flower	I_{80}	0.82	4.15	0.44	1.72	4	53	5	20
Swiss chard	I_{30}	2.82	6.62	0.44	2.09	6	155	13	43
Swiss chard	I_{50}	0.82	3.04	0.30	0.78	4	176	13	151
Swiss chard	I_{80}	1.19	4.21	0.78	2.78	12	264	26	108

[a]IWR- irrigation water regimes; [b]WP_n-normalised water productivity (WP); normalised nutritional water productivity (NWP_n) for [c]Fe (iron), [d]Zn (zinc), and [e]β (β-carotene); [f]WP-water productivity; nutritional water productivity (NWP) for [g]Fe, [h]Zn, and [i]β. I_{30}, I_{50}, and I_{80} are the well-watered, moderate water stress, and severe water stress irrigation water regimes, respectively.

Table 3A.4 Mean values (2013/14 and 2014/15 seasons) for micronutrient concentrations (iron and zinc), and vitamin A (µg RAE) for the estimated percentage nutrient contribution of three selected leafy vegetables to the daily recommended nutrient intake for four age groups

LVs[a]	Water regimes	Concentration	1-3 years %	4-18 years %	Male %	Female %
Iron (mg 100 g^{-1})						
Amaranth	I_{30}	6.6	57	10	24	11
Amaranth	I_{50}	7.6	65	12	28	13
Amaranth	**I_{80}**	**5.5**	**48**	**8**	**20**	**9**
Spider flower	I_{30}	11	95	17	40	19
Spider flower	I_{50}	13	114	20	48	22
Spider flower	**I_{80}**	**16**	**139**	**25**	**59**	**27**
Swiss chard	I_{30}	5.2	44	8	19	9
Swiss chard	I_{50}	4.5	38	7	16	8
Swiss chard	**I_{80}**	**4.5**	**39**	**7**	**16**	**8**
Zinc (mg 100 g^{-1})						
Amaranth	I_{30}	1.1	6.5	3.7	3.8	5.5
Amaranth	I_{50}	1.0	6.0	3.5	3.6	5.1
Amaranth	**I_{80}**	**0.9**	**5.3**	**3.0**	**3.1**	**4.5**
Spider flower	I_{30}	1.4	8.6	4.9	5.1	7.3
Spider flower	I_{50}	1.5	9.3	5.4	5.5	7.9
Spider flower	**I_{80}**	**1.9**	**11.3**	**6.5**	**6.7**	**9.6**
Swiss chard	I_{30}	0.5	3.3	1.9	1.9	2.8
Swiss chard	I_{50}	0.5	3.0	1.8	1.8	2.6
Swiss chard	**I_{80}**	**0.5**	**3.2**	**1.8**	**1.9**	**2.7**
β-carotene (µg RAE)						
Amaranth	I_{30}	1419	355	237	237	284
Amaranth	I_{50}	1483	371	247	247	297
Amaranth	**I_{80}**	**943**	**236**	**157**	**157**	**189**
Spider flower	I_{30}	1085	271	181	181	217
Spider flower	I_{50}	1148	287	191	191	230
Spider flower	**I_{80}**	**934**	**233**	**156**	**156**	**187**
Swiss chard	I_{30}	147	37	24	24	29
Swiss chard	I_{50}	145	36	24	24	29
Swiss chard	**I_{80}**	**202**	**50**	**34**	**34**	**40**

Micronutrient concentration and Vitamin A are on fresh mass basis. [a]LVs- selected leafy vegetables. I_{30}, I_{50}, and I_{80} are the well-watered, moderate water stress, and severe water stress, respectively.

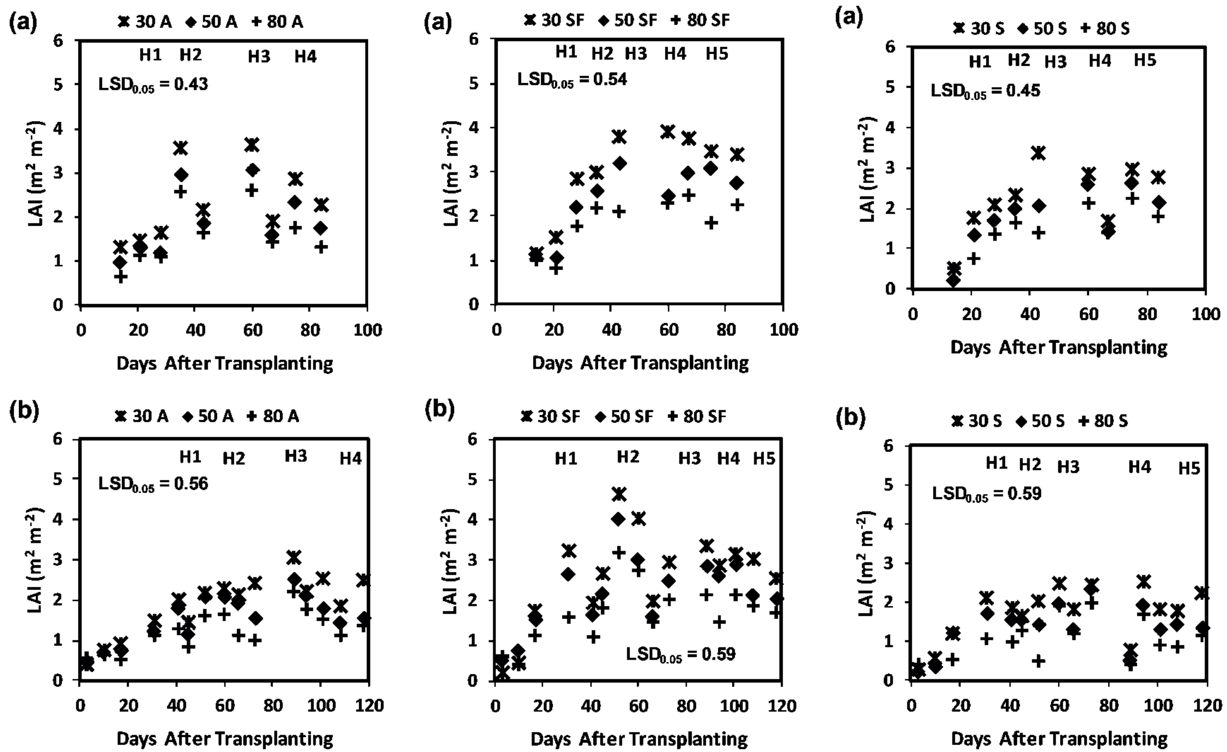

Figure 3A.1 The effect of irrigation water regimes [30% (well-watered), 50% (moderate water stress), and 80% (severe water stress)] on leaf area Index (LAI) for Amaranth (A), Spider flower (SF), and Swiss chard (S). **a** and **b** are the 2013/14 and 2014/15 seasons. H_1……. H_n means harvesting period during the growing season.

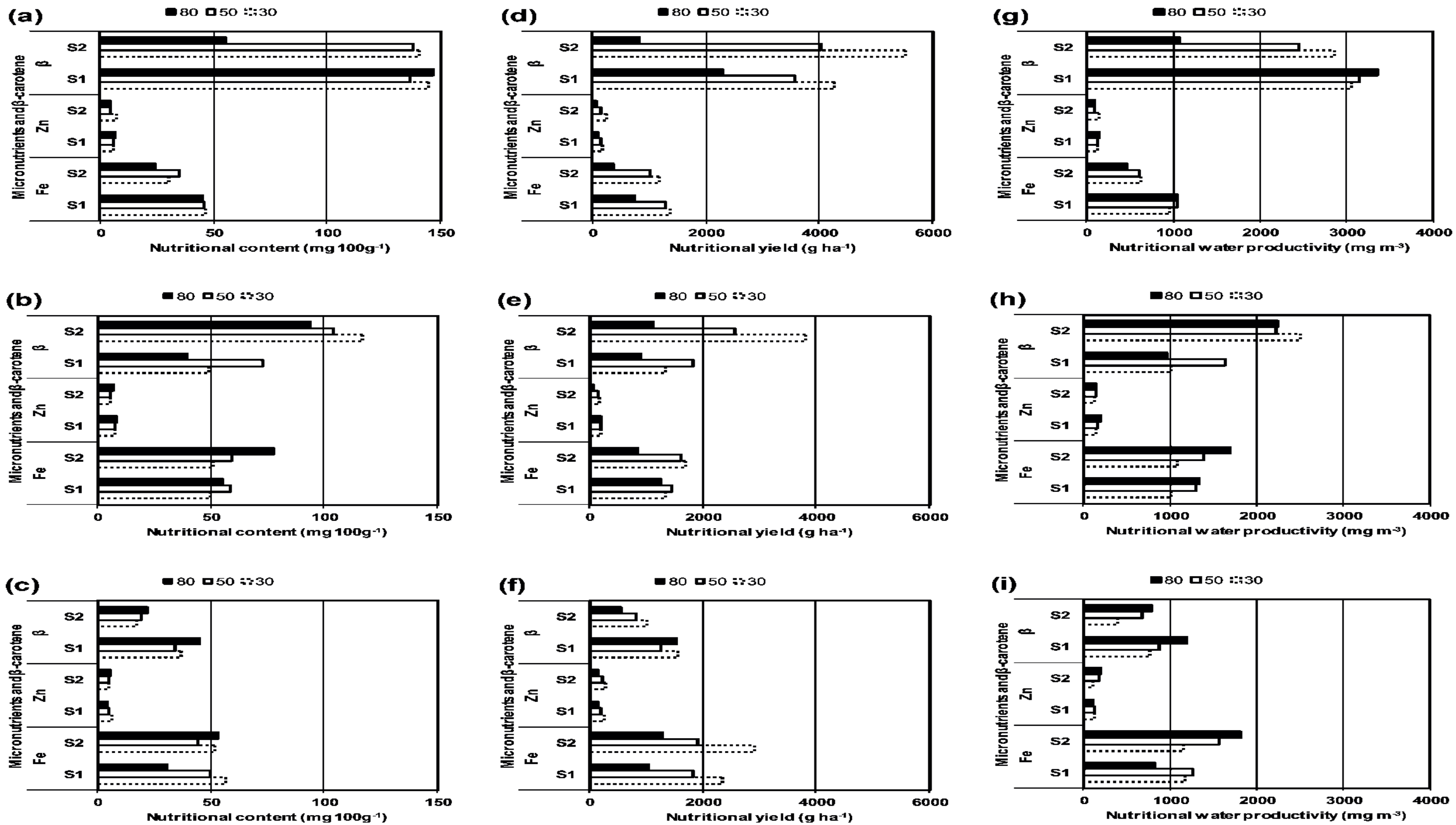

Figure 3A.2 Iron (Fe), Zinc (Zn), and β-carotene (β) nutritional content (**a,b,c**), nutritional yield (**d,e,f**), and nutritional water productivity (**g,h,i**) for Amaranth (**a,d,g**), Spider flower (**b,e,h**), and Swiss chard (**c,f,i**). S_1 is 2013/14 season, whereas S_2 is 2014/15 season. 30% (well-watered), 50% (moderate water stress), and 80% (severe water stress) are the three irrigation water regimes, respectively.

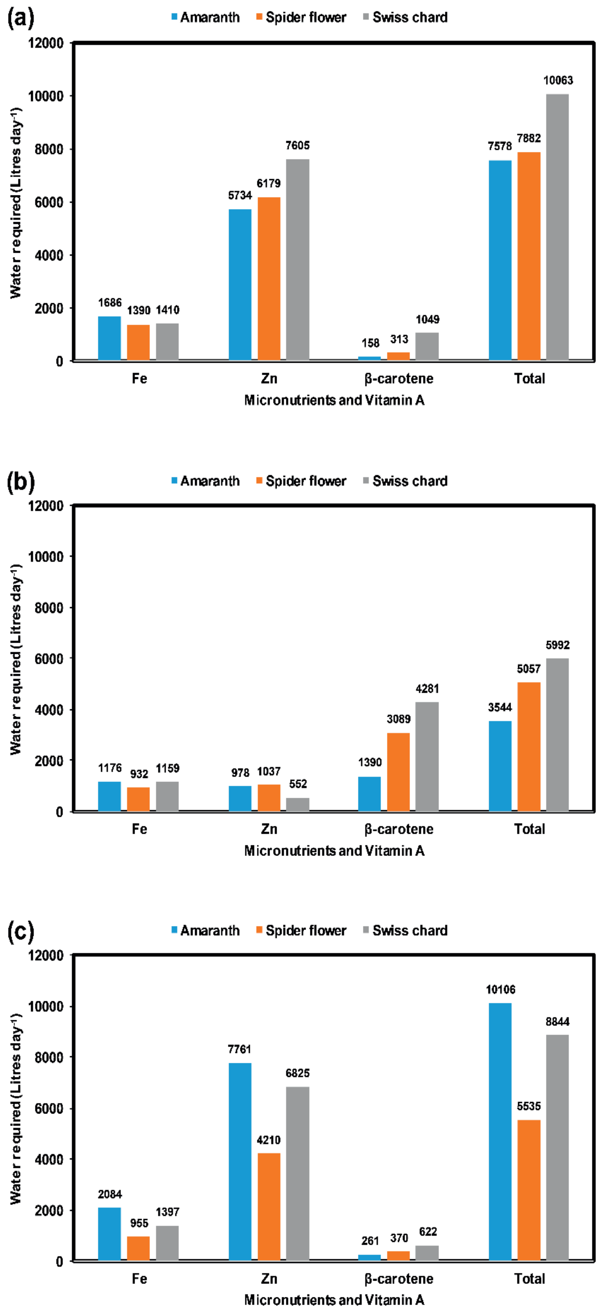

Figure 3A.3 Amount of water required to meet total human nutrition requirements for iron (Fe), zinc (Zn), and vitamin A (β-carotene): **a** is the well-watered irrigation water regime, **b** is the moderate water stress, and **c** is the severe water stress.

Chapter

4

Calibration and validation of the AquaCrop model for repeatedly harvested leafy vegetables grown under different irrigation regimes

This chapter is based on:

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Abstract

Traditional leafy vegetables (TLVs') are vegetables that were introduced in an area a long time ago, where they adapted to local conditions and became part of the local culture. In Sub-Saharan Africa, the use of TLVs' as a nutrient dense alternative food source to combat micronutrient deficiency of rural resource-poor households (RRPHs), has gained attention in debates on food and nutrition security. However, TLVs' are underutilised because of lack of information on their yield response to water and fertiliser. To better assess TLVs' yield response to water stress, the AquaCrop model was calibrated (using 2013/14 data) and validated (using 2014/15 data) for three repeatedly harvested leafy vegetables [*Amaranthus cruentus* (amaranth), *Cleome gynandra* (spider flower), and *Beta vulgaris* (Swiss chard)] in Pretoria, South Africa. Experiments were conducted during two consecutive seasons, in which the selected leafy vegetables were subjected to two irrigation regimes; well-watered (I_{30}) and severe water stress (I_{80}). Measured parameters were canopy cover (CC), soil water content (SWC), aboveground biomass (AGB), actual evapotranspiration (ET_a), and water productivity (WP). Statistical indicators [root mean square error (RMSE), RMSE-standard deviation ratio (RSR), R^2, and relative deviation] showed good fit between measured and simulated ($0.60 < R^2 < 0.99$, $0.94 < RMSE < 5.44$, and $0.04 < RSR < 0.79$) values for the well-watered treatment. However, the fit was not as good for the water stressed treatment for CC, SWC, ET_a and WP. Nevertheless, the model simulated the selected parameters satisfactorily. These results revealed that there was a clear difference between transpiration water productivity (WP_{Tr}) for C_4 crops (amaranth and spider flower) and a C_3 crop (Swiss chard); WP_{Tr} for the C_4 crops ranged from 4.61 to 6.86 kg m^{-3}, whereas for the C_3 crop, WP_{Tr} ranged from 3.11 to 4.43 kg m^{-3}. It is a challenge to simulate yield response of repeatedly harvested leafy vegetables because the model cannot run sequential harvests at one time; therefore, each harvest needs to be simulated separately, making it cumbersome. To design sustainable food production systems that are health-driven and inclusive of RRPHs, we recommend that more vegetables (including traditional vegetables) should be included in the model database, and that sequential harvesting be facilitated.

Key words: Crop modelling; water productivity; biomass; evapotranspiration, indigenous leafy vegetables

4.1 Introduction

Globally, the agricultural sector is utilising 70% of available fresh water. Projections indicate that the demand for water will increase due to population growth. By the year 2050, more water will be required to produce highly nutritious food for more than 9 billion people (IFPRI, 2016). Furthermore, climate change will increase temperature and carbon dioxide levels (Allan et al., 2013). An increase in carbon dioxide (from 380 - 550 ppm) at 25ºC has a benefit, depending on crop species. For C_3 crops, photosynthesis would increase by 38%, which in turn will increase yield; however, for C_4 crops, an increase in CO_2 level may not show an increase in photosynthetic activity, but an indirect increase in the efficiency of water use through reduction in stomatal conductance (Long et al., 2006). Several authors (Gido et al., 2017; Keatinge et al., 2011; Mabhaudhi et al., 2016b; Uusiku et al., 2010) averred that the current food system focus is on enhancing food security through the production of mainstream crops [*Zea mays* (maize), *Triticum species* (wheat), *Sorghum bicolor* (sorghum), *Oryza sativa* (rice), *Hordeum vulgare* (barley), and *Pennisetum glaucum* (millet)] under water scarcity. These crops contribute significantly to dietary energy requirements; however, they are deficient in micronutrients (iron and zinc) and vitamin A. Globally, two to three billion people suffer from micronutrient deficiency, with Sub-Saharan Africa (SSA) accounting for approximately one billion (IFPRI, 2016; Keatinge et al., 2011). Focusing on cereal production as a solution to combat hunger will not abate the widespread occurrence of micronutrient deficiency-related diseases, including stunted growth and impeded cognitive development. There is a need to increase the consumption of vegetables as a strategic intervention for addressing micronutrient (iron and zinc) and vitamin A deficiency. This can be done by constructing sustainable food systems that are inclusive of both rich and poor, and that are highly nutritious, climate-smart, and health-focused (Bello and Walker, 2017; IFPRI 2016; Mabhaudhi et al., 2016a; Tata-Ngome et al., 2017).

Research funding has focused on the production of vegetables with low β-carotene, iron, and zinc, such as cabbage and tomato, supported by large established consumer markets. This has undervalued the nutritional component of some vegetables (Keatinge et al., 2011). Consuming nutrient-dense vegetables is a first step in alleviating micronutrient deficiency. The World Health Organisation recommends a vegetable intake of at least 400 g $person^{-1}$ day^{-1} for a healthy and nutritious life; a requirement that is not met by half of the countries in SSA (Tata-Ngome et al., 2017). Sub-Saharan Africa has a wide variety of traditional leafy vegetables (TLVs') that are rich in vitamins, carotenoids, and other micronutrients (iron, zinc, magnesium) (Chivenge et al., 2015; Gido et al., 2017; Mabhaudhi et al., 2016b; Tata-Ngome et al., 2017; Nyathi et al., 2016). However, TLVs' are underutilised because of lack of information on their yield response to water and fertiliser, the threat of becoming extinct when collected from the wild or as "weeds" next to cropped land, and limited insight into the factors affecting their nutritional content (Mavengahama et al., 2013). These factors undermine the potential of TLVs' to contribute to nutritional food security. Traditional leafy vegetables present advantages over alien vegetables; their abundance in the ''wild'' or next to cereal crops, their high nutrient concentration (iron, zinc, β-carotene, magnesium), their drought tolerance, their resistance to pests and diseases, and the low need to apply water and fertiliser (Keatinge et al., 2011; Mavengahama et al., 2013; Tata-Ngome et al., 2017; Uusiku et al., 2010). These characteristics make TLVs' ideal crops for RRPHs.

In this paper, we do not wish to undermine the essential role played by modern cereal crops in combating the energy-deficiency of the food security quest. Following Smith (2013), we advocate for a sustainable intensification of food production as "*the process of delivering safer, nutritious food, (e.g. tonnes of cereals, grams of protein, and grams of micronutrients) per unit of resource (land area, water, fertiliser, and agrochemicals)*". There are approximately 500 million RRPHs in SSA and Asia, who provide 80% of the food produced there (IFPRI, 2016). However, they are vulnerable to nutritional food insecurity because of low productivity and over-reliance on a few selected vegetables that require high inputs such as water for irrigation and fertiliser. Introducing TLVs' to RRPHs as cultivated leafy vegetables have the potential of contributing significantly to the dietary diversification (Bello and Walker, 2017) under resource (water and fertiliser) constrained conditions. Experiments aimed at assessing the effect of two water stress levels on nutritional water productivity of *Amaranthus cruentus* (amaranth), *Cleome gynandra* (spider flower), and *Beta vulgaris* (Swiss chard *var. Ford hook Giant*) were conducted in South Africa during the 2013/14 and 2014/15 seasons. We chose amaranth and spider flower because they are underutilised in southern Africa, but have a high potential of being cultivated as leafy vegetables, whereas Swiss chard was included as a reference crop, because it is a widely accepted leafy vegetable that has been commercialised worldwide. The challenge with field experiments is that they yield location specific results that may not be applicable to other locations with different climate and soils. Conducting experiments for evaluating the yield response of crops to different deficit irrigation strategies is time-consuming, laborious, expensive, and complicated. Therefore, a combination of field experimentation and analysis based on crop water productivity models can be helpful to develop and assess different deficit irrigation strategies, identify various environmental and management strategies, separate evaporation and transpiration from evapotranspiration (to assess beneficial use of water by crops), and to aid decision-making for improved irrigation and cultivation management (Mustafa et al., 2017).

To make the results of our field experiments more generic and applicable, we selected the model AquaCrop (http://www.fao.org/aquacrop), which was developed by the Food and Agriculture Organisation to simulate yield responses of crops to water, especially where water is limiting for crop production. AquaCrop has been utilised in many studies (e.g. Abedinpour et al., 2012; Araya et al., 2016; Battisti et al., 2017; Bello and Walker, 2016; Greaves and Wang, 2017; Katerji et al., 2013; Mirsafi et al., 2016; Montoya et al., 2016; Mustafa et al., 2017; Paredes et al., 2014; Paredes et al., 2015; Pawar et al., 2017; Razzaghi et al., 2017; Tavakoli et al., 2015; Yuan et al., 2013) to assess yield response of crops [(*Beta vulgaris* (sugar beet), *Glycine max (*soya beans*)*, wheat (*Triticum spp.), Hordeum vulgare* (barley), *Pennisetum glaucum* (pearl millet), potato (*Solanum tuberosum*), maize (*Zea mays*), sunflower (*Helianthus annuus*), oats (*Avena sativa*), cabbage (*Brassica oleracea*), *Sorghum bicolor* (sorghum), *Crocus sativus* (saffron), and *Solanum lycopersicum* (tomato)] to water stress. Bello and Walker (2017) calibrated the model for amaranth. However, it was not clear how they accounted for repeatedly harvested leaves of amaranth. To our knowledge, the AquaCrop model has not been calibrated and validated for spider flower and Swiss chard. Therefore, our main objective was to calibrate and validate the model for amaranth, spider flower, and Swiss chard. In this study we: (1) parameterised AquaCrop for selected leafy vegetables under two water stress levels; (2) compared TLVs' yield response with that of Swiss chard; and, (3) considered the practice of harvesting these selected leafy vegetables repeatedly throughout the growing period, which is currently absent as a management practice in AquaCrop Version 4.0.

4.2 Materials and methods

4.2.1 Study site, experimental setup, irrigation water management, and agronomic practices

Experiments were conducted under a rain-shelter at the Agricultural Research Council, Vegetable and Ornamental Plants (ARC-VOP), Roodeplaat, Pretoria (25º 60' S; 28º 35' E; 1168 m a.s.l.), in the Gauteng Province of South Africa, during the 2013/14 and 2014/15 summer seasons. The rain-shelter has a rain sensor that triggers an electric motor during a rainfall event and the shelter automatically covers the experimental field. Therefore, the experiment experiences normal field conditions, except when it is raining (Mabhaudhi et al., 2014). Long-term climate data (1990-2015) shows a rainfall of approximately 650 mm per year on average, concentrated in the summer (October-March). January is the month with the highest average maximum temperature (30ºC). The experiment was a 3 x 2 factorial design; with three crops (amaranth, spider flower, and Swiss chard) and two irrigation water regimes (I_{30} – well-watered and I_{80} – severe water stress). Irrigation water regimes mean that crops were irrigated back to field capacity after 30% and 80% depletion of plant available water. The maximum effective rooting depth (0.6 m) for the selected leafy vegetables was determined using neutron probe readings. We executed the experiment as a randomised complete block design and it was replicated three times. Three water samples were sent to the ARC-Institute for Soil, Climate, and Water, to determine the quality (salinity, ds m^{-1}) of irrigation water. Irrigation scheduling was based on irrigation water regimes, using readings of the calibrated neutron water meter (CPN, 503 DR Hydroprobe). Aluminium access tubes were installed in the middle of each plot to a depth of 1 m. Soil water content (SWC) was measured twice a week at fixed depth increments of 0.2 m. Actual evapotranspiration (ET_a, mm) was calculated using the soil water balance equation (Eq. 1).

$$ET_a = I + \Delta W \quad (1)$$

Where I is the irrigation amount (mm), ΔW is the change in SWC (mm). There was no deep percolation because the rain-shelter kept rain out and irrigation was always to restore the top 0.6 m of the profile to field capacity. The ARC-VOP gene bank supplied seeds for amaranth and spider flower, whereas Swiss chard seedlings were procured. Amaranth and spider flower seeds were sown in seedling trays and covered with vermiculite, which was used as a medium for seed germination. The seedlings were planted in the field at an inter and intra row spacing of 0.3 m × 0.3 m after 8 weeks. The residual soil P (127 mg kg^{-1}) and K (132 mg kg^{-1}) values were very high, therefore we decided only to apply limestone ammonium nitrate (28% N) fertiliser at a recommended rate of 150 kg N ha^{-1}; 50 kg N ha^{-1} was applied at planting and the remaining 100 kg N ha^{-1} was applied as top-dressing at 25 kg N ha^{-1} after each harvest during the growing period. The crop management practices were similar for the 2013/14 and 2014/15 seasons.

4.2.2 AquaCrop model description

AquaCrop is a water driven model that simulates yield response to water (i.e. water productivity). Prior to AquaCrop, the Doorenbos and Kassam (1979) approach was utilised, to determine yield response to water for herbaceous and tree crops (Eq. 2), which led to the evolution of the AquaCrop model (Steduto et al., 2009). The benefit of AquaCrop is that (1) it separates ET_a into two separate components, namely soil evaporation (E_s) and transpiration (T_r). This means that it does not consider the non-productive use of water (E_s). (2) AquaCrop uses canopy cover (CC) instead of leaf area index (LAI), which is directly related to water loss. (3) Yield is simulated as a function of the harvest index (HI) and final aboveground biomass (Eq. 3). (4) Lastly, it considers the normalised water productivity (WP*), which is a conservative parameter that is applicable to different environmental and climatic conditions (Eq. 4) (Foster et al., 2017; Mirsafi et al., 2016; Montoya et al., 2016; Tavakoli et al., 2015). AquaCrop consists of two types of parameters: (1) Conservative parameters, which do not change with time, management, and location, and (2) non-conservative parameters that change with time, management, and location (Table 4.1) (Montoya et al., 2016; Parades et al., 2015). In addition, the model simulates SWC in the root zone based on the water balance approach, which makes it easy to understand irrigation management strategies (Tavakoli et al., 2015). The model estimates water use based on four stress factors (K_s); canopy expansion, stomatal closure, early canopy senescence, and aeration stress (Mabhaudhi et al., 2014; Vanuytrecht et al., 2014). In addition, AquaCrop calculates E_s and T_r using Eqs. 5 and 6. Details underlying concepts, principles, and the conceptual framework of AquaCrop model are explained by Foster et al. (2017), Hsiao et al. (2009), Raes et al. (2009), Steduto et al. (2009), and Vanuytrecht et al. (2014).

$$[(Y_x - Y_a)/ (Y_x)] = [(ET_x - ET_a) / (ET_x)] \quad (2)$$

$$Y = B \times HI \quad (3)$$

$$B = WP^* \times \sum (T_r / ET_0) \quad (4)$$

$$E_s = K_r [(1-CC^*) K_{ex}] ET_0 \quad (5)$$

$$T_r = (K_s K_{sTr} K_{cTr}) ET_0 \quad (6)$$

Where Y is the yield (t ha^{-1}); x and a are maximum and actual values; ET is evapotranspiration (mm). B is biomass (t ha^{-1}); HI is the harvest index (unitless). WP* is the normalised water productivity (g m^{-2}); T_r is transpiration (mm); ET_0 is the reference evapotranspiration (mm). E_s (mm) is soil evaporation; K_r is the evaporation reduction coefficient (0-1); CC* is the fractional canopy cover (%) adjusted for micro advective effects; K_{ex} is the maximum soil evaporation coefficient (non-dimensional). K_{sTr} is cold stress coefficient for crop transpiration; K_{cTr} is the crop transpiration coefficient.

Table 4.1 Selected conservative and non-conservative parameters of amaranth (A), spider flower (SF), and Swiss chard (S)

Parameters	A	SF	S	Description
Photosynthetic pathway	C_4	C_4	C_3	Cultivar
Reference Harvest Index (%)	48	41	65	Cultivar
Aeration stress (%)	15	15	15	Cultivar
Initial canopy cover (%)	0.1	0.1	0.1	Non conservative
Planting density (plants ha^{-1})	6667	6667	6667	Non conservative
Maximum canopy cover (%)	80	90	90	Non conservative
Minimum rooting depth (m)	0.3	0.3	0.4	Non conservative
Maximum effective rooting depth (m)	0.8	0.8	0.8	Non conservative
Maximum rooting depth (GDD)	351	415	415	Non conservative
Duration to recover (GDD)	64	64	30	Non conservative
Duration of biomass build up (harvest) (GDD)	342	297	312	Non conservative
Maximum canopy cover (GDD)	342	297	312	Non conservative
Canopy growth coefficient (% GDD^{-1})	38	40	39	Conservative
Canopy decline coefficient (% GDD^{-1})	0.23	0.20	0.19	Conservative
Rooting depth shape factor (ratio)	1.5	1.5	1.5	Conservative
Base temperature (ºC)	7	7	5	Conservative
Upper temperature (ºC)	40	40	35	Conservative
Upper threshold for canopy expansion (P_{upper})	0.14	0.15	0.10	Conservative
Lower threshold for canopy expansion (P_{lower})	0.44	0.45	0.41	Conservative
Upper threshold for stomata closure	0.51	0.55	0.25	Conservative
Normalised crop water productivity (g m^{-2})	30	30	16	Conservative

Parameters presented are for the first harvest period only

4.2.3 Data collection for the AquaCrop model

During the growing seasons (2013/14 and 2014/15), the following data were collected and used as inputs into AquaCrop model:

(1) Daily meteorological data were obtained from an automatic weather station, located 5 m away from the rain shelter. Meteorological variables included minimum and maximum temperatures (ºC), total radiation (MJ m^{-2} day^{-1}), vapour pressure deficit (kPa), wind speed (m s^{-1}), and reference evapotranspiration (mm day^{-1}) (Table 4.2). The automatic weather station uses the CS-500 Vaisala probe (Campbell Scientific, Unites States of America, Logan, UT) to measure temperature and relative humidity (converted into vapour pressure deficit), L1-200 pyranometer (Campbell Scientific, Unites States of America, Logan, UT) to measure solar radiation, and the Penman-Monteith equation to calculate reference evapotranspiration. Thereafter, meteorological data collected were transmitted wirelessly and downloaded from a computer.

Table 4.2 Meteorological conditions for the 2013/14 (S_1) and 2014/15 (S_2) seasons

Month	T_{max}[a]		T_{min}[b]		Radiation		ET_0[c]		VPD[d]	
	S_1	S_2	S_1	S_2	S_1	S_2	S_1	S_2	S_1	S_2
	ºC	ºC	ºC	ºC	MJ m^{-2}	MJ m^{-2}	mm	mm	kPa	kPa
November	30.3	27.8	14.6	14.3	768	631	159	131	1.43	1.08
December	27.9	28.7	16.3	16.3	697	731	140	147	0.94	0.99
January	30.8	30.2	16.9	16.5	798	764	163	161	1.27	1.13
February	30.5	31.9	17.4	16.0	616	756	128	152	1.14	1.35
					2879[e]	**2881**[f]	**591**[g]	**592**[h]		

The reported values are average monthly climatic data during two growing seasons; from day of transplanting to end of harvest. [a]T_{max}- maximum temperature; [b]T_{min}-minimum temperature; [c]ET_0- reference evapotranspiration; [d]VPD- vapour pressure deficit; e f, g, and h are cumulative radiation and reference evapotranspiration for 2013/14 (S_1) and 2014/15 (S_2) seasons

(2) The LAI was measured every two weeks using an LAI-2000 canopy analyser (Licor, Lincoln, NE, United States of America). However, AquaCrop uses CC; therefore, Eq. 7 was used to convert LAI to CC. Canopy cover values were used to determine maximum CC (CC_x) and the period taken to reach, CC_x. Canopy extinction coefficient (*k*) values for selected leafy vegetables were obtained from Archontoulis et al. (2011). The stomatal conductance was measured at 10, 25, 35, 45, 55, and 75 days after planting using the SC-1 leaf porometer (Decagon Devices, Pullman, WA, United States of America). Measurements were taken in the afternoon to ensure that the effect of water stress on conductance was captured. Stomatal conductivity results were used to determine crop sensitivity to water stress for the AquaCrop model; i.e. the severe water stressed treatment was used to determine whether selected leafy vegetables are moderately tolerant, sensitive, or extremely sensitive to water stress.

$$CC = [1 - \exp^{(-LAI \times k)}] \times 100 \quad (7)$$

(3) The aboveground biomass (AGB, g m^{-2}) was harvested four times for amaranth and five times for spider flower and Swiss chard. To avoid border effects, only data from the middle rows were utilised (1.8 m^2). At every harvest, the fresh mass was determined by weighing freshly harvested AGB (leaves and stems) and above ground edible biomass (AGEB). Thereafter, plant samples (AGB and AGEB) were oven dried at 75ºC for 3-4 days to determine dry mass (AGB and AGEB). Total dry biomass was calculated as the sum of subsequent harvests ($\sum H_1 + H_2 + \ldots\ldots H_n$). Eq. 8 was used to compute the harvest index (HI). Planting dates, harvest dates, and crop growth stages were recorded. Calendar days were converted into thermal time (Eq. 9) using the method described by McMaster and Wilhelm (1997).

$$HI = Y/AGB \quad (8)$$

$$GDD = \Sigma[(T_{max} + T_{min})/2 - T_{base}] \quad (9)$$

HI (unit-less); Y (AGEB) is total dry mass leaves (g m^{-2}); GDD is growing degree-days; T_{max} and T_{min}, are the maximum and minimum temperatures, respectively; T_{base} is the base temperature of the crop. If $T_{max} < T_{base}$, then $T_{max} = T_{base}$ and if $T_{min} < T_{base}$, then $T_{min} = T_{base}$ (Mabhaudhi et al., 2014).

(4) Prior to the experiment, a soil profile was dug to 1 m depth and soil samples were taken to the ARC-Institute for Soil, Climate and Water for textural class analysis. Soil physical characteristics (% sand, % silt, and % clay) were determined using the United States Department of Agriculture taxonomic system (https://hrsl.ba.ars.usda.gov/soilwater/Index.htm). The soil was classified as a sandy loam, with 78.3% sand, 5.4% silt, 16.3% clay, and a soil pH (H_2O) of 6.87. Field capacity and permanent wilting point were determined using the gravimetric method. The field capacity (FC) was 168 mm m^{-1}, permanent wilting point (PWP) was 37 mm m^{-1}, saturated hydraulic conductivity (K_s) was 840 mm day^{-1}, and the bulk density of the soil was 1.5 g cm^{-3}.

The data collected (daily meteorological data, LAI, dry biomass, dry raw leaves, planting dates, harvesting dates, crop growth stages, soil physical characteristics, amount of irrigation water, salinity of irrigation water, and agronomic practices) were used to create files for the AquaCrop model (climate, crop, irrigation, and soil file). Vanuytrecht et al. (2014) describe these files in details.

4.2.4 Model calibration and validation

We used the data measured during the 2013/14 season for calibration of the model and the data of the 2014/15 for the validation of the model. The calibration processes involved creating the crop file in AquaCrop; thereafter, we entered the initial canopy cover [(CC_o, determined from planting density) (%)], CC_x, days to maturity (GDD), maximum rooting depth (m), as well as base and upper temperature (°C) for crop development. The model was able to calculate the planting density, canopy growth coefficient (CGC), and the canopy decline coefficient (CDC). Normalised water productivity was chosen based on crop species (whether it was a C_3 or C_4 crop). The model output was compared with the measured AGB, AGEB, ET_a, CC, SWC, and water productivity (WP. However, AquaCrop version 4.0 is not capable of running sequential harvests in a single run to simulate yield response of crops that are harvested several times during a season. Therefore, each harvest was calibrated and validated separately, by assuming that after each harvest; approximately 1-2% of CC was left on the plot, which becomes the CC_0 for the subsequent harvest cycle. To calibrate for water stress, the canopy expansion, stomatal closure, and aeration stresses were adjusted until the measured data matched the simulated data. Early canopy senescence was not considered because leafy vegetables do not reach that stage.

4.2.5 Statistics

After the calibration and validation of AquaCrop model, the goodness of fit between measured and simulated datasets were assessed using the root mean square error (RMSE, Eq. 10), RMSE- standard deviation ratio (RSR, Eq. 11), the coefficient of determination (R^2), and relative deviation (D, Eq. 12) (Moriasi et al., 2007). These were calculated using a Microsoft Excel spreadsheet (2016);

$$RMSE = [n^{-1} \sum (O_i - P)^{2}]^{0.5} \quad (10)$$

$$RSR = RMSE/STDV \quad (11)$$

$$D = (O_i – P_i) / O_i \quad (12)$$

Where *n* is the number of observations; O_i is the observed value; P_i is the simulated value; STDV is the observed standard deviation. The RMSE is a frequently used measure of the difference between values predicted by a model and values actually observed from the experiment that is being modelled. RSR standardises the RMSE using the STDV of the observed values; it varies from zero (indicating perfect simulation) to a large positive value, therefore the lower the RSR, the better the model simulation performance. The coefficient of determination (R^2) describes the degree of co-linearity between simulated and measured data; R^2 ranges from zero to one, with higher values indicating less error variance and values greater than 0.5 are acceptable. Lastly, the relative deviation (D) assesses the deviation of the simulated values from the observed values; the closer the D value to zero, the better agreement between observed and simulated values (Araya et al., 2016).

4.2.6 Water productivity and transpiration to evapotranspiration ratio

Water productivity was calculated as AGB (∑AGB made up of several harvests, kg ha^{-1}) per actual evapotranspiration (∑ET_a made up of several harvests, mm) and as AGB (∑AGB made up of several harvests, kg ha^{-1}) per estimated transpiration (∑T_{rEst} made up of several harvests, mm), to assess the beneficial use of water (T_{rEst}). T_{rEst} was calculated using Eq. 13:

$$T_{rEst} = (T_{rSim}/ ET_{Sim}) \times ET_{aMes} \quad (13)$$

Where T_{rSim} (mm) is the simulated transpiration by the AquaCrop model; ET_{Sim} (mm) is the simulated evapotranspiration by the AquaCrop model; and ET_{aMes} (mm) is measured actual evapotranspiration. T_{rSim} divided by ET_{Sim} is the transpiration to evapotranspiration ratio (T:ET).

4.3 Results

4.3.1 AquaCrop model parameterisation

Table 4.1 presents cultivar, non-conservative, and conservative parameters resulting from the calibration of AquaCrop for the selected leafy vegetables. Non-conservative parameters included planting density (6667 plants ha^{-1}), maximum canopy cover (amaranth = 80%; spider flower = 90%; Swiss chard = 90%), effective rooting depth (0.8 m), duration of period to recover after transplanting (amaranth = 64 GDD; spider flower = 64 GDD; and Swiss chard = 30 GDD), and duration of the biomass accumulation period (amaranth = 342 GDD, spider flower = 297 GDD and Swiss chard = 312 GDD). These results show that for the C_4 plant species (amaranth and spider flower), the duration of the period to recover after transplanting was longer than for the C_3 species (Swiss chard = 30 GDD). However, the duration of biomass accumulation to harvest was well above 300 GDD for amaranth and Swiss chard, whereas for spider flower it was 297 GDD. This suggests that amaranth and Swiss chard took longer to reach their CC_x, whereas spider flower was quicker by approximately 9%. Table 4A.1 presents other non-conservative parameters for subsequent harvests. During the calibration process, measured planting spacing (0.3 m × 0.3 m ≈ 111,111 plant ha^{-1}) was entered in the crop file and AquaCrop computed initial canopy cover (CC_0 = 1.67%). Surprisingly, the model overestimated maximum canopy cover (CC_x), but when the CC_0 was reduced from 1.67 % to 0.1 %, there was a good fit between measured CC_x and simulated CC_x (Table 4.3 and Figure 4.1). This suggests that AquaCrop requires a very small CC_0, which raised major concerns during the calibration. Similarly, neutron probe readings showed that the maximum rooting depth (Z_r) was 0.6 m. However, AquaCrop underestimated canopy cover (CC), soil water content (SWC), and evapotranspiration (ET) when this value was used as an input. Previous experiments conducted at the ARC-VOP showed that the Z_r for Swiss chard was 0.8 m. Therefore, 0.8 m was used and the model managed to simulate CC, SWC and ET for selected leafy vegetables with acceptable accuracy. The conservative parameters included the canopy growth coefficient (CGC), canopy decline coefficient (CDC), base and upper temperatures, and thresholds (lower and upper) for canopy expansion and stomatal closure. The normalised water productivity (WP*) for amaranth and spider flower was 30 g m^{-2}, whereas for Swiss chard, it was 16 g m^{-2}.

Table 4.3 AquaCrop model performance for canopy cover and soil water content

	Canopy cover			Soil water content		
Crops and treatments	RMSE[a]	RSR[b]	R^2	RMSE	RSR	R^2
Calibration	%			mm m^{-1}		
Amaranth I_{30}	0.06	0.04	0.99	1.43	0.10	0.87
Amaranth I_{80}	1.24	0.05	0.98	1.48	0.07	0.93
Spider flower I_{30}	0.15	0.04	0.98	1.03	0.07	0.85
Spider flower I_{80}	0.08	0.05	0.98	1.34	0.04	0.96
Swiss chard I_{30}	1.22	0.03	0.98	1.51	0.15	0.92
Swiss chard I_{80}	0.81	0.04	0.98	1.47	0.07	0.90
Validation						
Amaranth I_{30}	1.26	0.12	0.98	1.44	0.10	0.80
Amaranth I_{80}	1.65	0.79	0.64	1.56	0.06	0.88
Spider flower I_{30}	1.45	0.19	0.94	1.61	0.13	0.76
Spider flower I_{80}	1.28	0.15	0.97	1.61	0.06	0.94
Swiss chard I_{30}	1.58	0.04	0.98	2.19	0.20	0.79
Swiss chard I_{80}	0.94	0.04	0.98	1.84	0.08	0.69

[a]RMSE-root mean square error; [b]RSR-RMSE standard deviation ratio. I_{30} and I_{80} are well-watered and severe water stressed treatments, respectively

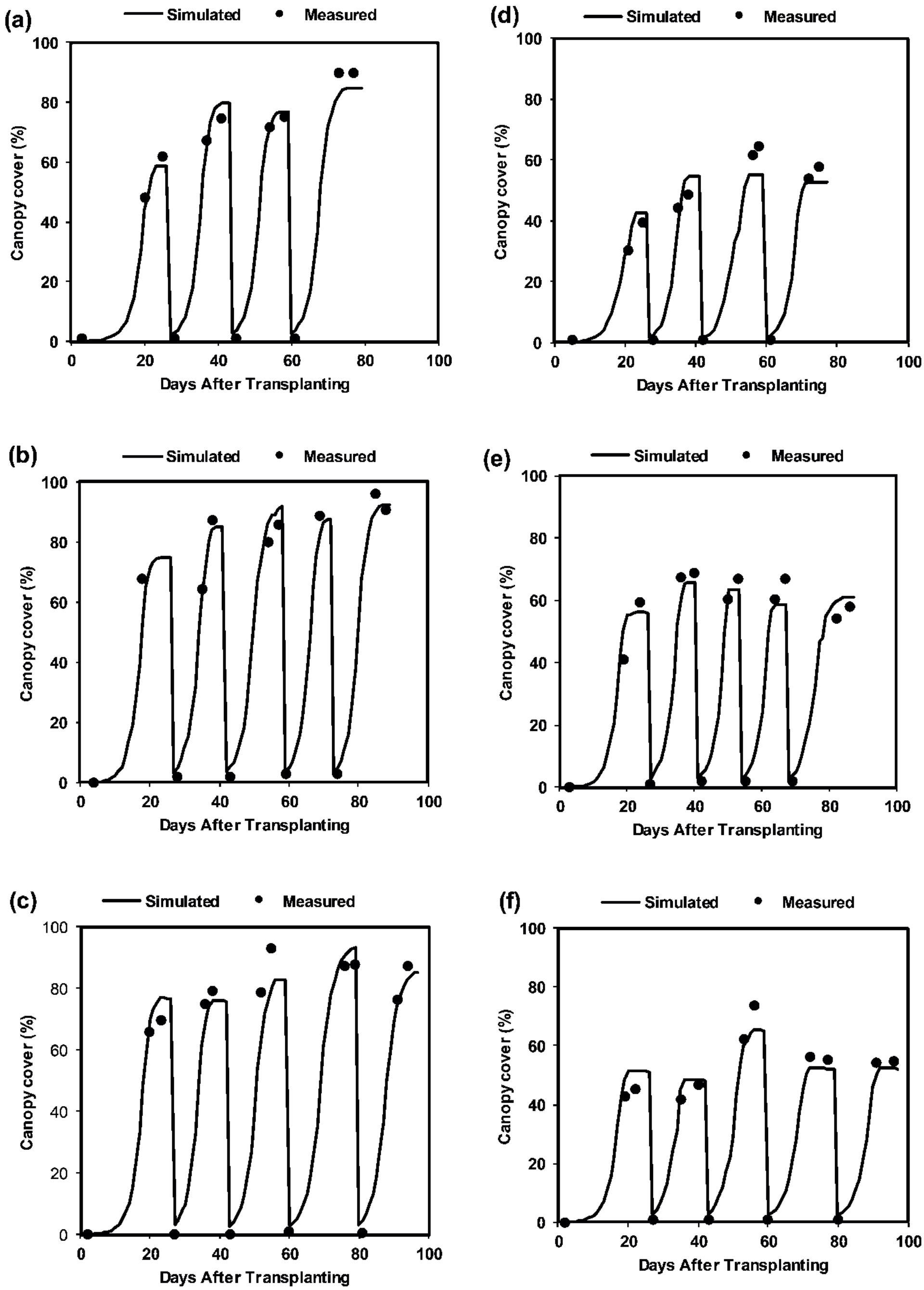


Figure 4.1 Simulated and measured canopy cover against days after transplanting for amaranth (**a, d**), spider flower (**b, e**), and Swiss chard (**c, f**) for AquaCrop model calibration (2013/14): **a b c** are for $\mathbf{I_{30}}$ (well-watered) and **d e f** for $\mathbf{I_{80}}$ (water stress) treatments, respectively

4.3.2 Calibration of AquaCrop for well-watered and water stress conditions

Canopy cover

Figure 4.1 shows simulated and measured canopy cover (CC) for the selected leafy vegetables during the 2013/14 growing season. For the well-watered (I_{30}) treatment, maximum CC reached during the growing period was 90% for amaranth, 96% for spider flower, and 93% for Swiss chard. Inducing water stress (I_{80} treatment) reduced CC to 62% for amaranth, 68% for spider flower, and 74% for Swiss chard during the growing period. The statistical indicators suggest that AquaCrop was able to simulate CC with acceptable accuracy for these treatments. The median root mean square error (RMSE) was 0.48%, highest RMSE was 1.58% (amaranth, I_{80}), RMSE standard deviation ratio (RSR) ranged from 0.03 to 0.52, and the minimum R^2 was 0.98 (Table 4.3).

Soil water content and evapotranspiration

There was strong agreement between measured and simulated soil water content (SWC) (Table 4.3). The calibration results were as follows: RMSE ranged from 1.03 to 1.51 mm m^{-1}, RSR from 0.10 to 0.15, and the minimum R^2 was 0.87. These statistics suggest that AquaCrop was calibrated satisfactorily. Figure 4.2 shows that water stress occurred at 12 days after transplanting (DAT) for amaranth, 15 DAT for spider flower, and 20 DAT for Swiss chard. The SWC simulated by the model followed the trend of observed values for SWC.

Table 4.4 presents estimated transpiration (T_{rEst}), estimated soil evaporation (E_{Est}), measured actual evapotranspiration (ET_{aMes}), simulated ET, and transpiration to evapotranspiration ratio (T:ET). Actual evapotranspiration ranged from 108 to 281 mm; TLVs' showed lower ET_a values by 23% for amaranth and 22% for spider flower, relative to Swiss chard for the I_{30} treatment. The I_{80} treatment reduced ET_a by 54% for amaranth, 32% for spider flower, and 38% for Swiss chard, relative to the well-watered treatments. Estimated transpiration (T_{Est}) values varied between the selected leafy vegetables; amaranth exhibited the lowest T_{Est} values (50-107 mm), whereas Swiss chard showed the highest T_{Est} values (105-174 mm). Amaranth and spider flower indicated lower T:ET (0.40-0.59) values than Swiss chard (0.61-0.62). The goodness of fit between measured and simulated ET_a was as follows; deviation (D) ranged between -0.11 and +0.07 and the median values were 2.01 mm for RMSE, 0.27 for RSR, and 0.93 for R^2

Table 4.4 Estimated transpiration, soil evaporation, measured and simulated evapotranspiration, and transpiration to evapotranspiration ratio

Crops and treatments	T_{rEst}[a] mm	E_{Ets}[b] mm	ET_{aMes}[c] mm	ET_{Sim}[d] mm	T:ET[e]	Dev[f]	RMSE[g] mm	RSR[h]	R^2
Calibration									
Amaranth I_{30}	107	132	239	222	0.45	0.07	4.76	0.54	0.98
Amaranth I_{80}	50	58	108	121	0.46	-0.11	1.67	0.51	0.93
Spider flower I_{30}	143	100	243	240	0.59	0.01	1.28	0.05	0.97
Spider flower I_{80}	65	99	164	163	0.40	0.01	1.60	0.13	0.92
Swiss chard I_{30}	174	107	281	278	0.62	0.01	2.76	0.17	0.99
Swiss chard I_{80}	105	68	173	187	0.61	-0.08	2.34	0.37	0.75
Validation									
Amaranth I_{30}	115	140	255	235	0.45	0.08	5.44	0.57	0.88
Amaranth I_{80}	67	69	136	127	0.50	0.07	3.81	0.37	0.60
Spider flower I_{30}	174	222	396	387	0.44	0.02	2.32	0.15	0.92
Spider flower I_{80}	104	148	252	263	0.41	-0.04	3.56	0.24	0.88
Swiss chard I_{30}	207	103	310	291	0.67	0.06	3.51	0.32	0.82
Swiss chard I_{80}	122	72	194	190	0.63	0.02	3.15	0.40	0.69

Values presented are for the full seasons (2013/14 and 2014/15 = 100 days). [a]T_{rEst}- estimated transpiration; [b]E_{Est}- estimated soil evaporation; [c]ET_{aMes}-measured actual evapotranspiration; [d]ET_{Sim}-simulated evapotranspiration; [e]T:ET-transpiration to ET_a ratio; [f]deviation; [g]RMSE-root mean square error; [h]RSR-RMSE standard deviation ratio. I_{30} and I_{80} are well-watered and severe water stressed treatments, respectively

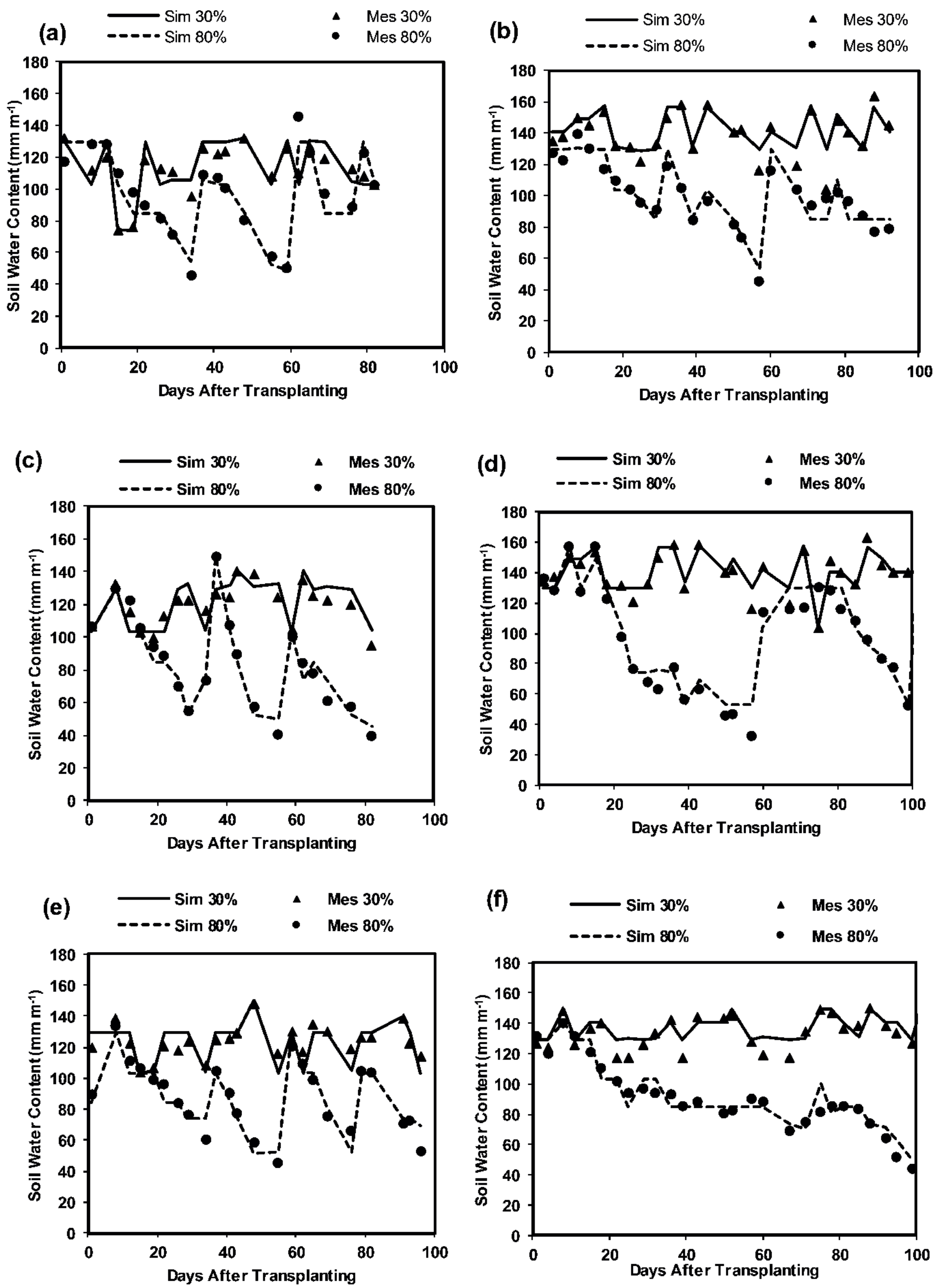


Figure 4.2 Measured and simulated soil water content for amaranth (**a, b**), spider flower (**c, d**), and Swiss chard (**e, f**): **a c e** are for calibration (**I_{30}, I_{80}**) and **b d f** are for validation (**I_{30}, I_{80}**). I_{30} and I^{80} are well-watered and water stress treatments, respectively

Aboveground biomass and aboveground edible biomass

For the I_{30} treatment, the selected leafy vegetables showed similar measured total aboveground biomass (∑AGB made up of several harvests) (amaranth = 6.13 t ha^{-1}, spider flower = 6.58 t ha^{-1}, and Swiss chard =6.39 t ha^{-1}). Inducing water stress reduced AGB by approximately 44% for amaranth, 33% for spider flower, and 26% for Swiss chard, relative to the I_{30} (Table 4.5). The goodness of fit statistics showed that the model simulated AGB with high accuracy (Table 4.5); the minimum RMSE was 0.02 t ha^{-1} and the maximum was 0.06 t ha^{-1}; the RSR ranged from 0.04 to 0.17, and the minimum R^2 was 0.93. The harvest index (HI) for Swiss chard was larger than that of amaranth and spider flower, which is a consequence of the different plant structure of Swiss chard that produces fewer stems and thus has a higher ratio of aboveground edible biomass (AGEB).

Water productivity

Table 4.6 presents measured and simulated values of actual evapotranspiration water productivity (WP_{ETa}) and transpiration water productivity (WP_T) for the selected leafy vegetables. Measured WP values were closer to the simulated WP from the experiment; relative deviation (D) ranged from -0.12 to +0.14, whereas the RMSE ranged from 0.08 to 0.45 kg m^{-3}. Actual evapotranspiration WP for amaranth (2.56-3.18 kg m^{-3}) and spider flower (2.68-2.71 kg m^{-3}) was larger than for Swiss chard (2.27-2.70 kg m^{-3}). For amaranth and Swiss chard, increased water stress (from I_{30} - I_{80}) improved WP_{ETaMes} and WP_{TMes}, whereas for spider flower, WP_{ETaMes} (I_{30} = 2.71 kg m^{-3} and I_{80} = 2.68 kg m^{-3}) remained the same and WP_{TMes} improved by approximately 46%. Our results indicate that by considering the productive use of water (T_r), WP_{TMes} of C_4 crops (amaranth and spider flower) improved by approximately 50%, whereas WP_{TMes} of a C_3 crop (Swiss chard) improved by approximately 30%, regardless of water stress treatment.

4.3.3 Validation of AquaCrop for water stress and well-watered conditions

Canopy cover

For the validation year (2014/15), more measured leaf area index (LAI) data (converted to CC) were collected compared to the calibration year, which resulted in more measured data points for CC (Figure 4.3). Therefore, the goodness of fit statistical results for CC validation was higher than for CC calibration (Table 4.3). They ranged from 0.94 to 1.65 % for RMSE, 0.04 to 0.79 for RSR, and the maximum R^2 was 0.98. Table 4.3 illustrates that AquaCrop underestimated CC (R^2 = 0.64) for amaranth under water stress conditions. Generally, CC was validated satisfactorily for the crops considered.

Table 4.5 Measured and simulated total dry biomass and dry edible biomass

Crops and treatments	HI_{mes}[a]	Mes[b]	Sim[c]	Dev[d]	RMSE[e]	RSR[f]	R^2	Mes	Sim	Dev	RMSE	RSR	R^2
		Total biomass						Dry edible biomass					
		t ha^{-1}	t ha^{-1}		t ha^{-1}			t ha^{-1}	t ha^{-1}		t ha^{-1}		
Calibration													
Amaranth I_{30}	0.48	6.13	6.40	-0.04	0.06	0.12	0.98	2.94	3.07	-0.04	0.03	0.12	0.98
Amaranth I_{80}	0.46	3.43	3.30	+0.04	0.04	0.17	0.93	1.58	1.52	+0.04	0.02	0.17	0.93
Spider flower I_{30}	0.52	6.58	6.25	+0.05	0.05	0.08	0.98	3.42	3.25	+0.05	0.39	0.46	0.98
Spider flower I_{80}	0.41	4.40	4.63	-0.05	0.04	0.10	0.98	1.80	1.90	-0.06	0.02	0.10	0.98
Swiss chard I_{30}	0.65	6.39	6.47	-0.01	0.02	0.04	0.98	4.15	4.21	-0.01	0.01	0.04	0.99
Swiss chard I_{80}	0.73	4.67	4.52	+0.03	0.06	0.15	0.93	3.41	3.30	+0.03	0.05	0.15	0.93
Validation													
Amaranth I_{30}	0.62	6.58	6.65	-0.01	0.04	0.07	0.98	4.08	4.12	-0.01	0.03	0.09	0.98
Amaranth I_{80}	0.46	3.11	3.69	-0.19	0.10	0.79	0.64	1.43	1.70	-0.19	0.05	0.79	0.64
Spider flower I_{30}	0.34	9.76	9.82	-0.01	0.15	0.19	0.94	3.32	3.34	-0.01	0.05	0.19	0.94
Spider flower I_{80}	0.20	5.43	6.16	-0.14	0.08	0.15	0.97	1.09	1.23	-0.14	0.03	0.18	0.86
Swiss chard I_{30}	0.92	6.57	6.63	-0.01	0.08	0.13	0.91	6.04	6.10	-0.01	0.08	0.13	0.92
Swiss chard I_{80}	0.57	3.78	4.16	-0.10	0.08	0.17	0.78	2.16	2.37	-0.10	0.04	0.17	0.91

[a]HI_{mes}- measured harvest index; [b] Mes- Measured total biomass; [c] Sim- Simulated total biomass; [d] Dev- Deviation; [e] RMSE- root mean square error; [f] RSR- RMSE standard deviation ratio. I_{30} and I_{80} are well-watered and severe water stressed treatments, respectively

Table 4.6 Measured and simulated water productivity (WP) for actual evapotranspiration (ET_a) and transpiration (T_r)

Crops and treatments	WP_{ETaMes} [a]	WP_{ETSim} [b]	Dev [c]	RMSE [d]	WP_{Trmes} [e]	WP_{Trsim} [f]	Dev	RMSE
	kg m^{-3}	kg m^{-3}		kg m^{-3}	kg m^{-3}	kg m^{-3}		kg m^{-3}
Calibration								
Amaranth I_{30}	2.56	2.88	-0.12	0.32	5.75	6.46	-0.12	0.71
Amaranth I_{80}	3.18	2.73	0.14	0.45	6.86	5.89	0.14	0.97
Spider flower I_{30}	2.71	2.60	0.04	0.10	4.61	4.43	0.04	0.18
Spider flower I_{80}	2.68	2.84	-0.06	0.16	6.73	7.12	-0.06	0.40
Swiss chard I_{30}	2.27	2.33	-0.02	0.05	3.68	3.76	-0.02	0.09
Swiss chard I_{80}	2.70	2.42	0.10	0.28	4.43	3.96	0.10	0.46
Validation								
Amaranth I_{30}	2.58	2.83	-0.10	0.25	5.72	6.27	-0.10	0.55
Amaranth I_{80}	2.29	2.91	-0.27	0.62	4.61	5.86	-0.27	1.25
Spider flower I_{30}	2.46	2.54	-0.03	0.07	5.61	5.78	-0.03	0.17
Spider flower I_{80}	2.15	2.34	-0.09	0.19	5.20	5.65	-0.09	0.45
Swiss chard I_{30}	2.12	2.28	-0.08	0.16	3.18	3.42	-0.08	0.24
Swiss chard I_{80}	1.95	2.19	-0.12	0.24	3.11	3.50	-0.12	0.38

[a]WP_{MesETa}- measured water productivity (WP) for ET_a; [b]WP_{ETaSim}- simulated WP for ET; [c]Dev- relative deviation; [d]RMSE- root mean square error; [e]WP_{TrMes}- measured WP for transpiration; [f]WP_{TrSim}- simulated WP for transpiration. I_{30} and I_{80} are well-watered and severe water stressed treatments, respectively

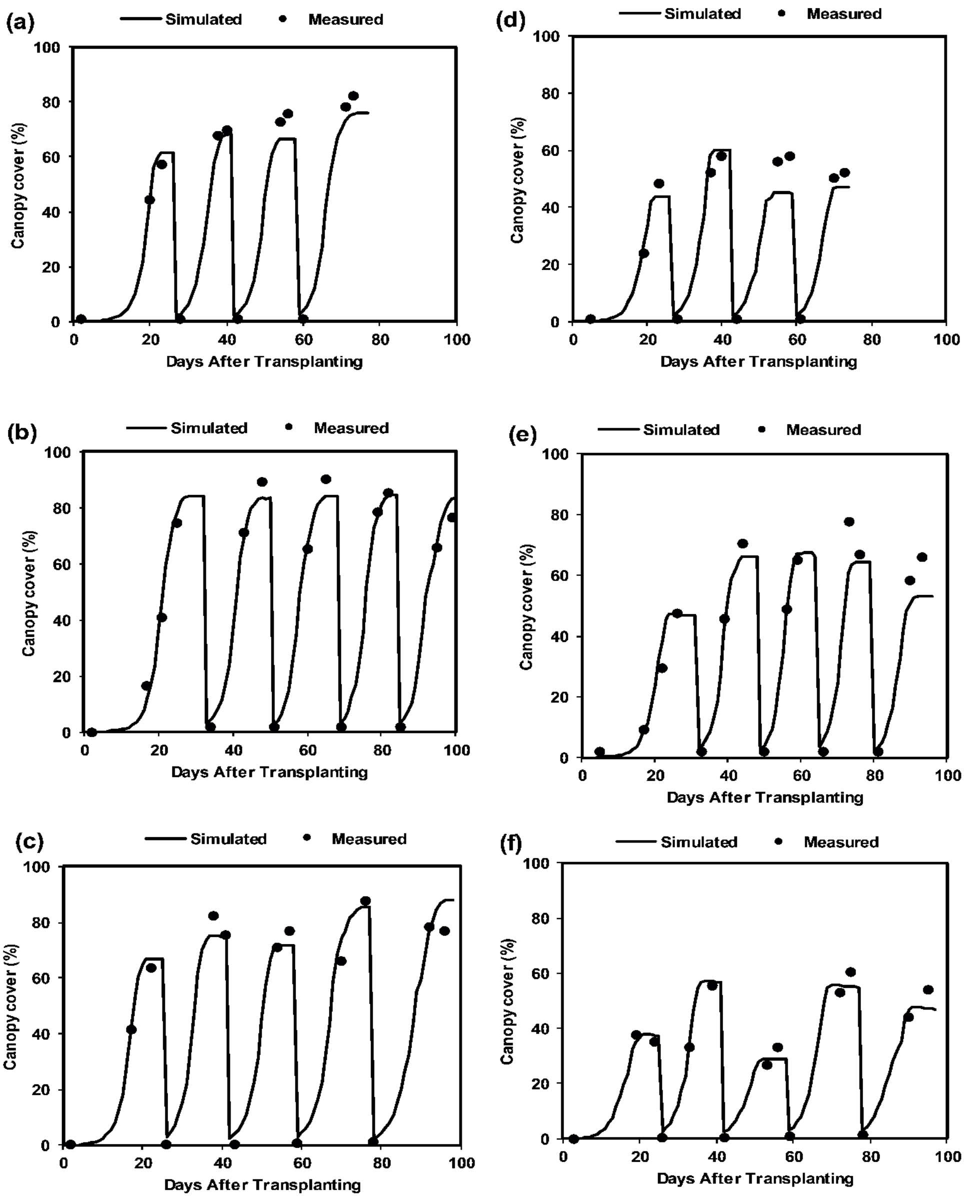


Figure 4.3 Simulated and measured canopy cover against days after transplanting for amaranth (**a, d**), spider flower (**b, e**), and Swiss chard (**c, f**) for AquaCrop model validation (2014/15): **a b c** are for **I_{30}** (well-watered) and **d e f** for **I_{80}** (water stress) treatments, respectively

Soil water content and evapotranspiration

Figure 4.2 indicates that there was a clearer distinction between the I_{30} and I_{80} treatments for SWC in the validation season compared to the calibration season. This is attributed to improved irrigation management for the 2014/15 season compared with the 2013/14 season. Swiss chard SWC for the I_{80} treatment showed a rapid decline throughout the season (2014/15); total irrigation amount for the 2013/14 season was 129 mm, whereas for the 2014/15 season, it was 90 mm (Figure 4.4). For the validation, AquaCrop was able to simulate SWC for I_{30} and I_{80} very well, indicating good model performance (RMSE= 1.44-2.19 mm m^{-1}; RSR= 0.06-0.20; R^2= 0.69-0.94), except for the validation of Swiss chard, I_{30} (RMSE= 1.26 mm; R^2= 0.69); the model overestimated SWC at 20, 40, and 60 DAT (Figure 4.2 and Table 4.3). Seasonal ET_{aMes} values ranged from 136 to 396 mm, which was larger than the 2013/14 season ET_a values (108-281 mm) (Table 4.4). AquaCrop managed to simulate ET very well, with the statistics for goodness of fit for the validation season superior to those of the calibration season (RMSE= 2.32-5.44 mm; RSR= 0.15-0.57; R^2= 0.60-0.92).

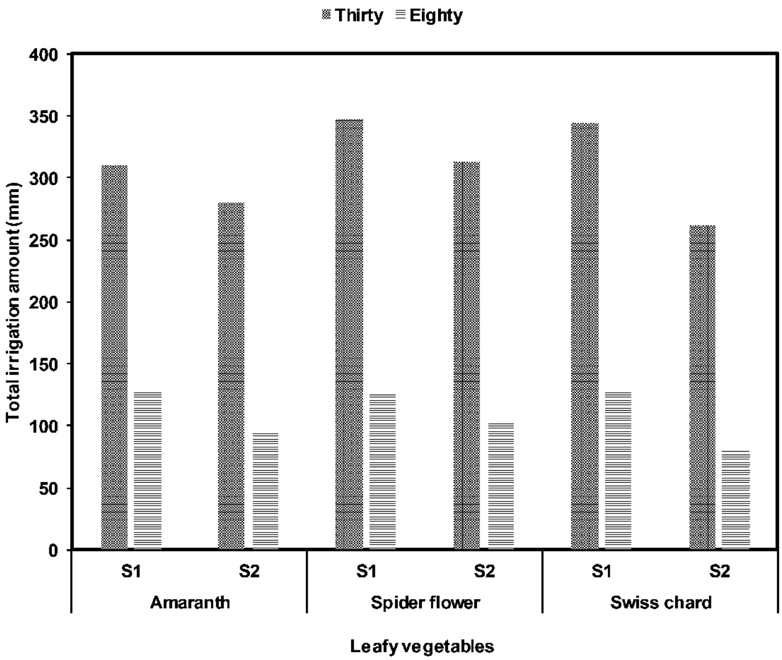


Figure 4.4 Seasonal irrigation amount for amaranth, spider flower, and Swiss chard: 2013/14 (S_1) and 2014/15 (S_2) seasons. Well-watered (**I_{30}**) and water stress (**I_{80}**) treatments

Aboveground biomass and raw edible biomass

For the I_{30} treatment, measured AGB values for the validation were larger (by 7% for amaranth, 32% for spider flower, and 3% for Swiss chard) than the values for the calibration (Table 4.5). Increasing water stress from I_{30} to I_{80} reduced measured AGB by approximately 53 % for amaranth, 44 % for spider flower, and 42 % for Swiss chard. The harvest index (HI) ranged from 0.20-0.92; Swiss chard showed a larger HI than amaranth and spider flower. Similarly, the measured AGEB ranged from 1.09 to 6.04 t ha^{-1}, which was higher than the AGEB for the calibration (1.80-4.15 t ha^{-1}). AquaCrop managed to simulate AGB and AGEB very well (RMSE= 0.03-0.15 t h^{-1}; RSR= 0.07-0.79; R^2= 0.64-0.98; deviation = 0.01-0.19).

Water productivity

The goodness of fit results showed that measured WP values were closer to simulated WP values for the validation season (2014/15) than for the calibration season (2013/14).; relative deviation ranged from -0.27 to -0.03, whereas the RMSE ranged from 0.07 to 0.62 (Table 4.6). In contrast, the validation results differed with the calibration results; (1) increased water stress (from I_{30}-I_{80}) reduced WP_{ETaMes} and WP_{TMes}; and (2) for the well-watered treatment (I_{30}), WP_{ETaMes} values were similar for amaranth (2.85 kg m^{-3}), spider flower (2.46 kg m^{-3}) and Swiss chard (2.12 kg m^{-3}). A similar trend was maintained whereby WP_{TrMeas} improved by approximately 50% for C_4 crops (amaranth and spider flower) and by approximately 30% for a C_3 crop (Swiss chard), under water stress.

4.4 Discussion

This was a first attempt to develop parameters for spider flower and Swiss chard. Bello and Walker (2017) parameterised AquaCrop for amaranth; however, there were large discrepancies compared to the parameters we developed. Firstly, their upper temperature was 30ºC, whereas ours was 40ºC. Secondly, their maximum effective rooting depth (Z_r) was 1.75 m and normalised water productivity (WP*) was 28 t ha^{-1} (2800 g m^{-2}). These values are too high and might be suitable for deep-rooted crops such as maize and sorghum: Z_r for maize and sorghum are reported to range from 1.0 to 2.3 m and the WP* for C_4 crops ranges from 30 to 35 g m^{-2} in AquaCrop (Araya et al., 2016; Paredes et al., 2014). For the calibration, our results showed a good fit between measured and simulated parameters [(canopy cover (CC), soil water content (SWC), aboveground biomass (AGB) and actual evapotranspiration (ET_a)] when the initial canopy cover (CC_0) was reduced from 1.67% to 0.1%. Bello and Walker (2017) proposed that AquaCrop required a smaller value of CC_0 because it might make provision for transplanting shock; plants are inclined to grow slowly because they need to recover. In this study, transplanted seedlings were well-irrigated to ensure crop establishment, which might have assisted plants to develop a larger CC_0 than the simulated CC_0 (Bello and Walker, 2017). Similarly, the Z_r was increased from 0.60 to 0.80 m to improve the correspondence between simulated and measured parameters. Mabhaudhi et al. (2014) reported similar findings, whereby the actual observed Z_r for *Colocasia esculenta* L. Schott (taro) was 0.45 m but a good match between measured and simulated values for biomass was found at 0.80 m. The model is limited in parameters for leafy vegetables. Studies reported the normalised water productivity (WP*) to range from 13 to 19 g m^{-2} for C_3 crops (Malik et al., 2017; Montoya et al., 2016; Paredes et al., 2015; Razzaghi et al., 2017; Tavakoli et al., 2015) and from 30 to 34 g m^{-2} for C_4 crops (Araya et al., 2016; Bello and Walker, 2016; Greaves and Wang, 2017; Paredes et al., 2014).

These results show that the level of water stress affected CC development and ET_a. AquaCrop underestimated CC for the validation of amaranth and spider flower, whereas a good fit was observed for Swiss chard (Figure 3.3 and Table 4.3). This observation is consistent with findings by Bello and Walker (2017) for amaranth where there was a poor match between measured and simulated CC (RMSE =20.82 %; R^2 = 0.55), although our validation results showed better goodness of fit. The contrast between Bello and Walker (2017) with our results might be that; (1) they did not account for the fact that amaranth was harvested repeatedly during the growing period, (2) the effective rooting depth was not measured but estimated from literature, and (3) they used an empirical equation to convert leaf area index (LAI) to CC, which might have underestimated CC. Studies by Greaves and Wang (2017), Pawar et al. (2017), and Razzaghi et al. (2017) showed that AquaCrop was capable of simulating CC for maize, cabbage and potato, but not under water-stressed conditions. The strength of AquaCrop is its ability to separate ET_a into soil evaporation (E_s) and transpiration (T_r) (Hsiao et al., 2009; Raes et al., 2009; Steduto et al., 2009), which enables the assessment of productive (T_r) and non-productive (E_s) water use. The T:ET ranged from 0.41 to 0.67; Swiss chard (0.61-0.67) showed higher ratios than amaranth (0.45-0.50) and spider flower (0.40-0.59) (Table 4.3). The higher T:ET for Swiss chard can be accounted for by the quicker development of foliage biomass, which shades the soil from direct sunlight; therefore, reducing the non-productive use of water (E_s). Generally, our results suggest that water loss was more through E_s than T_r for amaranth (50-55%) and spider flower (41-60%) (Table 4.3). This contrast can be ascribed to the practice of harvesting biomass repeatedly; we suspect that the model assumed that the soil was left bare for a longer period during each harvesting period, resulting in higher E_s losses than T_r. A study conducted by Giménez et al. (2017) on soybean tested AquaCrop under five water stress levels [(full irrigation, rainfed, and deficit irrigation at; (1) flowering to grain filling, (2) vegetative period, and (3) during vegetative to grain filling)] and found that AquaCrop gave smaller T_r values and larger E_s values. This is consistent with other studies (Bello and Walker, 2017; Greaves and Wang, 2017; and Katerji et al., 2013), which reported similar findings.

For the calibration and validation of AquaCrop, a trend was observed, whereby under the well-watered treatment (I_{30}), the aboveground biomass (AGB) productivity of the selected leafy vegetables was similar, except for spider flower, which showed a huge increase (9.82 t ha^{-1}) for the validation season. Larger AGB values were witnessed for the validation compared to the calibration season. A validation test conducted by Bello and Walker (2017) on amaranth at three-water stress levels (full irrigation, moderate irrigation and rainfed), reported AGB ranging from approximately 7 to 13 t ha^{-1}. In contrast with our AGB results (Table 4.5), the fully irrigated treatment (8 t ha^{-1}) showed similar AGB with their rainfed treatment (7 t ha^{-1}), whereas their moderately irrigated treatment indicated the highest (13 t ha^{-1}) AGB. Information relating to the calibration and validation of AquaCrop for spider flower and Swiss chard AGB is limited to this study. These results should therefore be considered benchmarks.

In southern Africa, rural resource-poor households consume amaranth and spider flower as food “safety nets”; the softest stems and leaves are utilised (Mavengahama et al., 2013). Therefore, it is crucial to consider the aboveground edible biomass (AGEB), which ranged from 1.09 to 4.08 t ha^{-1} for amaranth and spider flower, whereas for Swiss chard, it ranged from 3.41 to 6.04 t ha^{-1}. Swiss chard showed a higher proportion of AGEB because its harvest index (HI) was larger than that of amaranth and spider flower (Table 4.5). The validation test under severe water stress (I_{80}) represents very dry conditions, of which rural resource-poor households grow their crops. Our results show that under water-stressed conditions, the AGEB will decrease by approximately 59% for amaranth, 63% for spider, and 61% for Swiss chard.

Most studies (Bello and Walker, 2016; Bello and Walker, 2017; Mabhaudhi et al., 2014; Mirsafi et al., 2016; Montoya et al., 2016; Razzaghi et al., 2017) conducted on AquaCrop for selected crops [Saffron (*Crocus sativus L.*), tomato (*Solanum lycopersicum*), pearl millet (*Pennisetum* *glaucum*), amaranth (*Amaranthus cruentus*), Irish potato (*Solanum tuberosum*) Taro (*Colocasia esculenta*)] did not assess their WP. In addition, the majority of WP values reported by literature consider ET_a as a denominator, which includes the non-productive (E_s) use of water, because of difficulty in separating E_s and T_r. Our study tested AquaCrop for its performance on simulating WP_{ETa} and WP_{Tr} (Table 4.6). Clear trends were absent between the calibration and validation of AquaCrop for water productivity (WP_{ETa} and WP_{Tr}); the calibration results showed that increasing water stress, improved WP_{ETa} and WP_{Tr}, whereas the validation results revealed the opposite (Table 4.6). This can be explained by different meteorological conditions (radiation, reference evapotranspiration, and vapour pressure deficit) prevailing during the growing seasons (Table 4.2); for the validation season, ET_a of the severe water stress treatment increased by 21% for amaranth, 35% for spider flower, and 11% for Swiss chard (Table 4.4), relative to that of the previous season. There was a clear distinction between WP_{Tr} for the C_4 crops (amaranth and spider flower) and the C_3 crop (Swiss chard) (Table 4.6). This concurs with Renault and Wallender (2000), Van Halsema and Vincent (2012), and Wenhold et al. (2012) that C_4 crops are more productive than C_3 crops per unit of water used. It is a challenge to compare WP from different locations because of varying climatic conditions, methods used in calculating WP, irrigation water management, soil fertility management, and vapour pressure deficit (Zwart and Bastiaanssen, 2004); other studies report the total amount of water applied, whereas others report ET_a. For example, Pawar et al. (2017) reported WP_{ETa} of cabbage ranging from 50 to 69 kg ha^{-1} mm^{-1}, however, the denominator was total irrigation water applied. Wenhold et al. (2012) benchmarked WP_{ETa} of leafy vegetables using a dataset (AGB per ET_a) that was derived from different literature sources and reported values ranging from 2 to 90 kg ha^{-1} mm^{-1} for selected leafy vegetables. The merit of our study is that datasets (meteorological data, crop evapotranspiration, above ground biomass) used to assess WP were collected from the same location.

4.5 Conclusions and recommendations

This was the first attempt to calibrate and validate AquaCrop for spider flower and Swiss chard. Therefore, these results should be considered the benchmark. The goodness of fit statistics indicated that the model was calibrated and validated satisfactorily for selected parameters (canopy cover, soil water content, actual evapotranspiration, above ground biomass, above ground edible biomass, and water productivity) under well-watered and severe water stress conditions. The model estimated water loss to be more by evaporation than transpiration, which has been alluded by other studies (Bello and Walker, 2017; Giménez et al., 2017; Greaves and Wang, 2017; Katerji et al., 2013). This may be caused by the practice of harvesting leafy vegetables repeatedly; with the soil left bare for extended periods. An innovative approach has been applied and tested to enable the simulation of multiple harvests. However, this approach is cumbersome when simulating large datasets, because AquaCrop currently can only run each harvest separately. These results provide a foundation for further improving AquaCrop in simulating yield responses of leafy vegetables, and indeed many pasture crops that are also harvested several times in a growing season. Based on this study, we recommend the following;

- The impact of water stress should be validated by testing the calibrated model using datasets from other locations.
- A crop module that can run multiple harvests in a single season's simulation should be included in AquaCrop.

- To find a good fit between measured and simulated canopy cover, AquaCrop required a much smaller initial canopy cover (0.1 %) compared to estimated canopy cover (1.67 %) from planting density. Bello and Walker (2017) reported similar findings for the calibration of the model for amaranth. We recommend that the Food and Agricultural Organisation should fine-tune the model to accept measured initial canopy cover for leafy vegetables.
- The model has a tendency to under-estimate soil water depletion, which was alluded by Mabhaudhi et al. (2014). Although this can be solved by increasing the effective rooting depth, further research is needed to improve and adjust the model on simulating effective rooting depth.
- Currently, the database of the model caters for mainstream crops. Limited vegetables [(*Solanum lycopersicum* (tomato) and *Beta vulgaris* (but then as sugar beet and not as a leafy vegetable)] with conservative parameters are included in the database. Tomato contains minimal amounts of micronutrients and vitamins. To construct sustainable food systems that are health-focused and inclusive of rural resource-poor households, we recommend that more vegetables (including traditional vegetables) with conservative parameters are included in the model database.
- We invite the modelling community to consider adding a module that can simulate nutritional content (iron, zinc and β-carotene) of crops. This will enable crop modelling of nutritional yield and nutritional water productivity.
- AquaCrop predicts more evaporation than transpiration, which seems unrealistic; therefore, the current method for partitioning actual evapotranspiration into evaporation and transpiration should be investigated.

Appendix 4A

Table 4A.1 Non-conservative parameters of other harvesting periods of selected leafy vegetables

Parameters	Amaranth			Spider flower				Swiss chard			
	H_2	**H_3**	**H_4**	**H_2**	**H_3**	**H_4**	**H_5**	**H_2**	**H_3**	**H_4**	**H_5**
Initial canopy cover (%)	0.1	0.1	0.1	0.1	0.3	0.2	0.2	0.2	0.3	1.0	0.6
Crop stand (plants ha^{-1})	6667	6667	6667	6667	20001	13335	13335	13334	20001	66668	40002
Maximum canopy cover (%)	90	90	90	99	99	99	99	90	90	98	90
Duration of recovery period (GDD)	27	27	14	47	16	16	16	17	17	17	17
Duration of biomass build up (harvest) (GDD)	280	320	388	247	245	317	304	264	313	403	430
Start of canopy senescence (GDD)	280	320	388	247	245	317	304	264	313	403	430
Duration maximum canopy cover (GDD)	280	320	388	247	245	317	304	264	313	403	430

H_2………. H_n subsequent different harvesting periods

Chapter

5

The dual-purpose use of orange-fleshed sweet potato (*Ipomoea batatas* var. Bophelo) for improved nutritional food security

This chapter is based on:

Nyathi, M.K., Du Plooy, C.P., Halsema, G.E. Van, Stomph, T.J., Annandale, J.G., Struik, P.C., 2019a. The dual-purpose use of orange-fleshed sweet potato (Ipomoea batatas var . Bophelo) for improved nutritional food security. Agric. Water Manag. 217, 23–37. doi:10.1016/j.agwat.2019.02.029

Abstract

Orange-fleshed sweet potato (OFSP) leaves can be utilised as a fresh green leafy vegetable, in addition to the traditional use of storage root; therefore, OFSP can be seen as a ‘‘dual-purpose’’ crop. We hypothesised that no vine harvesting combined with fertiliser application and irrigation will improve the storage root yield and selected plant parameters (water productivity, leaf and storage root nutrient concentrations, nutritional yield, and nutritional water productivity). The objectives of the study were to (i) evaluate the effect of vine harvesting on the selected plant parameters, and, (ii) assess the effect of irrigation regimes and soil fertilisation on these selected parameters. Field experiments were conducted at ARC-VOP, Pretoria, South Africa, during the 2013/14 and 2014/15 seasons. Treatments included irrigation regimes [well-watered (W1) and supplemental irrigation (W2)], soil fertilisation [well-fertilised (F1) and no fertiliser application (F2)], and vine harvesting [no vine harvesting (H1) and vine harvesting (H2)]. For the 2014/15 season, the well-watered regime improved total storage root yield (W1 = 13.0 t DM ha^{-1}; W2 = 7.5 t DM ha^{-1}). Under the practice of vine harvesting, soil fertility treatments did not affect (total dry storage root yield and dry marketable storage root yield) storage root production. Our results further revealed that vine harvesting reduced storage root nutrient concentrations (23 % for iron; 14 % for zinc; 12 % for β-carotene). Nevertheless, total nutritional yields increased; the highest total nutritional yields for iron, zinc, and β-carotene were found under the water and nutrient input regime (W1F1). Assessments showed that boiled orange-fleshed sweet potato aboveground edible biomass could potentially contribute to the daily-recommended nutritional requirement of iron and vitamin A for a family of six people. More water was needed to meet the daily-recommended nutrient intake (iron, zinc, and vitamin A) with OFSP grown as a storage root crop only than when grown as a dual-purpose crop. Our results indicated that there is an opportunity to utilise OFSP as a dual-purpose crop for rural resource-poor households because total nutritional yields (iron, zinc, and β-carotene) and total nutritional water productivities (iron, zinc, and β-carotene) were improved. More research is needed to assess the effect of vine harvesting on a range of OFSP varieties and should be conducted on the farm. Rural resource-poor households are encouraged to produce OFSP for their own consumption and the surplus could be sold at the local market

Keywords: Micronutrient deficiency; Nutritional water productivity; Vitamin A; Green leafy vegetable; Water stress

5.1 Introduction

In sub-Saharan Africa, micronutrient deficiencies (known as "hidden hunger") are a major problem, affecting rural resource-poor households (RRPHs). The most common deficiencies in some sub-Saharan Africa countries are iron, zinc and vitamin A (Harika et al., 2017). Harika et al. (2017) assessed the prevalence of micronutrient deficiencies in Ethiopia, Kenya, Nigeria, and South Africa. Their findings revealed that the prevalence of iron deficiency stands at 28 % in South Africa. Moreover, in South Africa, vitamin A deficiency is more prevalent (22 %) than in Ethiopia (4 %) or Nigeria (4 %). This highlights that nutritional food insecurity is pervasive in rural areas of South Africa. Several approaches are being followed in combating micronutrient deficiencies; these include supplementation through the distribution of capsules that are rich in micronutrients, fortification of staple foods with micronutrients, and through changing diets to achieve adequate intake of micronutrient-rich foods (Mitra, 2012). In South Africa, food-based approaches are preferred because 34 % of rural resource-poor households rely on agriculture; therefore, this is the main vehicle to address nutritional food insecurity (Nyathi et al., 2018b). Through plant breeding, several orange-fleshed sweet potato varieties (A-15, Beauregard, Bophelo, Excel, Jewel, Resisto, and W-119) were developed. These varieties are rich in β-carotene, which the body converts into vitamin A. In addition, orange-fleshed sweet potato varieties contain significant quantities of iron and zinc (Laurie et al., 2012 a, b; 2015; 2018).

Previous studies (Claessens et al., 2008; Larbi et al., 2007; Megersa et al., 2012; Mussoline and Wilkie, 2017) evaluated the potential of using sweet potato as a dual-purpose crop, i.e. harvesting the aboveground biomass as fodder for livestock feed and harvesting the storage root for human consumption. Sweet potato is not a staple crop in South Africa; its estimated overall consumption is 1.1 kg fresh mass per person per year (Laurie et al., 2018). The practice of using sweet potato as a dual-purpose food crop is not common in South Africa, despite the high levels of micronutrient deficiencies (Schönfeldt et al., 2017). The leaves can be used as a green leafy vegetable during the summer season and could potentially alleviate food shortages (Sun et al., 2014). In the northern parts of South Africa and other frost-free areas, sweet potato can be cultivated throughout the year. We presume that if rural resource-poor households were to utilise sweet potato as a dual-purpose food crop (green leafy vegetable and storage root for human consumption) in South Africa, the consumption rate per person per year might increase. Boiling, roasting, or baking (Laurie et al., 2018) are some of the methods used to prepare sweet potato for consumption. Studies by Gomes and Carr (2001, 2003 a, b) and An et al. (2003) showed that increasing the frequency of vine harvesting improved leaf yield, but total storage root yield decreased. Several studies (Gomes and Carr 2001, 2003a; Laurie et al., 2012a; Motsa et al., 2015) reported that sweet potato is a drought tolerant crop. However, water stress reduces canopy growth, which causes a reduction in light interception and thus in storage root yield. Laurie et al. (2012a) showed that a well-watered treatment resulted in a two to four-fold increase in total storage root yield compared with a water-stressed treatment. However, the well-watered treatment showed a lower β-carotene concentration than the water-stressed treatment. Applying fertiliser at 50 % of the recommended rate increased total storage root yield two-fold, whereas fertiliser application at 100 % of the recommended rate, increased storage root yield three-fold, relative to no fertiliser application. In addition, fertiliser application improved the β-carotene concentration of the storage root, from 134 µg g^{-1} for the unfertilised treatment, to 151 µg g^{-1} for the treatment receiving fertiliser (Laurie et al., 2012a, b). This shows that irrigation and fertiliser application are essential for improving orange-fleshed sweet potato storage root yield and β-carotene concentration.

Studies by Laurie et al. (2012a, b) evaluated the effect of water regimes and soil fertility in different environments (Roodeplaat, Giyani, Hazyview and Empangeni) on water productivity, nutrient concentrations (iron, zinc), and β-carotene nutritional yield of different sweet potato varieties. However, the effect of vine harvesting on these crop parameters was not considered. To the best of our knowledge, this study is the first to assess the potential use of orange-fleshed sweet potato (var. Bophelo) as a dual-purpose food crop (green leafy vegetable and as a storage root for human consumption) in South Africa. The objectives of the study were: (1) to evaluate the effect of vine harvest on selected plant parameters [total storage root yield, marketable storage root yield, nutrient concentrations (iron, zinc, and β-carotene), nutritional yield, water productivity, and nutritional water productivity], and, (2) to assess the effect of irrigation regimes and soil fertilisation on these selected plant parameters. We selected orange-fleshed sweet potato (var. Bophelo) because it is popular in the informal markets of South Africa, it is highly productive and has acceptable levels of β-carotene (6708 µg 100 g^{-1} on a fresh mass basis) (Laurie et al., 2018). We imposed two irrigation regimes, two soil fertilisation levels, and two vine-harvest treatments. Our hypotheses were that (1) Vine harvesting of orange-fleshed sweet potato will reduce storage root yield and the other selected plant parameters (water productivity, nutrient concentration, nutritional yield, and nutritional water productivity). (2) No vine harvesting combined with fertiliser application and irrigation will improve storage root yield and the selected plant parameters.

5.2 Materials and methods

5.2.1 Site description, experimental setup, environmental conditions and irrigation regimes

Field experiments were conducted at ARC-VOP, Roodeplaat, Pretoria (25° 59' S; 28° 35'' E; 1168 m.a.s.l.), in the Gauteng Province of South Africa, during two summer seasons: 2013/14 (December-May), and 2014/15 (November-May). The soil was classified (Soil classification working group, 1991) as a yellow-brown Oakleaf form, Buchuberg family (Oa 1120), with a depth of 0.65 to 0.85 m and clay content of 20 %. The field capacity of the soil was 292 mm m^{-1} and the permanent wilting point was 55 mm m^{-1}. Table 5.1 presents the chemical properties of the soil for the top 0.3 m layer.

The experiment had a 2×2×2 factorial design; factors were irrigation regime [well-watered (W1) and supplemental irrigation (W2)], soil fertilisation [recommended N, P, and K application (F1) and no fertiliser application (F2, control)], and vine harvest [no vine harvesting (H1) and vine harvesting every 4 weeks (H2)]. The W1 treatment aimed to keep soil water content above 30 % of plant available water and the W2 treatment was supplemental irrigation; if it did not rain for 4 weeks and soil water content reached a depletion of 80 %, we irrigated back to 50 % of plant available water. The experiment was a randomised complete block design, replicated three times (24 plots of 9 m^2 each). Nyathi et al. (2018a) presented the long-term weather data [rainfall amount (mm), maximum and minimum temperatures (°C)] of the study site. Table 5.2 presents the meteorological conditions [maximum and minimum temperatures (°C), total solar radiation (MJ m^{-2}), total rainfall (mm), cumulative reference evapotranspiration (mm), and vapour pressure deficit (kPa)] during the two growing seasons. Prior to planting, aluminium access tubes were installed in the middle of each plot to a depth of 1 m. A neutron water meter (CPN, 503 DR Hydroprobe, USA) calibrated for the site with measurements from a wet and dry profile was utilised to measure soil water content. Compensating non-leaking (CNL) Urinam dripper lines, with a discharge dripper rate of 2.3 L h^{-1} were used for irrigation. Irrigation scheduling was based on irrigation regimes (W1 and W2). The soil water balance was estimated using Equation 1 (Table 5.3).

Table 5.1 Chemical properties of the topsoil layer (0.3 m) for the experimental 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

Note: the ranges represents different sampling points within the same field

Table 5.2 Monthly meteorological data for the 2013/14 (S_1) and 2014/15 (S_2) growing seasons

	T_{max}[a]		T_{min}[b]		Radiation		Rainfall		ET_0[c]		VPD[d]	
	S_1	S_2	S_1	S_2	S_1	S_2	S_1	S_2	S_1	S_2	S_1	S_2
Month	**ºC**	**ºC**	**ºC**	**ºC**	**MJ m^{-2}**	**MJ m^{-2}**	**mm**	**mm**	**mm**	**mm**	**kPa**	**kPa**
November	30.3	27.8	14.6	14.3	768	631	88	95	159	131	1.4	1.1
December	27.9	28.7	16.3	16.3	697	731	186	175	140	147	0.9	1.0
January	30.8	30.2	16.9	16.5	798	789	1	136	163	161	1.3	1.1
February	30.5	31.9	17.4	16.0	616	744	1	33	128	152	1.1	1.4
March	26.4	30.2	15.9	14.7	479	686	115	72	94	135	0.6	1.2
April	25.2	27.4	9.2	10.8	516	537	26	44	95	101	0.7	0.9
May	25.6	27.6	5.3	6.1	479	545	1	0	89	95	0.8	1.1
					4354[e]	**4663**[f]	**417**[g]	**554**[h]	**869**[i]	**923**[j]		

The reported values are monthly means of daily climatic data during the two growing seasons; from day of transplanting to end of harvest. [a] T_{max}- maximum temperature; [b] T_{min}- minimum temperature; [c] ET_0- reference evapotranspiration; [d] VPD- vapour pressure deficit; [e,f,g,h, i and j] are cumulative values.

Table 5.3 Equations used to calculate the selected parameters

Equations	Description	Number
$ET_a = I + P \pm \Delta W$	Where ET_a (mm) is the actual evapotranspiration, I is the irrigation amount (mm), ΔW is the change in soil water content (mm). Deep percolation (mm) was considered negligible because irrigation was done to supplement rain-received refill back to field capacity.	(1)
$HI = [(Y_{Tsr})/ (Y_{Tsr} + AGB)]$	HI is the harvest index (unit-less); Y_{Tsr} is total storage root yield (t ha^{-1}); AGB is above ground biomass (t ha^{-1}).	(2)
$WP_{Total} = [(Y_{Tsr} + AGB)/ (ET)]\times1000$	WP_{Total} is water productivity for the total biomass (kg ha^{-1} mm^{-1}); ET is actual evapotranspiration (mm).	(3)
$NY_{AGEB\ (Fe,\ Zn,\ and\ \beta)} = [(MC\times AGEB)/100]$	NY_{AGEB} is the above ground biomass nutritional yield (NY, kg ha^{-1}) for iron (Fe), zinc (Zn), and β-carotene; MC is mass concentrations of Fe, Zn, and β (mg 100 g^{-1}); AGEB is the above ground edible biomass (t ha^{-1}).	(4)
$NY_{Tsr\ (Fe,\ Zn,\ and\ \beta)} = [(MC\times Y_{TSr})/100]$	NY_{Tsr} is the total storage root NY (g ha^{-1}) for Fe, Zn, and β; MC of Fe, Zn, and β (mg 100 g^{-1}); Y_{Tsr} (t ha^{-1}).	(5)
$NY_{Total} = [(MC\times AGEB)/100] + [(MC\times Y_{TSr})/100]$	NY_{Total} (kg ha^{-1}) is total nutritional yield	(6)
$NWP_{Tsr} = WP_{Tsr} \times MC \times 10$	Where NWP_{Tsr} is nutritional water productivity (mg m^{-3}) of the total storage roots; WP_{Tsr} is water productivity of the T_{sr} (kg m^{-3}); MC (mg $100g^{-1}$) of Fe, Zn, and β.	(7)
$NWP_{Total} = [(AGEB\times MC\times1000)+(T_{sr}\times MC\times1000)]/ET$	Where NWP_{Total} is total nutritional water productivity (mg m^{-3}); AGEB (t ha^{-1}); T_{sr} (t ha^{-1}); MC (mg $100g^{-1}$) of Fe, Zn, and β; ET (mm).	(8)

5.2.2 Soil fertilisation and crop management

For both seasons, fertilisers [limestone ammonium nitrate (28 % N), Calsiphos (12 % P and 14 % Ca), potassium chloride (50 % K), and calcium nitrate Ca $(NO_3)_2$ (24 % Ca and 15.5 % N)] were applied providing N, P, K and Ca based on the soil analysis and target yields as recommended by ARC-VOP. The application rates for full fertilisation (F1) were 150 kg N ha^{-1}, 74 kg P ha^{-1}, 200 kg K ha^{-1} and 160 kg Ca ha^{-1}, of which half was applied at planting and the remaining half top dressed in equal portions at 14 and 30 days after planting. Orange-fleshed sweet potato (var. Bophelo) cuttings were obtained from the ARC-VOP plant breeding division. The cuttings were planted on ridges (0.3 m high and 0.2 m wide) at a spacing of 1 m between ridges and 0.3 m within ridges (33 333 plants ha^{-1}). At planting, three nodes above and below ground were maintained to allow the cuttings to develop roots from the nodes. The newest five well-developed leaves were plucked at 4, 8, 12, and 16 weeks after planting in the vine harvesting treatments.

5.2.3 Sampling procedure, plant parameters, and potential contribution to human nutrition

Orange-fleshed sweet potato aboveground edible biomass (AGEB) were separated into leaf blades and petioles; leaf blades were sampled (500 g) at 4 and 12 weeks after planting and thoroughly washed with distilled water to remove debris. Thereafter, samples were put in transparent airtight plastic polythene bags and immediately sent to NviroTek laboratories to be analysed for iron and zinc mass concentrations. At the end of the growing seasons (2013/14 and 2014/15), total storage root yield (small + mechanically damaged + long-curved + sprouts + groves + cracked + marketable) and marketable storage root yield were measured fresh and oven dried. Three marketable medium-sized storage roots were sampled from each plot for nutritional analysis and weighed fresh. Thereafter, these samples were washed with distilled water to remove debris and analysed for iron and zinc by NviroTek Laboratories. Analysis of β-carotene concentration of AGEB and storage roots was conducted at the ARC-VOP biotechnology laboratory. Storage roots were peeled and dried with a paper towel. Two opposite quarters from the longitudinal storage root were combined, homogenised, aliquots weighed, and stored at -80 ^{o}C for a week before freeze-drying. Details of the equipment, reagents, and extraction methods used in determining iron, zinc, and β-carotene concentrations were as described by Nyathi et al. (2018b).

β-carotene concentration was converted into vitamin A [(µg RAEs (retinol activity equivalents)] based on Trumbo et al. (2003) (1µg RAE = 1µg retinol = 12 µg of β-carotene). The daily-recommended nutrient intakes (DRNI) for iron, zinc and β-carotene were sourced from Uusiku et al. (2010). Percentage contribution to the DRNI was calculated [nutrient concentrations (iron, zinc, and β-carotene in mg 100 g^{-1}) divided by nutrient requirements in mg $day^{-1} \times 100$]. The potential nutritional contribution (iron, zinc, and vitamin A) from one hectare for a family of six (one male adult; one female adult; two 1-3 year infants; two 4-9 year old children) was calculated using nutritional yield (NY) data [iron, zinc and β-carotene NYs (kg ha^{-1}) divided by the DRNI (mg $100g^{-1}$). We assumed that 30 % of β-carotene is lost during cooking (boiling) as mentioned by Laurie et al. (2012a) and Van Jaarsveld et al. (2006). For iron and zinc, around 50 % is lost; 5% due to boiling and 45% due to bioavailability inside human bodies (Amagloh et al., 2017; Gupta et al., 2006).

5.2.4 Statistical analysis

Two models of the generalised linear mixed model procedures for GenStat (version 14, VSN, UK) were used for data analysis. We used Model 1 to assess the fixed effects (irrigation regime, soil fertilisation level, harvesting and season) and random effects (block/plot) on the studied variables. Model 2 was used to assess the fixed effects (irrigation regime, soil fertilisation and season) and random effects (block/plot) on the vines harvested during growing seasons (4, 8, 12, and 16 weeks after planting) and nutrient concentrations (iron, zinc, β-carotene) of the AGEB. Checks for normality and homogeneity of variance were carried out using Shapiro Wilk's and Bartlett's *tests, respectively*. Post-hoc mean separation was done using Fischer's least significance difference test at a 5 % significance level. Table 5.3 presents the equations used to calculate selected plant parameters

5.3 Results

5.3.1 Rainfall and irrigation amount

Total rainfall was 474 mm during the 2013/14 season, whereas for the 2014/15 season, total rainfall was 554 mm. The total irrigation amount was 495 mm (W1) and 210 mm (W2) in the 2013/14 season. During the 2014/15 season, total irrigation amount was 338 mm (W1) and 218 mm (W2) (Figure 5.1a). The similarity in irrigation of W2 treatments for both seasons resulted from the difference in the duration of the growing period; during season 1, orange-fleshed sweet potato storage root was harvested 130 days after planting, and for season 2, storage root was harvested 180 days after planting.

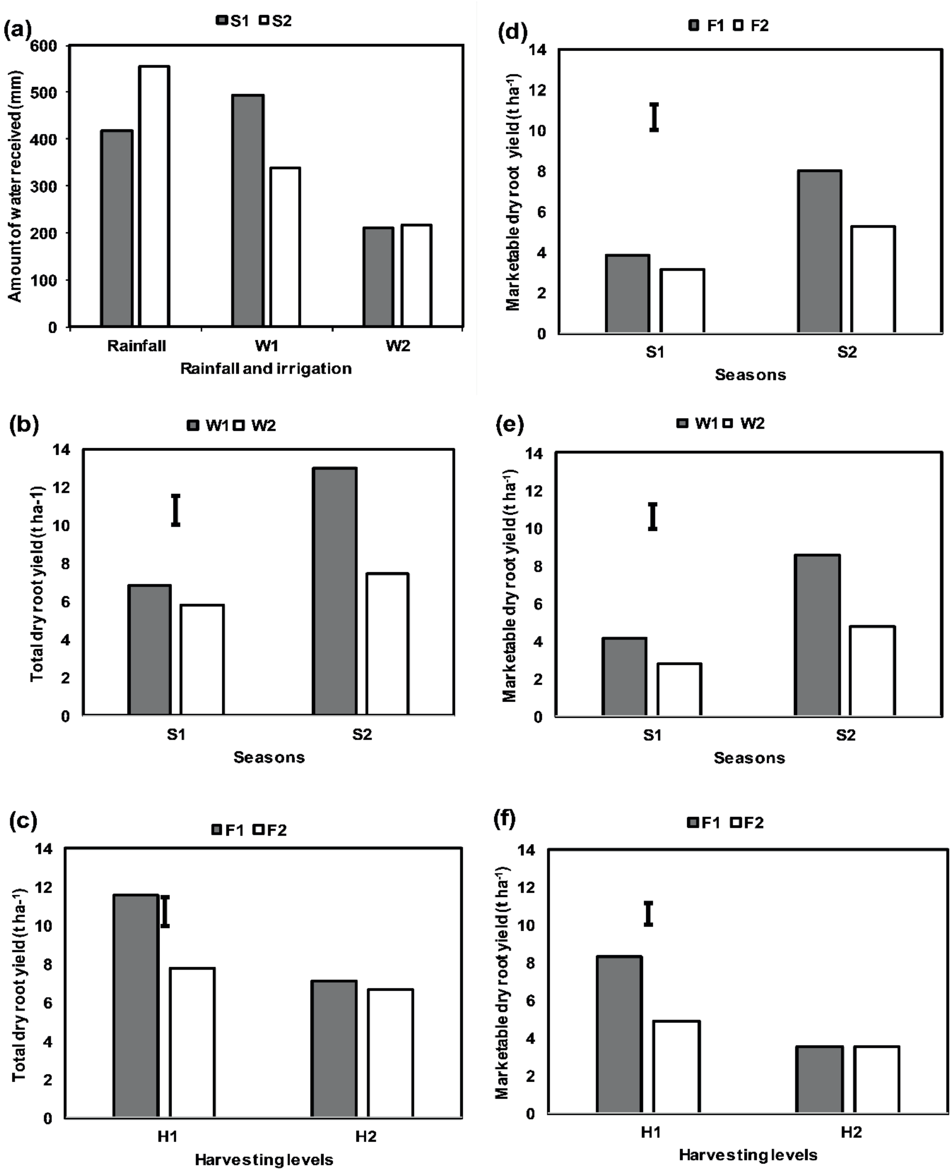


Figure 5.1 Total rain and irrigation amount (**a**). Treatment effect on total storage root yield (**b, c**) and on marketable storage root yield (**d, e, and f**). Total storage root yield includes marketable storage roots yield and unmarketable storage roots yield (small + mechanical damage + long-curved + groves + cracked). W1- well-watered regime; W2- supplemental regime; F1- 100 % N, P, and K application; F2- 0 % N, P, and K application (control); H1-no vine harvesting; H2- vine harvesting; S1-2013/14 season; S2-2014/15 season. Values are averaged over the treatments that are not mentioned, for instance in pane b yields are averaged over fertilisation and vine harvesting levels. Bars represent the $LSD_{0.05}$

5.3.2 Total storage root yield, marketable storage root yield, and aboveground edible leaves

The four-way and three-way interactions between irrigation regime, soil fertilisation, vine harvesting, and season were not significant ($P > 0.05$). However, there was a significant ($P < 0.05$) interaction between irrigation regime and season for total storage root yield and marketable storage root yield (Figures. 5.1 b, e). For the 2013/14 season, irrigation regimes did not affect ($P > 0.05$) both storage root yields. In contrast, the 2014/15 results revealed that the well-watered regime significantly ($P < 0.05$) increased both storage root yield over the supplemental regime; for total storage root yield, it was higher by ≈ 42 %, whereas for marketable storage root yield, it was higher by ≈ 44 %. Correspondingly, the soil fertilisation by vine harvesting interaction significantly ($P < 0.05$) affected total storage root yield and marketable storage root yield (Figures. 5.1 c, f). Without vine harvesting, applying fertiliser increased total storage root yield (≈ 33 %) and marketable storage root yield (≈ 41 %) compared to the control (no fertiliser application). Interestingly, with vine harvesting, soil fertilisation had no effect ($P > 0.05$) on total storage root yield and marketable storage root yield. With no fertiliser applied, both storage root yields were comparable whether vines were harvested or not. There was a significant ($P = 0.04$) interaction effect between season and soil fertilisation for marketable storage root yield (Figure 5.1d). In the 2013/14 season, soil fertilisation did not affect ($P > 0.05$) marketable storage root yield. On the contrary, the well-fertilised treatment improved marketable storage root yield by ≈ 44 % compared to the control in the 2014/15 season. There were no significant effects ($P > 0.05$) of irrigation regimes and soil fertilisation for the aboveground edible biomass harvested during the growing seasons; yet, our results revealed that between 0.9 to 1.1 t DM (dry matter) ha^{-1} (2013/14 season) and between 1.2 to 1.5 t DM ha^{-1} (2014/15 season) were harvested (Table 5A.1).

5.3.3 Micronutrients, β-carotene, nutritional yield, and potential contribution to human nutrition

There were no significant ($P > 0.05$) interactions for main effects on moisture content; this implies that moisture did not compromise differences in mass concentrations reported here and established on a fresh mass basis. For the aboveground edible biomass, moisture content ranged from 0.78 to 0.80 and for the storage root, moisture content ranged from 0.74 to 0.81 (Figure 5A.1). Similarly, irrigation regime, soil fertilisation, and the season had no effect ($P > 0.05$) on iron, zinc, and β-carotene mass concentrations in the aboveground edible biomass and storage roots. The aboveground edible biomass was superior in micronutrient concentrations [grand means (50 mg Fe 100 g^{-1}; 2.8 mg Zn 100g^{-1})] compared to the storage root [grand means (4.6 mg Fe 100 g^{-1}; 1.2 mg Zn 100 g^{-1})]. However, the storage root was rich in β-carotene, with mean values ranging from 173 to 229 mg β-carotene 100 g^{-1} (Table 5.4). In addition, the mean results (2013/14 and 2014/15) for micronutrient and β-carotene mass concentrations illustrated that without vine harvesting, low input management (supplemental irrigation regime and no fertiliser application treatments) improved storage root concentrations by ≈ 79 % for iron and ≈ 22 % for β-carotene, whereas for zinc, it remained the same, in comparison to the highest input regime (well-watered and well-fertilised treatments). In contrast, vine harvesting reduced storage root concentrations by ≈ 20 % for iron and 2 % for zinc, whereas for β-carotene concentration, it was improved by ≈ 9 %, compared to the highest input regime.

Table 5.4 Nutrient concentrations (iron, zinc, and β-carotene) of orange-fleshed sweet potato var. Bophelo for the aboveground edible biomass (AGEB) and storage roots (Tubers) for 2013/14 (S1) and 2014/15 (S2) seasons

Treatments	Iron		Zinc		β-carotene	
	AGEB	Tubers	AGEB	Tubers	AGEB	Tubers
	mg 100g^{-1}	mg 100g^{-1}	mg 100g^{-1}	mg 100g^{-1}	mg 100g^{-1}	mg 100g^{-1}
No vine harvesting (H1)						
W1F1S1	n.d	3.9 (0.1)	n.d	1.7 (0.2)	n.d	235 (0.3)
W1F1S2	n.d	4.5 (0.2)	n.d	1.3 (0.1)	n.d	221 (0.1)
W1F2S1	n.d	5.1 (0.2)	n.d	1.4 (0.1)	n.d	185 (0.3)
W1F2S2	n.d	7.0 (0.1)	n.d	1.1 (0.2)	n.d	221 (0.2)
W2F1S1	n.d	2.9 (0.1)	n.d	1.4 (0.3)	n.d	182 (0.1)
W2F1S2	n.d	8.7 (0.2)	n.d	1.2 (0.1)	n.d	248 (0.3)
W2F2S1	n.d	3.8 (0.1)	n.d	1.7 (0.2)	n.d	214 (0.2)
W2F2S2	n.d	11.2 (0.1)	n.d	1.3 (0.1)	n.d	293 (0.1)
Grand means	**n.d**	**6.0**	**n.d**	**1.4**	**n.d**	**225**
Vine harvesting (H2)						
W1F1S1	53 (4.0)	4.6 (0.4)	3.2 (0.8)	1.6 (0.4)	43 (4.7)	214 (0.8)
W1F1S2	48 (3.4)	3.5 (0.1)	2.5 (1.0)	0.9 (0.2)	37 (4.3)	173 (0.1)
W1F2S1	69 (3.4)	4.8 (0.2)	3.0 (0.1)	1.6 (0.3)	63 (3.5)	182 (0.2)
W1F2S2	44 (11)	7.0 (0.1)	2.0 (6.3)	1.0 (0.2)	38 (17)	173 (0.2)
W2F1S1	45 (6.7)	4.3 (0.2)	3.1 (0.3)	1.3 (0.1)	44 (6.5)	203 (0.2)
W2F1S2	48 (20)	6.2 (0.1)	2.6 (3.1)	1.0 (0.3)	48 (23)	218 (0.5)
W2F2S1	45 (4.7)	2.7 (0.3)	3.0 (1.0)	1.4 (0.1)	47 (5.5)	193 (0.4)
W2F2S2	46 (24)	3.8 (0.1)	2.6 (6.4)	1.1 (0.1)	48 (31)	229 (0.1)
Grand means	**50**	**4.6**	**2.8**	**1.2**	**46**	**198**

W1 is the well-watered regime; W2 is the supplemental regime; F1 is 100 % N, P, and K fertiliser application; F2 is the 0 % N, P, and K fertiliser application. Number in brackets represents the standard deviation of the means. Moisture content values for the AGEB and storage roots for fresh mass are presented by Figure 5A.1. n.d mean there are no data values for the no vine harvesting since the leaves are not consumed

For both seasons (2013/14 and 2014/15), there was no significant ($P > 0.05$) interaction effect between soil fertilisation and vine harvesting for iron nutritional yields [storage root and total biomass (storage root plus the aboveground edible biomass)] (Table 5.5). However, the main effects (vine harvesting and season) were highly significant ($P < 0.001$) for total iron nutritional yield. Our results displayed that vine harvesting (0.73 kg Fe ha^{-1}) improved total iron nutritional yield compared to no vine harvesting (0.39 kg Fe ha^{-1}). For the 2014/15 season, total iron nutritional yield (0.72 kg Fe ha^{-1}) was higher than for the 2013/14 season (0.41 kg Fe ha^{-1}). Zinc nutritional yields (storage root and total biomass) and β-carotene nutritional yields (storage root and total biomass) were affected ($P < 0.05$) by the interaction of soil fertilisation and vine harvesting (Table 5.5). Our results illustrated that vine harvesting reduced zinc and β-carotene nutritional yields for the storage root, relative to no vine harvesting. Generally, the reductions were larger under the well-fertilised treatment (zinc = 43 %; β-carotene = 43 %) compared to the control (zinc = 11 %; β-carotene = 19 %). Similarly, vine harvesting reduced total nutritional yields (storage root plus aboveground edible biomass) for zinc and β-carotene under the well-fertilised treatment. Without fertiliser, vine harvesting improved total β-carotene nutritional yield. For the same season (2013/14), there was a significant ($P < 0.05$) interaction between irrigation regime and soil fertilisation for β-carotene nutritional yields; mean values ranged from 11 to 18 kg β-carotene ha^{-1} (Table 5.5). Under well-watered conditions, total β-carotene nutritional yield declined from 18 to 11 kg β-carotene ha^{-1} when fertiliser was withheld, whereas under the supplemental irrigation regime, soil fertility had no effect on total β-carotene nutritional yield.

During the 2014/15 season, only zinc nutritional yields (storage root and total biomass) were affected ($P < 0.05$) by the interaction of soil fertilisation and vine harvesting (Table 5.5). However, the main effects (irrigation regime, fertilisation, and vine harvesting) were significant ($P < 0.05$) for β-carotene nutritional yields (storage root and total biomass). The well-watered regime improved both β-carotene nutritional yields (storage root = 25.3 kg ha^{-1}; total biomass= 25.5 kg ha^{-1}) compared to the supplemental irrigation regime (storage root = 18.6 kg ha^{-1}; total biomass= 18.9 kg ha^{-1}). Correspondingly, applying fertiliser enhanced both β-carotene nutritional yields (storage roots = 24.4 kg ha^{-1}; total biomass= 24.7 kg ha^{-1}) compared to no fertiliser application (storage roots = 19.5 kg ha^{-1}; total biomass = 19.7 kg ha^{-1}). Our results further revealed that vine harvesting reduced storage root β-carotene nutritional yield (from 28.1 to 15.8 kg ha^{-1}) and total biomass β-carotene nutritional yield (from 28.1 to 16.3 kg ha^{-1}). Zinc nutritional yields (storage root and total biomass) were affected ($P < 0.05$) by the interaction between soil fertilisation and vine harvesting; mean values ranged from 0.09 to 0.17 kg ha^{-1} for the storage root and 0.11 to 0.17 kg ha^{-1} for the total biomass. The 2014/15 results (for the effects of soil fertilisation and vine harvesting) were similar to the 2013/14 results. Firstly, vine harvesting reduced zinc nutritional yields (storage roots and total biomass) relative to no vine harvesting. Secondly, reductions were larger under well-fertilised conditions. In the 2014/15 season, iron nutritional yield for the storage root and iron nutritional yield for total biomass were not affected ($P > 0.05$) by the irrigation regime (Table 5.5). In contrast, zinc nutritional yield and β-carotene nutritional yield were affected ($P < 0.05$) by irrigation regime; the well-watered regime increased zinc nutritional yields (storage roots ≈ 43 %; total biomass ≈ 38 %) and β-carotene nutritional yields (≈ 26 % for storage roots and total biomass) compared to the supplemental irrigation regime.

Table 5.5 Nutritional yields (NYs) of iron (Fe), zinc (Zn), and β-carotene (β) for orange-fleshed sweet potato var. Bophelo storage roots and total NY (total storage roots yield plus above ground edible biomass) for the 2013/14 and 2014/15 seasons

Treatments	**Storage root NY (kg ha^{-1})**			**Total NY (kg ha^{-1})**		
	Fe	**Zn**	**β**	**Fe**	**Zn**	**β**
2013/14						
FxH[a]						
F1H1	0.33	0.14	19	0.33	0.14	19
F1H2	0.23	0.08	11	0.71	0.11	12
F2H1	0.26	0.09	12	0.26	0.09	12
F2H2	0.20	0.08	10	0.80	0.11	10
$LSD_{0.05}$	0.174	0.036	3.84	0.174	0.036	3.88
P_{value}	0.949	**0.043**	**0.030**	0.189	**0.047**	**0.029**
WxF[b]						
W1F1	0.34	0.13	18	0.60	0.15	18
W1F2	0.29	0.09	11	0.67	0.10	11
W2F1	0.22	0.09	12	0.43	0.10	13
W2F2	0.18	0.08	11	0.40	0.09	11
$LSD_{0.05}$	0.174	0.036	3.84	0.174	0.036	3.88
P_{value}	0.949	0.110	**0.040**	0.381	0.125	**0.047**
2014/15						
Water						
W1	0.68	0.14	25.3	1.01	0.16	25.5
W2	0.59	0.08	18.6	0.89	0.1	18.9
$LSD_{0.05}$	0.439	0.025	4.64	0.451	0.025	4.62
P_{value}	0.655	**<0.001**	**0.008**	0.591	**<0.001**	**0.008**
FxH						
F1H1	0.87	0.17	33	0.87	0.17	33
F1H2	0.42	0.08	16	1.1	0.12	17
F2H1	0.75	0.11	24	0.75	0.11	24
F2H2	0.50	0.09	15	1.07	0.12	16
$LSD_{0.05}$	0.62	0.035	6.56	0.638	0.035	6.54
P_{value}	0.639	**0.013**	0.069	0.834	**0.023**	0.07

[a]F×H- soil fertility by harvest interaction; [b]W×F- water by soil fertility interaction. W1- well-watered regime; W2- supplemental regime; F1- 100 % N, P, and K application; F2- 0 % N, P, and K application (control); H1-no vine harvesting; H2- vine harvesting. $LSD_{0.05}$ is the least significant differences of the means. P values in bold are lower than 0.05.

Figure 5A.2 presents mean values of the amount of boiled orange-fleshed sweet potato (var. Bophelo) aboveground edible biomass harvested during the growing season to meet iron, zinc, and vitamin A daily-recommended nutrient intakes. Assessments showed that orange-fleshed sweet potato aboveground edible biomass could potentially contribute to the daily-recommended nutrient intake for iron and vitamin A, whereas it cannot meet the daily-recommended nutrient intake for zinc. This is mainly because of the large amounts of orange-fleshed sweet potato that are needed to be consumed. For example, under the highest input regime (well-watered and well-fertilised treatments), a family of six people would need to consume 2465 grams per day (≈ 411 grams per day for an individual) to meet iron nutritional requirements and 616 grams per day (≈ 103 grams per day for an individual) to meet vitamin A requirements. For zinc nutritional requirements, a family of six would need to consume an impossible 22096 grams per day (≈ 3682 grams per day for an individual) of boiled orange-fleshed aboveground edible biomass. It was interesting to realise that under the low input regime (water stressed and no fertiliser application growing conditions), daily iron and vitamin A nutritional requirements for a family of six people could still be met [≈ 2694 grams per day for iron (449 grams per day for an individual) and 642 grams per day for vitamin A (107 grams per day for an individual)].

5.3.4 Evapotranspiration, water productivity, and nutritional water productivity

For the 2013/14 and 2014/15 seasons, there was no significant interaction ($P > 0.05$) between irrigation regime, soil fertilisation, and vine harvesting for actual evapotranspiration (ET_a) (Figure 5.2). However, ET_a values for different treatment combinations (Box 1) ranged from 427 to 491 mm for the well-watered treatment (2013/14 season) and from 592 to 658 mm for the 2014/15 season (Table 5A.1). For the supplemental regime, ET_a of different treatment combinations ranged from 219 to 257 mm (2013/14 season) and from 439 to 467 mm for the 2014/15 season. There was no significant effect ($P > 0.05$) on water productivity of the treatments (irrigation regime, fertilisation, and vine harvesting) during both seasons (Table 5A.1). For the 2013/14 season, two main effects (irrigation regime and soil fertilisation) were significant ($P < 0.05$) for water productivity. Our results showed that supplemental irrigation (35 kg DM ha^{-1} mm^{-1}) improved water productivity compared to the well-watered regime (22 kg DM ha^{-1} mm^{-1}). Correspondingly, the well-fertilised treatment (31 kg DM ha^{-1} mm^{-1}) had superior water productivity compared to the control (26 kg DM ha^{-1} mm^{-1}). For the 2014/15 season, all main effects (irrigation regime, soil fertilisation, and vine harvesting) were significant ($P < 0.05$) for water productivity. The results of the study illustrated that water productivity values were similar regardless of the main effect (W1 = 25 kg DM ha^{-1} mm^{-1} and W2 = 21 kg DM ha^{-1} mm^{-1}; F1 = 25 kg DM ha^{-1} mm^{-1} and F2 = 21 kg DM ha^{-1} mm^{-1}; and H1 = 25 kg DM ha^{-1} mm^{-1} and H2 = 21 kg DM ha^{-1} mm^{-1}). However, water productivity for irrigation regime displayed contradicting results compared to the 2013/14 season; the well-watered regime indicated water productivity superior to that of the supplemental regime. In addition, our results displayed that vine harvesting reduced water productivity.

Table 5.6 presents iron, zinc, and β-carotene nutritional water productivities for both storage root and total biomass (storage root plus the aboveground edible biomass) (2013/14 and 2014/15 seasons). Irrigation regime did not affect ($P > 0.05$) iron nutritional water productivities (storage root and total biomass); however, zinc and β-carotene nutritional water productivities were affected ($P < 0.05$) by irrigation regime (2013/14 season). Our results showed that the supplemental irrigation regime improved storage root nutritional water productivity (≈ 50 % for zinc and ≈ 56 % for β-carotene) and total biomass nutritional water productivity (≈ 52 % for zinc and ≈ 56 % for β-carotene), relative to the well-watered regime. Vine harvesting affected ($P < 0.05$) iron and β-carotene nutritional water productivities for the storage root and total biomass, except for zinc total biomass nutritional water productivity ($P = 0.383$). Generally, vine harvesting reduced nutritional water productivity for both storage root and total biomass [except for the huge increase shown by total biomass iron nutritional water productivity [60 %)) compared to no vine harvesting (2013/14 season)]. In the 2014/15 season, water regimes affected only zinc nutritional water productivity for the storage root (P = 0.045) significantly; there was no effect (P > 0.05) for other storage root nutritional water productivities (iron and β-carotene) and total biomass nutritional water productivities (iron, zinc, and β-carotene). Our results showed that storage root zinc nutritional water productivity decreased under the supplemental irrigation regime, relative to the well-watered regime. Iron nutritional water productivities (storage root and total biomass) were not affected (P > 0.05) by vine harvesting, whereas zinc and β-carotene nutritional water productivity were affected (P < 0.05) by vine harvesting. The results of this study showed that the vine harvesting treatment reduced both nutritional water productivities for zinc (storage roots = 63 % and total biomass = 18 %) and β-carotene (storage roots = 72 % and total biomass = 66 %), relative to the no vine harvesting treatment.

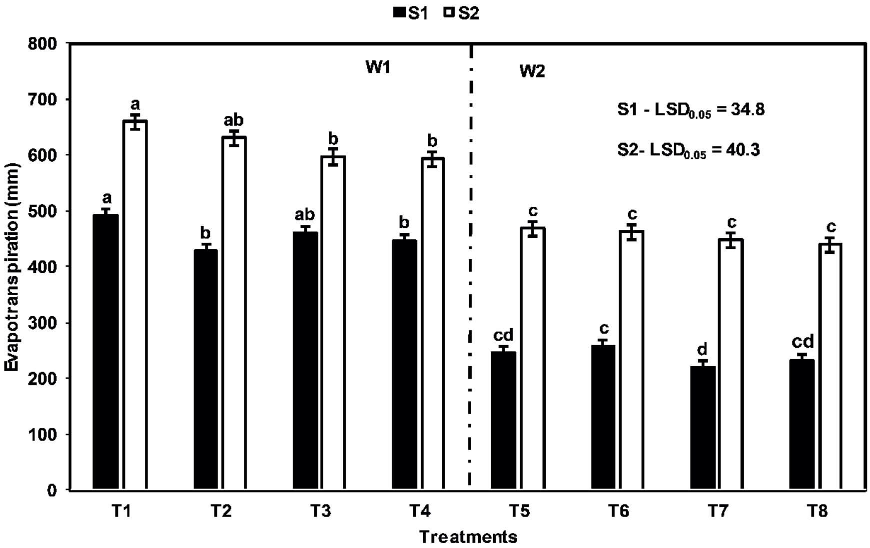


Figure 5.2 Actual evapotranspiration for S1 (2013/14 season) and S2 (2014/15 season); T1 to T8 represents treatment combinations (**Box 1**); W1- well-watered regime, W2- supplemental regime, F1- 100 % N, P, and K application, F2- 0 % N, P, and K application (control), H1-no vine harvesting; H2- vine harvesting. Averages within a season accompanied by the same letter are not significantly different.

Box 1 treatments combinations for Figure 5.2

T1- W1F1H1; T2-W1F1H2; T3-W1F2H1;T4-W1F2H2; T5-W2F1H1; T6-W2F1H2; T7- W2F2H1; T8- W2F2H2

Table 5.6 Nutritional water productivities (NWPs) of iron (Fe), zinc (Zn), and β-carotene (β) for orange-fleshed sweet potato var. Bophelo during the growing seasons (2013/14 and 2014/15)

Treatments	Storage roots NWP (mg m^{-3})			Total NWP (mg m^{-3})		
	Fe	Zn	β	Fe	Zn	β
2013/14						
Water						
W1	68	24	3137	142	27	3201
W2	85	36	4893	169	41	4978
$LSD_{0.05}$	23	7.6	1060	39	7.6	1071
P_{value}	0.135	**0.004**	**0.003**	0.162	**0.002**	**0.003**
Harvest						
H1	89	36	4830	89	36	4830
H2	65	23	3201	223	33	3349
$LSD_{0.05}$	23	7.6	1059.5	39	7.6	1071
P_{value}	**0.044**	**0.003**	**0.005**	**<0.001**	0.383	**0.010**
2014/15						
Water						
W1	113	23	4071	164	26	4113
W2	129	18	4080	195	22	4146
$LSD_{0.05}$	83	4.6	888	84.8	4.7	887
P_{value}	0.682	**0.045**	0.983	0.454	0.121	0.937
Harvest						
H1	155	26	5153	155	26	5153
H2	86	16	2998	203	22	3106
$LSD_{0.05}$	83	4.6	888.4	85	4.7	887
P_{value}	0.095	**<0.001**	**<0.001**	0.243	**0.036**	**<0.001**

W1- well-watered regime; W2- supplemental regime; H1-no vine harvest; H2- vine harvest. $LSD_{0.05}$ is the least significant differences of the means. P-values in bold are lower than 0.05

5.4 Discussion

This study evaluated the potential of utilising orange-fleshed sweet potato (var. Bophelo) as a dual-purpose food crop; producing a green leafy vegetable and storage roots for human consumption. The well-watered orange-fleshed sweet potato produced the highest storage root yields (total storage root and marketable storage root) for both seasons; however, the 2014/15 season gave a larger storage root yield than the 2013/14 season (Figure 5.1 b and e). This resulted because, firstly, the 2014/15 season received more and better-distributed rain compared to the 2013/14 season (Figure 5.1a). Secondly, in the 2013/14 season, storage roots were harvested ≈ 130 days after planting, whereas in 2014/15, the growing season was almost two months longer, with harvest ≈ 180 days after planting; therefore, more solar radiation was intercepted during the 2014/15 season than during the 2013/14 season, resulting in higher productivity. We made a calculation of orange-fleshed sweet potato productivity per day for the well-managed treatment (well-watered, full fertilisation, and no vine harvesting) based on the assumption that storage root formation starts at ≈ 52 days after planting. Our findings indicated that orange-fleshed sweet potato productivity per day was the same for both seasons (at 132 kg DM ha^{-1} day^{-1} in 2013/14 and 133 kg DM ha^{-1} day^{-1} in 2014/15.) During the 2013/14 season, storage root yields for the well-watered and the supplemental irrigation treatments were similar (Figures 5.1b and e). Perhaps the length (130 days) of the growing season caused the similarity in that the duration of water stress was shorter during the 2013/14 season than for the 2014/15 season where there was a clear difference in storage root yield between the two water treatments (Figures 5.1 b and e).

Vine harvesting reduced storage root yields (total storage root and marketable storage root), as found in studies by Gomes and Carr (2001, 2003a) and An et al. (2003). This authenticates our hypothesis that vine harvesting of orange-fleshed sweet potato reduces storage root yield. The 2014/15 results of this study showed that under low input management (supplemental rather than full irrigation and no fertiliser application); storage root production (total storage root and marketable storage root) was reduced (Figures 5.1 b, c, d, e, and f). In addition, our results highlighted that when considering orange-fleshed sweet potato as a dual-purpose food crop, trade-off considerations have to be made. For example, utilising orange-fleshed sweet potato as a dual-purpose food crop is not an ideal practice for market-oriented farming; the loss of marketable storage root was ≈ 50 % under well-fertilised conditions (Figure 5.1f). For subsistence-oriented farming (rural resource-poor households), using orange-fleshed sweet potato as a dual-purpose food crop makes more sense, as the aboveground edible biomass is available for consumption during the growing season (Table 5A.1). At the end of the growing season, storage roots can then be consumed. However, the consequence of vine harvesting is a reduction in the total storage root yield (Figure 5.1c). Our results indicated that without fertiliser application, total storage root productivity declined from 7.8 to 6.7 t DM ha^{-1}, whereas under full fertilisation, the penalty of vine harvesting was higher; total storage root yield dropped from 11.6 to 7.1 t DM ha^{-1}. This implies that for subsistence-oriented-farming, soil fertilisation combined with vine harvesting is not an ideal practice because the reduction in total storage root yield is huge. The grand mean results of this study further displayed that the vine harvesting treatment reduced iron, zinc, and β-carotene concentrations of the storage root (Table 5.4), in line with our hypothesis. This has implications for nutritional food security of rural resource-poor households. The loss in nutrients of harvested storage root caused by vine harvesting was compensated by the availability of highly nutritious green aboveground edible biomass, which rural resource-poor households can consume as a relish with maize porridge (Mavengahama et al., 2013). In the winter season, the storage root becomes available for consumption; this spreads food availability over a longer period, thereby improving the nutritional food security of rural resource-poor households.

We expected that vine harvesting of orange-fleshed sweet potato would reduce storage root nutritional yield. Our results concurred with our hypothesis; however, vine harvesting improved total nutritional yields of iron and zinc, whereas there was a minimal increase for total β-carotene nutritional yield (Table 5.5). This is mainly because the aboveground edible biomass of orange-fleshed sweet potato contributed the least amount of β-carotene to the total nutritional yield. Irrigation and fertiliser application are considered important inputs that determine nutritional yields of iron, zinc, and β-carotene (Laurie et al., 2012a). The results of this study agreed with our expectations that high inputs (well-fertilised and well-watered treatments) improve the nutritional yield of selected nutrients. This agrees with Laurie et al. (2012a) findings, which showed that optimum management is the best for an improved nutritional yield of the storage root (Table 5.5). However, the consequence of vine harvesting combined with no fertiliser application is a reduction in total nutrients that can be harvested; it was reduced by ≈ 42 % for iron, ≈ 45 % for zinc, and ≈ 52 % for β-carotene, relative to no vine harvesting and fertiliser application. Similarly, vine harvesting combined with supplemental irrigation resulted in the reduction of nutrients by ≈ 47 % for iron, ≈ 38 % for zinc, and ≈ 39 % for β-carotene, relative to no vine harvesting and full irrigation. Laurie et al. (2012a) showed that planting one hectare of sweet potato by community members is feasible. For boiled orange-fleshed sweet potato total storage root, assessments showed that the number of people one could feed for a period of 90 days from one hectare for the requirements of iron and zinc is very low under high input (iron = 7 people and zinc = 4 people) and low input (iron = 7 people and zinc = 2 people) optimization (Table 5A.2). Practically, this suggests that people would need to consume huge amounts of boiled orange-fleshed sweet potato storage root to meet their daily iron and zinc dietary requirements; therefore, the storage root cannot be recommended as a food source for iron and zinc. However, for β-carotene, one hectare of orange-fleshed sweet potato storage root could potentially supply 1570 (≈ 262 households) people with the required amount of vitamin A for a period of 90 days, under high input regime. The number of households that can be fed for vitamin A requirement were reduced by ≈ three-fold under the low input regime (Table 5A.2). Our results showed that treatments (irrigation regime, soil fertilisation, and vine harvesting) did not affect β-carotene potential contribution to the daily-recommended nutrient intake for all age groups; under the low input management, storage roots could still provide more than the daily-recommended nutrient requirements by ≈ 6-fold (Table 5A.3). A study conducted by Nyathi et al. (2018b) indicated that boiled aboveground edible biomass of amaranth (*Amaranthus cruentus*) and spider flower (*Cleome gynandra*) could potentially meet human nutritional requirements for iron and zinc. To consume a balanced diet that can alleviate micronutrients deficiency (iron, zinc, and vitamin A), we recommend that rural resource-poor households should prepare a side dish made up of orange-fleshed sweet potato plant tissues (storage root and the aboveground biomass), combined with amaranth and spider flower.

The main aim of the water productivity concept is to produce ‘‘more crop’’ with limited water use (actual evapotranspiration) (Nyathi et al., 2018b). Our results (2013/14) concurred with other studies (Chimonyo et al., 2016; Laurie et al., 2012a;, Mabhaudhi et al., 2013; Motsa et al., 2015; Nyathi et al., 2018b) that showed superior water productivity for sorghum (*Sorghum bicolor*), taro (*Colocasia esculenta*), sweet potato (*Ipomoea batatas*), and selected leafy vegetables [amaranth (*Amaranthus cruentus*), spider flower (*Cleome gynandra*), and Swiss chard (*Beta vulguris*)] under water stress and well-fertilised conditions. The results of this study further revealed that there was a variation in water productivity between seasons; the 2014/15 results indicated lower water productivity compared to the 2013/14 season (Table 5A.4). In addition, water productivity results for the 2014/15 season exhibited contrary results compared with the 2013/14 season; the well-watered regime and soil fertilisation improved water productivity. We expected consistency in terms of the effect of water stress and soil fertilisation on water productivity for both seasons. The difference in water productivity for both seasons might have been caused by different meteorological conditions (temperature, rain, radiation, and vapour pressure deficit) (Table 5.2) and the length of the growing season (Steduto et al., 2007). Chibarabada et al. (2017) averred that water use in agriculture, crop production, and nutritional requirements are assessed in isolation; this procedure is not ideal because of the three aspects interlink. Several studies (Chibarabada et al., 2017; Mdemu et al., 2009; Nyathi et al., 2018b; Renault and Wallender, 2000) have assessed nutritional water productivity [NWP (an index that combines aspects of water use, crop production, and human nutrition)] of selected crops [cowpea (*Vigna unguiculata*), Bambara groundnut (*Vigna subterranea*), dry bean (*Phaseolus vulgaris*), groundnut (*Arachis hypogaea*), tomato (*Solanum lycopersicum*), rice (*Oryza sativa*), onion (*Allium cepa*), amaranth (*Amaranthus cruentus*), spider flower (*Cleome gynandra*), Swiss chard (*Beta vulgaris* var. Fordhook giant)]. As far as can be ascertained, our study is the first attempt to assess iron, zinc, and β-carotene nutritional water productivities of orange-fleshed sweet potato var. Bophelo [storage root and total edible biomass (storage root plus the aboveground edible biomass)] using datasets [storage root yield, aboveground edible biomass, evapotranspiration, and nutrient concentrations (iron, zinc, and β-carotene)] from the same experiment; therefore, this study serves as a benchmark. The mean for both seasons (2013/14 and 2014/15) displayed superior nutritional water productivities (storage root and total biomass) under the supplemental irrigation regime (Table 5.6). Interestingly, total nutritional water productivity was higher than the storage root nutritional water productivity. In addition, the mean for both seasons displayed that nutritional water productivity (iron, zinc, and β-carotene) for the storage root and total edible biomass, declined under the practice of vine harvesting (Table 5.6). This highlights that some compromises have to be made when considering orange-fleshed sweet potato as a dual-purpose food crop.

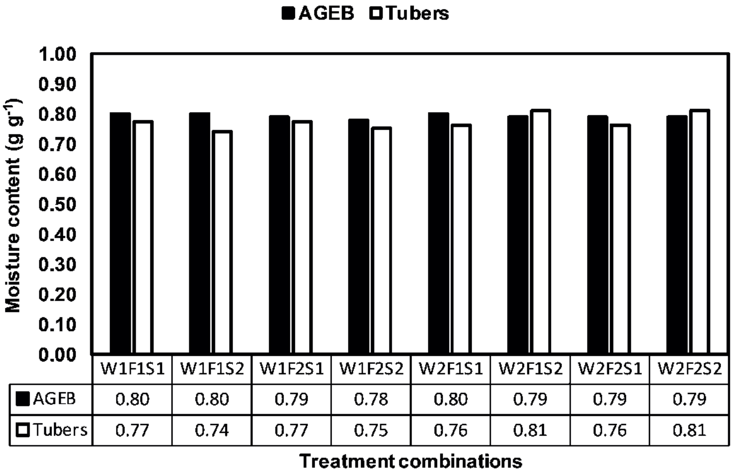
Quite surprisingly, utilising orange-fleshed sweet potato as a dual-purpose food crop can be recommended because selected micronutrients and β-carotene nutritional productivities were maximised per unit water used. Our results illustrated that considering orange-fleshed sweet potato as a dual-purpose food crop required less water to meet total human nutrition requirements (iron = 942 litres person^{-1} day^{-1}, zinc = 3915 litres person^{-1} day^{-1}, β-carotene = 12 litres person^{-1} day^{-1}) under low input management (Figure 5A3 b and c). In contrast, considering orange-fleshed sweet potato as a storage root only (Figure 5A3 a and c) required more water to meet total human nutrition requirements (iron = 3561 litres person^{-1} day^{-1}, zinc = 6091 litres person^{-1} day^{-1}, and β-carotene = 13 litres person^{-1} day^{-1}). Limited information exists on nutritional water productivity of crops; a study by Nyathi et al. (2018b) reported nutritional water productivity values for selected leafy vegetables ranging from 226 to 1323 mg m^{-3} for iron, 60 to 160 mg m^{-3} for zinc, and 365 to 1886 mg m^{-3} for β-carotene. At a glance, this suggests that selected leafy vegetables are more productive than orange-fleshed sweet potato storage root in terms of iron and zinc nutritional water productivities. However, caution has to be exercised when comparing leafy vegetables and orange-fleshed sweet potato storage root; the duration of the growing season differs. Sweet potato maximum growing period is ≈ 180 days, whereas for leafy vegetables it is ≈ 100 days. Therefore, orange-fleshed sweet potato utilises more water (219-658 mm) than leafy vegetables (147-457 mm) to produce selected micronutrients. This highlights the importance of crop diversification in meeting human nutrition requirements with less water consumed. For example, leafy vegetables are superior in iron and zinc per unit of water used, whereas orange-fleshed sweet potato is rich in β-carotene per unit of water used. A diet consisting of leafy vegetables and orange-fleshed sweet potato (leaves and storage root) will reduce the amount of water used to produce iron, zinc, and β-carotene.

5.5 Conclusions

This study showed that there is an opportunity of utilising orange-fleshed sweet potato var. Bophelo as a dual-purpose food crop (green leafy vegetable and staple storage root for human consumption). Our results showed that the dual use of orange-fleshed sweet potato is not ideal for market-oriented farming, because marketable storage root yield decreased by half.

In contrast, the dual use of orange-fleshed sweet potato can be considered for less market-oriented rural resource-poor households rural resource-poor households; the leaves could provide fresh greens for home consumption or for sale, in addition to the storage root. This spreads food availability over a longer period, hence an improvement in the nutritional food security of rural resource-poor households. However, the consequence of the dual use of orange-fleshed sweet potato is the reduction in total storage root yield, whose effect depends on soil fertilisation [no fertiliser application (7.8 to 6.7 t DM ha^{-1}) and N, P and K fertiliser application at a recommended rate (11.6 to 7.1 t DM ha^{-1})]. With vine harvesting, total storage root yield was reduced and total nutritional yield (iron, zinc, and β-carotene) was improved. The mean results for both seasons showed higher iron nutritional yield (0.94 kg DM ha^{-1}) under the practice of vine harvesting combined with no fertiliser application; the highest zinc (0.16 kg DM ha^{-1}) and β-carotene (26 kg DM ha^{-1}) nutritional yields were obtained under the practice of no vine harvesting combined with the well-fertilised treatment. Assessments showed that orange-fleshed sweet potato storage root cannot be recommended for iron and zinc dietary requirements, because of the huge amounts that need to be consumed; however, the storage root can meet vitamin A human nutritional requirements for all age groups even under the low input regime (water stressed and no fertiliser application conditions). It was interesting to note that more water was needed to meet the daily-recommended nutrient intake (iron, zinc, and β-carotene) if orange-fleshed sweet potato was grown for its storage root than when it was grown as a dual-purpose food crop. This highlights that nutritional water productivities of rural resource-poor households can be maximised. These results have to be taken into consideration when making decisions about the nutritional food security of rural resource-poor households. Future research is needed to confirm these findings across a large set of orange-fleshed sweet potato varieties that might respond differently to vine harvesting for selected plant parameters (storage root yield, evapotranspiration, water productivity, nutrient concentration, nutritional yield, and nutritional water productivity). This research should be conducted on the farm so that suitable varieties are selected for the dual use of orange-fleshed sweet potato. Rural resource-poor households are encouraged to produce orange-fleshed sweet potato for their own consumption and any surplus could be sold at the local market. We recommend that crop growth models such as AquaCrop, the Soil Water Balance (SWB) model, the Agricultural Production System Simulator (APSIM), and the World Food Studies (WOFOST) model should be calibrated and validated using field experimental data for the aboveground biomass, storage root yield, evapotranspiration, and water productivity. This will make the results of this study more generic and applicable to various locations.

Appendix 5A



	W1F1S1	W1F1S2	W1F2S1	W1F2S2	W2F1S1	W2F1S2	W2F2S1	W2F2S2
■AGEB	0.80	0.80	0.79	0.78	0.80	0.79	0.79	0.79
□Tubers	0.77	0.74	0.77	0.75	0.76	0.81	0.76	0.81

Figure 5A.1 Moisture content values for aboveground edible biomass (AGEB) and storage root (Tubers) for orange-fleshed sweet potato var. Bophelo

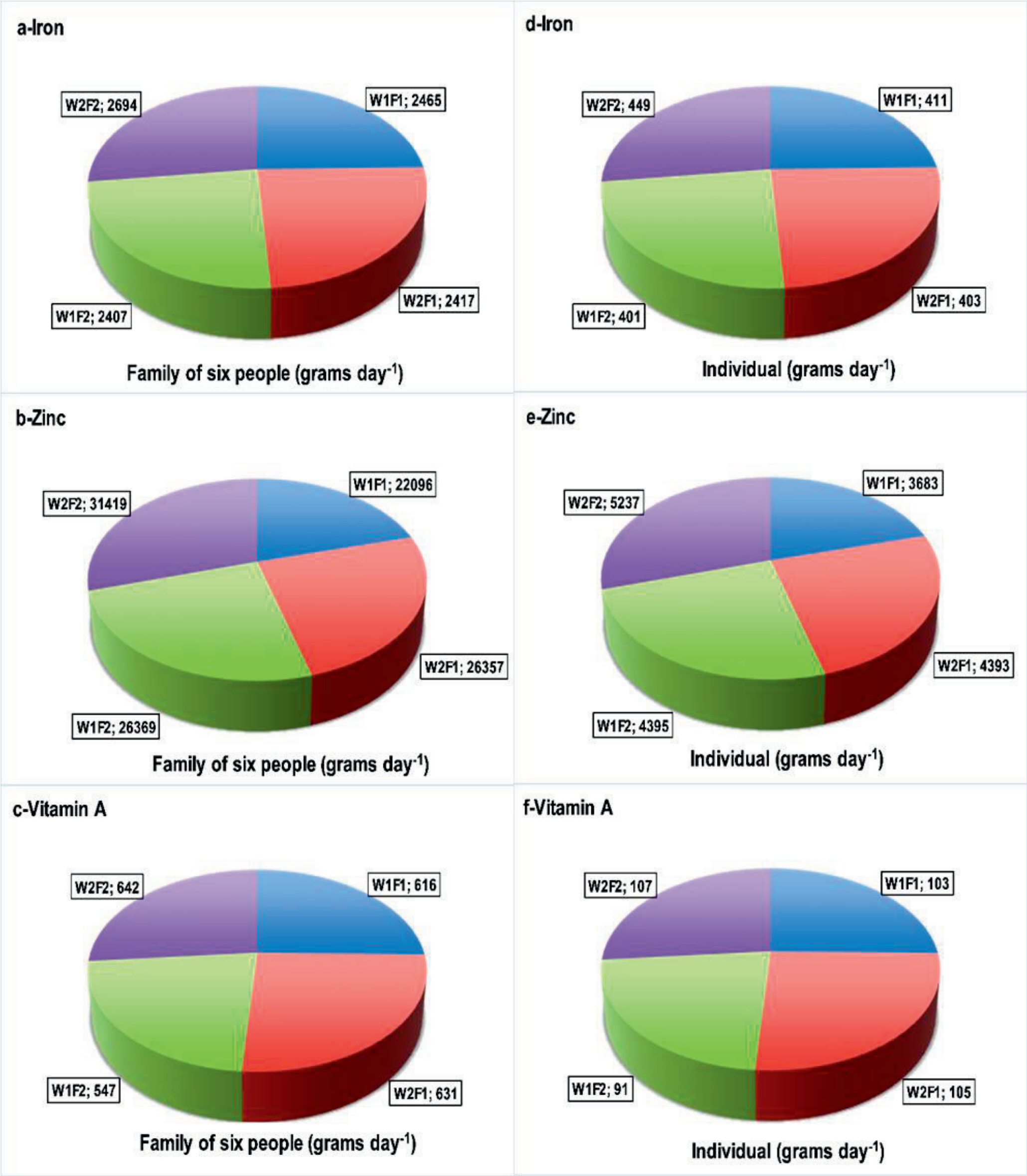


Figure 5A.2 The amount of boiled orange-fleshed sweet potato (var. Bophelo) aboveground edible biomass harvested during the growing seasons to meet iron, zinc, and vitamin A daily-recommended nutrient intakes for a family of six people (one male adult; one female adult; two 1-3 year infants; two 4-9 year old children). Irrigation regime [(W1-well-watered, W2-supplemental) and soil fertility [(F1- 100 % N, P, and K application, F2- 0 % N, P, and K application)]

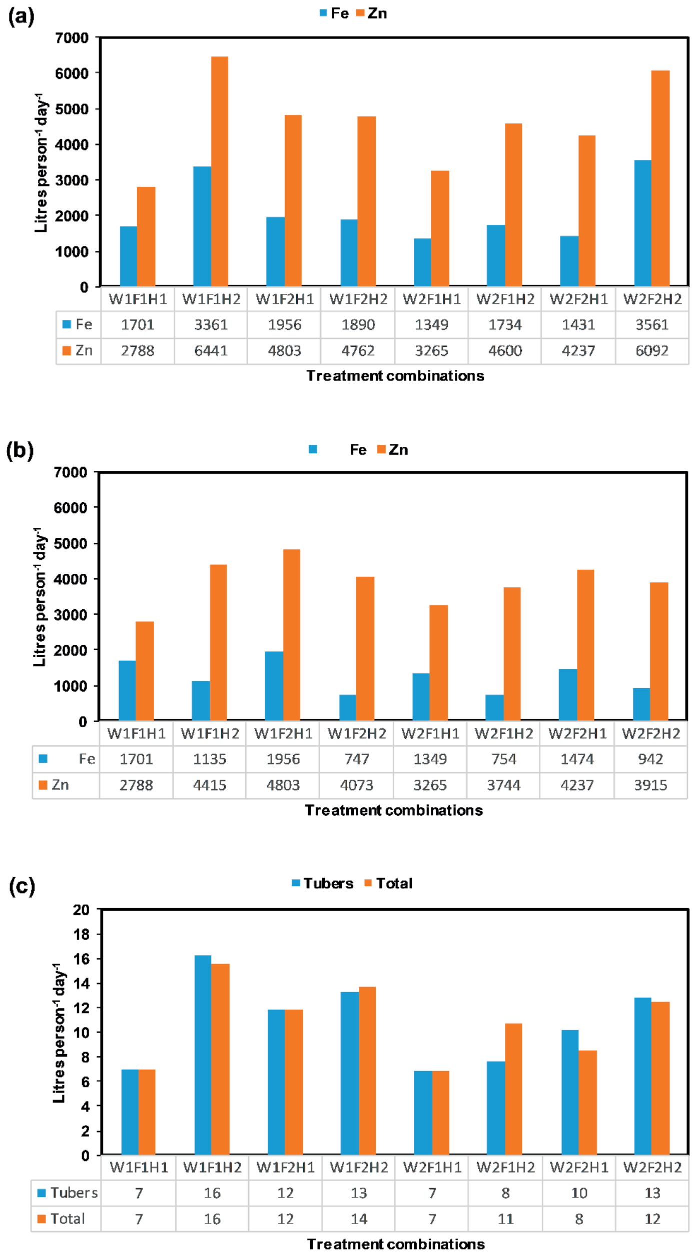


Figure 5A.3 The amount of water needed (Litres person^{-1} day^{-1}) to meet human nutrition requirements for iron (Fe), zinc (Zn), and vitamin A (β-Carotene). **a** is for Fe and Zn in storage root; **b** is for Fe and Zn in total (storage roots plus aboveground biomass harvested during the growing seasons), and **c** is for vitamin A [storage roots (Tubers) and Total (storage roots plus aboveground biomass harvested during the growing seasons)]

Table 5A.1 Treatment effects (water regime, soil fertilisation, and vine harvesting) on biomass (dry mass) and other selected plant parameters during the two growing seasons (2013/14 and 2014/15)

Treatments	AGEB[a]	Tuber[b]	Total AGB[c]	Total BM[d]	HI[e]	ET_a[f]	WP[g]
	$t\ ha^{-1}$	$t\ ha^{-1}$	$t\ ha^{-1}$	$t\ ha^{-1}$	unit less	mm	$kg\ ha^{-1}\ mm^{-1}$
2013/14							
W1F1H1	n.d[h]	10.0 (2.19)	2.5 (0.12)	13.0 (2.16)	0.80 (0.03)	491 (19)	26 (4.4)
W1F1H2	1.0 (0.12)	5.7 (0.30)	4.4 (0.20)	10.0 (0.13)	0.57 (0.02)	427 (28)	24 (1.5)
W2F1H1	n.d	5.8 (1.27)	2.4 (0.33)	8.2 (1.57)	0.70 (0.03)	244 (5.9)	34 (7.1)
W2F1H2	1.1 (0.08)	5.8 (1.04)	3.0 (0.30)	8.7 (1.20)	0.66 (0.04)	257 (6.7)	34 (5.1)
W1F2H1	n.d	8.1 (1.73)	1.9 (0.44)	10.0 (2.16)	0.81 (0.01)	460 (24)	22 (4.3)
W1F2H2	0.9 (0.10)	4.7 (0.67)	4.1 (0.32)	8.8 (0.55)	0.53 (0.05)	446 (11)	20 (1.6)
W2F2H1	n.d	5.9 (0.89)	1.2 (0.17)	7.1 (1.04)	0.83 (0.01)	218 (14)	33 (5.8)
W2F2H2	0.9 (0.23)	4.4 (1.18)	3.0 (0.42)	7.4 (0.76)	0.58 (0.10)	231 (3.8)	32 (3.8)
2014/15							
W1F1H1	n.d	17.0 (0.39)	2.6 (0.22)	2.00 (0.51)	0.87 (0.01)	658 (17)	30 (1.4)
W1F1H2	1.5 (0.05)	11.0 (3.41)	3.4 (0.20)	14.0 (3.36)	0.75 (0.07)	629 (40)	22 (3.9)
W2F1H1	n.d	13.0 (1.70)	2.1 (0.04)	15.0 (1.70)	0.86 (0.02)	467 (2.6)	32 (3.8)
W2F1H2	1.3 (0.06)	11.0 (2.17)	3.2 (0.23)	14.0 (2.36)	0.78 (0.03)	462 (8.2)	31 (5.4)
W1F2H1	n.d	11.0 (2.45)	1.9 (0.37)	13.0 (2.80)	0.85 (0.01)	595 (17)	22 (4.8)
W1F2H2	1.3 (0.10)	7.1 (0.43)	2.8 (0.24)	10.0 (0.19)	0.72 (0.03)	592 (23)	17 (0.6)
W2F2H1	n.d	6.5 (0.41)	1.7 (0.19)	8.2 (0.38)	0.79 (0.02)	447 (7.7)	18 (1.1)
W2F2H2	1.2 (0.12)	5.2 (1.56)	2.5 (0.34)	7.7 (1.90)	0.67 (0.04)	439 (8.0)	18 (4.4)

Values in brackets present the standard deviation of the means. W1- well-watered regime; W2- Supplemental regime; F1- 100 % N, P, and K application; F2- 0 % N, P, and K application. [a]AGEB- aboveground edible biomass; [b]Tuber- storage root; [c]Total AGB- total aboveground biomass; [d]Total biomass (storage root plus aboveground biomass); [e]HI- harvest index (computed as the ratio of storage root divided by total biomass); [f]ETa- actual evapotranspiration; [g]WP- water productivity; [h]n.d means there are no data values for the no vine harvesting since the leaves are not consumed

Table 5A.2 Number of people (iron, zinc, and β-carotene) and households (β-carotene) that one hectare of orange-fleshed sweet potato var. Bophelo could possibly feed (fresh edible portion) for a period of ninety days

Treatments	Iron		Zinc		β-carotene		β-carotene	
	Tuber	Total	Tuber	Total	Tuber	Total	Tuber	Total
	People	People	People	People	People	People	Households	Households
W1F1H1	7	7	4	4	1570	1570	262	262
W1F1H2	3	9	2	2	598	627	100	104
W1F2H1	6	6	2	2	994	994	166	166
W1F2H2	6	13	2	2	756	735	126	123
W2F1H1	6	6	2	2	937	937	156	156
W2F1H2	4	9	2	2	717	635	120	106
W2F2H1	4	4	2	2	707	707	118	118
W2F2H2	2	7	1	2	491	496	82	83
Mean	**5**	**8**	**2**	**2**	**846**	**838**	**141**	**140**

Table 5A.3 Mean values across 2013/14 and 2014/15 seasons of the estimated percentage nutrient contribution of orange-fleshed sweet potato (var. Bophelo) aboveground edible biomass (AGEB) and storage root of the daily recommended nutrient intake for four groups on the basis of 100 g fresh boiled product intake per person per day

	AGEB (H2)				Storage roots (H1)				Storage roots (H2)			
	Infants	Children	Male adults	Female adults	Infants	Children	Male adults	Female adults	Infants	Children	Male adults	Female adults
Iron	%	%	%	%	%	%	%	%	%	%	%	%
W1F1	87	15	37	17	8.9	1.6	3.8	1.7	9	2	2	2
W1F2	105	19	44	20	12.5	2.2	5.3	2.4	12	2	2	2
W2F1	82	15	35	16	10.8	1.9	4.6	2.1	10	2	2	2
W2F2	82	15	35	16	13.9	2.5	5.9	2.7	6	1	2	1
Zinc												
W1F1	6	3	4	5	2.2	1.3	1.3	1.9	1.8	1.1	1.1	1.6
W1F2	9	5	5	7	1.8	1.0	1.1	1.5	1.9	1.1	1.1	1.6
W2F1	7	4	4	6	1.7	1.0	1.0	1.4	1.5	0.9	0.9	1.3
W2F2	4	2	2	4	1.9	1.1	1.2	1.6	1.6	0.9	1.0	1.4
β-Carotene												
W1F1	117	78	78	93	815	543	543	652	691	461	461	553
W1F2	158	106	106	127	711	474	474	568	621	414	414	497
W2F1	138	92	92	110	674	449	449	539	660	440	440	528
W2F2	145	97	97	116	795	530	530	636	662	441	441	529

Calculations of micronutrient concentrations and Vitamin A were conducted on fresh mass basis. W1- well-watered regime and W2- supplemental regime; F1- 100 % N, P, and K application and F2- 0 % N, P, and K application; H1- no vine harvesting and H2- vine harvesting. The four age groups are infants (1-3 years), children (4-18 years), male adults (19-65 years), and female adults (19-65 years)

Table 5A.4 Storage root and total (storage root plus the aboveground edible biomass) nutritional water productivities (NWP) of iron (Fe), zinc (Zn), and β-Carotene (β) for orange-fleshed sweet potato var. Bophelo during the two growing seasons (2013/14 and 2014/15)

Season x treatment	Storage root NWP (mg m^{-3})			Total NWP (mg m^{-3})		
	Fe	Zn	β	Fe	Zn	β[a]
2013/14						
W1F1H1	84	35	4906	84	35	4906
W1F1H2	61	21	2875	186	29	2974
W1F2H1	64	18	2401	64	18	2401
W1F2H2	63	20	2367	235	28	2524
W2F1H1	99	**46**	**6119**	99	**46**	**6119**
W2F1H2	80	24	5893	**246**	35	4004
W2F2H1	**107**	45	3838	107	45	3838
W2F2H2	55	28	3724	226	39	3894
2014/15						
W1F1H1	116	**33**	5675	116	**33**	5675
W1F1H2	60	16	2689	170	24	2775
W1F2H1	135	23	4665	135	23	4665
W1F2H2	139	20	3256	**236**	22	3338
W2F1H1	**210**	27	**5966**	210	27	**5966**
W2F1H2	99	15	3336	235	22	3468
W2F2H1	160	19	4307	150	19	4307
W2F2H2	47	13	2712	174	21	2845

The values represent the interaction of irrigation regime [(W1-well-watered, W2-supplemental), soil fertility [(F1- 100 % N, P, and K application, F2- 0 % N, P, and K application)], and harvest [(H1- no vine harvest, H2- vine harvest)] for the 2013/14 and 2014/15 growing seasons. Values in bold are the highest values within a column

Chapter

6

Synthesis

6.1 Main results

The main objective of this thesis is to evaluate nutritional water productivity of selected traditional vegetables in South Africa. To achieve the objectives of the thesis, four research questions were formulated (section 1.6) and each research question is addressed through a main Chapter, resulting in specific findings for each research question. The first section of the synthesis summarises the main research findings of each question and the second section reflect on the main findings.

6.1.1 Are traditional vegetables superior to alien vegetables for selected plant parameters (aboveground biomass plus stems and/ or storage organ, nutrient concentration, nutritional yield, and nutritional water productivity)? (Chapter 2)

Repeatedly, literature (Chivenge et al., 2015; Maseko et al., 2018; Mavengahama et al., 2013) presents anecdotal information to back up claims that traditional vegetables are more productive (in terms of biomass and water productivity) and more nutrient dense (iron, zinc, and β-carotene) than alien vegetables. Chapter 2 sought to investigate these claims using datasets [biomass (aboveground biomass and/ or storage organ), nutrient concentration, and evapotranspiration] sourced from literature (peer-reviewed journal articles, books, research reports, and conference proceedings, the United States Department of Agriculture Food Composition, and the Food and Agricultural Composition/In Foods). Common databases such as Google Scholar, Scopus, CAB Abstracts, and Web of Science were used for the literature search. Data [biomass (aboveground biomass and/or storage organ), water use, and nutrient concentration] sourced from the literature were used to compute water productivity, nutritional yield, and nutritional water productivity of selected vegetables.

Key findings revealed that alien vegetables were more productive than traditional vegetables in terms of biomass (aboveground biomass and/ or storage organ). In this Chapter, we iterated that reported yield values for traditional vegetables might have happened under sub-optimal conditions, whereas yield values for alien vegetables, might have occurred under optimal conditions. Through plant breeding, alien vegetables have been improved for high performance under well-managed growing conditions (Nalley et al., 2018), whereas traditional vegetables have not been improved through plant breeding for higher productivity. In addition, the production of traditional vegetables occurs under low input (rainfed and minimal soil fertility optimisation), resulting in lower yield values. In Chapter 2, we found that traditional vegetables were more nutrient dense than alien vegetables for iron and zinc, whereas alien vegetables were superior to traditional vegetables in β-carotene concentration. This contradicts anecdotal information, which presented traditional vegetables as being nutrient dense in all nutrients (iron, zinc, and β-carotene). In addition, nutrient concentration values of selected vegetables were not conserved. Bumgarner et al. (2012) argued that it is a bit unfortunate to assess the nutrient concentration of crops without considering yield because both account for nutritional yield per unit area of land. Our results illustrated that traditional vegetables were high in iron and zinc nutritional yields (Table 2.5) and alien vegetables were superior in β-carotene nutritional yield (Table 2.5). Practically, nutritional yield values can be used to assess the number of people a hectare could potentially supply; for example, butternut could potentially supply 264 children aged between 4 to 18 years with the daily-recommended vitamin A intake for a period of 90 days. In Chapter 2, we found that water productivity of traditional vegetables (1.29 kg m^{-3}) was similar to the water productivity of alien vegetables (1.37 kg m^{-3}) (Table 2.1).

In terms of nutritional water productivity, traditional vegetables were more productive per unit of water used to produce iron and zinc, whereas alien vegetables were more productive per unit of water used to produce vitamin A (Table 2.5). Productivity per unit of water used in producing micronutrients and vitamin A can be maximised through crop diversification, especially for rural resource-poor households in sub-Saharan Africa. This Chapter demonstrated that traditional vegetables could play a crucial role in alleviating micronutrient deficiency of rural resource-poor households.

In Chapter 2, we evaluated nutritional water productivities of ten traditional vegetables and ten alien vegetables using two independent databases (the water productivity and the nutrient concentration databases). This approach is similar to the methodology used by other authors (Renault and Wallender, 2000, Oelofse and Van Averbeke, 2012, Wenhold et al., 2012, and Mdemu et al., 2009) who generated nutritional water productivity of crops using datasets from various locations. We acknowledged that our approach is not ideal because these two independent datasets have some level of uncertainty. However, this was the only pragmatic approach to generate first-order estimates of nutritional water productivity of selected vegetables. Chapter 3 closed this research gap by assessing nutritional water productivity of two traditional leafy vegetables (amaranth and spider flower) and compared it with nutritional water productivity of an alien vegetable (Swiss chard) using datasets (aboveground edible biomass, evapotranspiration, and nutrient concentration) from the same location. We further investigated yield response of amaranth, spider flower, and Swiss chard to three irrigation water regimes (no water stress, moderate water stress, and severe water stress) and developed ‘‘new variables" (above ground edible biomass, nutrient concentration, nutritional yield, and nutritional water productivity) for selected vegetables as suggested in Chapter 2.

Some traditional vegetables (cowpea, pumpkin, orange-fleshed sweet potato) and alien vegetables (beetroot and onions) have a potential of being utilised as a dual-purpose food crop; green leafy vegetable and the storage organ for human consumption (Chapter 2). This could possibly improve the nutritional food security of rural resource-poor households in that the aboveground edible biomass can be consumed during the growing period and at the end of the growing period, the storage organ becomes available (Nyathi et al., 2019b). However, the effect of harvesting the aboveground edible biomass on the storage organ is not known. Chapter 5 addressed this concern by evaluating the effect of vine harvesting on selected plant parameters (storage root yield, nutrient concentration, nutritional yield, water productivity, and nutritional water productivity) for orange-fleshed sweet potato (var. Bophelo).

6.2.2 Are traditional vegetables [spider flower (*Cleome gynandra*) and amaranth (*Amaranthus cruentus*)] superior to an alien vegetable [(Swiss chard (*Beta vulgaris*)] in terms of the aboveground biomass (aboveground edible biomass plus stems), nutrient concentration, nutritional yield, and nutritional water productivity? (Chapter 3)

This Chapter assessed nutritional water productivity of two traditional vegetables (amaranth and spider flower) and compared it with the nutritional water productivity of an alien vegetable (Swiss chard), using datasets from the same location. The two traditional vegetables were selected because they are nutrient dense (high concentrations of iron, zinc, and β-carotene) and consumed by rural resource-poor households as a relish. Swiss chard was selected because it is a leafy vegetable that is highly nutritious (high concentrations of iron, zinc, and β-carotene), it has been commercialised many decades ago, and is consumed as a relish in sub-Saharan Africa. In this Chapter, data collected from field experiments were used to compute nutritional yield (aboveground edible biomass × nutrient concentration), water productivity (aboveground biomass per evapotranspiration), and nutritional water productivity [(aboveground edible biomass/ evapotranspiration) × nutrient concentration].

The results of this study showed that the aboveground biomass of the two traditional vegetables (amaranth and spider flower) was comparable with an alien vegetable (Swiss chard) under the well-watered irrigation regime (Table 3.3). This contradicts anecdotal information from literature, which suggested that traditional vegetables are more productive than alien vegetables in terms of biomass (aboveground biomass and/ or storage organ). Swiss chard exhibited the highest aboveground edible biomass due to its higher harvest index (Table 3.3). In Chapter 2, key findings showed that traditional vegetables were more nutrient dense than alien vegetables in iron and zinc, whereas alien vegetables were superior in β-carotene concentration (β-carotene can be converted into vitamin A inside human bodies). The results of this Chapter concurred with key findings of Chapter 2, which showed that selected traditional vegetables were nutrient dense (iron, zinc, and β-carotene) (Table 3.4). The difference is that Chapter 2 findings showed that alien vegetables were rich in β-carotene concentration. This is because Chapter 2 compared ten traditional vegetables and ten alien vegetables, whereas Chapter 3 compared two traditional vegetables with one alien vegetable. In addition, key findings of Chapter 3 showed that nutrient concentrations (iron, zinc, and β-carotene) vary due to water stress, different seasons, and crop species. This agreed with Uusiku et al. (2010) who reported that nutrient concentration of vegetables is not conserved. In this Chapter, we show that selected traditional vegetables are high in iron, zinc, and β-carotene concentrations. We further iterated that nutritionists utilise nutrient concentration data to assess a portion (per 100 g) that should be consumed by different age groups (box 3.1) to meet their human nutritional requirements. Nutritional yield data showed that Swiss chard was rich in iron and zinc nutritional yields due to the higher proportion of the aboveground edible biomass for Swiss chard. Amaranth was superior in β-carotene nutritional yield (Table 3.4). This is not consistent with Chapter 2 findings, which revealed that traditional vegetables were superior in iron and zinc nutritional yields, whereas alien vegetables were high in β-carotene nutritional yield. It is crucial to note that severe water stress reduced nutritional yields for selected nutrients (iron, zinc, and β-carotene) for amaranth, spider flower, and Swiss chard (Table 3.4). Chapter 3 brought new insight into the importance of considering nutritional yield as a parameter for assessing nutrient richness of crops in that crops can be higher in nutrient concentration but lower in nutritional yield when the total amount of nutrients (nutritional yield) that can be harvested per unit area of land are considered.

In this Chapter, we hypothesised that the two selected traditional vegetables are more productive than an alien vegetable. Astonishingly, water productivity of amaranth (C_4) and spider flower (C_4) was similar to that of Swiss chard (C_3) (Table 3.5). This is unexpected; Van Halsema and Vincent (2012) argued that C_4 plants are more productive than C_3 plants. In Chapter 2, we highlighted the importance of using beneficial use of water (transpiration rather than evapotranspiration) when computing water productivity. Chapter 3 findings revealed that amaranth and spider flower are more productive than Swiss chard when transpiration was used as a denominator. In addition, key findings of this Chapter showed that water stress did not affect nutritional water productivity of selected leafy vegetables. This highlight that in times of water scarcity, growing leafy vegetables provide a good strategy to obtain the maximum nutritional yield per unit of water consumed. Under drought conditions, the yield of selected leafy vegetables was low compared to optimal conditions and nutrient concentration was higher under drought conditions compared to optimal conditions (Table 3.5). The drought conditions are typical to the production conditions of rural resource-poor households. It was interesting to realise that selected traditional leafy vegetables were superior in β-carotene nutritional water productivity, whereas an alien vegetable was higher in iron and zinc nutritional water productivities (Table 3.5). Similarly, the higher portion of the aboveground edible biomass for Swiss chard has translated to higher nutritional water productivity for iron and zinc. This highlight the need for crop diversification in order to maximise the amount of nutrients produced per unit of water used. For example, a diet consisting of amaranth, spider flower, and Swiss chard used as side dishes will reduce the amount of water needed to produce iron, zinc, and β-carotene (Table 3.5). In this Chapter, we show that there is some opportunity of alleviating micronutrient deficiency of rural resource-poor households under drought conditions.

6.2.3 Can the AquaCrop model be calibrated and validated for repeatedly harvested vegetables such as amaranth, spider flower, and Swiss chard? (Chapter 4)

In the decades to come, irrigated agriculture will be faced with the challenge of producing more food with less resources (water and fertiliser), due to population growth, water scarcity and adverse impacts of climate change (Godfray et al., 2010). Global warming is causing changes in temperature and rainfall patterns and has increased the frequency and severity of extreme events (Ewert et al., 2015). This shows that the current food systems have to adapt to meet the challenge of improving the food security of rural resource-poor households under climate change. In Chapters 2 and 3, we proposed that traditional vegetables need to be ‘‘re-introduced'' into the current food system based on literature claims that traditional vegetables are nutrient dense, drought tolerant, and require less inputs in terms of water and fertiliser. If these claims are valid, traditional vegetables can be used for crop diversification and climate change adaptation (Challinor et al., 2018). However, the yield response of traditional vegetables to water and fertility stresses is unknown. In Chapter 3, we conducted experiments under a rain shelter and measured selected plant parameters [aboveground biomass (aboveground edible biomass plus stems), evapotranspiration and nutrient concentration (iron, zinc, and β-carotene)]. The main challenge with field experiments is that results are location specific and may not be applicable to other locations with different climatic conditions. In addition, it is not cost effective to conduct experiments in various locations. To make the results of our experiments generic, we used data collected from Chapter 3 to calibrate and validate the AquaCrop model for selected repeatedly harvested leafy vegetables. We selected the AquaCrop model (http://www.fao.org/aquacrop), which simulates the yield response of crops, especially where water is limiting. The AquaCrop model has been calibrated and validated for several crops (Table 6.1), including amaranth (Bello and Walker, 2017). To the best of our knowledge, AquaCrop l has not been calibrated and validated for spider flower and Swiss chard.

Table 6.1 Calibration and validation of AquaCrop for several crops

Common name	Scientific name
Sugar beet	*Beta vulgaris*
Soya beans	*Glycine max*
Wheat	*Triticum spp.*
Barley	*Hordeum vulgare*
Pearl millet	*Pennisetum glaucum*
Potato	*Solanum tuberosum*
Maize	*Zea mays*
Sunflower	*Helianthus annuus*
Oats	*Avena sativa*
Cabbage	*Brassica oleracea*
Sorghum	*Sorghum bicolor*
Saffron	*Crocus sativus*
Tomato	*Solanum lycopersicum*

However, AquaCrop model (version 4.0) is not capable of running sequential harvests in a single run to simulate yield response of crops that are harvested repeatedly during the growing period (Nyathi et al., 2018a). In Chapter 4, we applied and tested an innovative approach for the simulation of multiple harvests during the growing period by assuming that after each harvest; approximately 1 to 2 % of aboveground biomass remains on the plot, which becomes the initial canopy cover for the subsequent harvest cycle. This made it possible to simulate yield response of repeatedly harvested leafy vegetables, using the AquaCrop model for selected plant parameters (canopy cover, soil water content, above ground biomass, actual evapotranspiration, and water productivity). The goodness of fit statistical indicators [root mean square error (RMSE), RMSE-standard deviation ratio (RSR), R^2, and relative deviation] showed that AquaCrop model was calibrated very well ($0.60 < R^2 < 0.99$, $0.94 < RMSE < 5.44$, and $0.04 < RSR < 0.79$) for the well-watered treatment. The fit for canopy cover, soil water content, actual evapotranspiration, and water productivity for the water-stressed treatment was not good when compared to the well-watered treatment. We used transpiration values from Chapter 4 to compute the water productivity for selected vegetables in Chapter 3. In this Chapter, we show that the AquaCrop model can be used to simulate yield response of repeatedly harvested leafy vegetables. Calibrated crop models can be used to investigate the impacts of climate change variables (temperature, precipitation, and carbon dioxide) on potential future yields and crop productivity (Ewert et al., 2015).

6.1.4 What is the effect of utilising orange-fleshed sweet potato (*Ipomoea batatas* var. Bophelo) as a dual-purpose food crop (green leafy vegetable and storage root for human consumption) on storage root yield? (Chapter 5)

The effect of leaf harvesting on the storage organ yield and nutrient concentration of potential dual-purpose vegetables (cowpea, pumpkin, sweet potato, beetroot, and onions) is unknown (Chapter 2); for example, do the storage organ yield increase or decrease? How does leaf harvesting affect the nutrient concentration of the storage organ? Out of the suggested dual-purpose vegetables, we selected orange-fleshed sweet potato var. Bophelo because it is widely utilised to alleviate vitamin A deficiency of rural resource-poor households in South Africa. In Chapter 5, we assessed the possibility of utilising orange-fleshed sweet potato var. Bophelo as a dual-purpose food crop; i.e. green leafy vegetable and storage root for human consumption. In this Chapter, we measured selected plant parameters [aboveground biomass, storage root yield (marketable and total), nutrient concentration (iron, zinc, and β-carotene), nutritional yield (iron, zinc, and β-carotene), water productivity, and nutritional water productivity]. The results showed that orange-fleshed sweet potato (250-440 g m^{-2}) is less productive than traditional vegetables (331-977 g m^{-2}) in terms of the aboveground biomass (Chapters 3 and 5), as the aboveground biomass for sweet potato has been partitioned into the storage root yield. In Chapter 5, we show that the consequence of vine harvesting during the growing season is the reduction in total storage root yield. Under no fertiliser application, total storage root yield declined from 7.8 to 6.7 t DM ha^{-1}, whereas under full fertilisation, total storage root dropped from 11.6 to 7.1 t DM ha^{-1} (Figure 5.1). In terms of nutrient concentrations, selected traditional vegetables were superior in zinc and β-carotene concentrations, whereas orange-fleshed sweet potato aboveground edible biomass was higher in iron nutrient concentrations (Tables 3.4 and 5.4). In addition, vine harvesting reduced iron, zinc, and β-carotene nutrient concentrations. This has implications for nutritional food security of rural resource-poor households if they utilise sweet potato as a dual-purpose food crop. The loss in nutrient concentration of storage root is compensated by the availability of high nutritious green leafy vegetable, which rural resource-poor households could consume (Table 5.4). Our results show that selected traditional vegetables (Chapter 3) are more productive per unit of water used to produce iron and zinc, whereas orange-fleshed sweet potato storage root was more productive per unit of water used in producing β-carotene (Tables 3.5 and 5A.4). In Chapter 5, we recommended that in order to meet human nutritional requirements for iron, zinc, and vitamin A using less water, it is prudent that rural resource-poor households practice crop diversification. For example, a diet consisting of selected leafy vegetables and orange-fleshed sweet potato (aboveground edible biomass and storage root) will reduce the amount of water needed to produce iron, zinc, and β-carotene.

Our results showed that there is a possibility of utilising orange-fleshed sweet potato as a dual-purpose food crop depending on the purpose. For market-oriented farming system, the dual use of orange-fleshed sweet potato is not an ideal practice, because the loss of marketable storage root was half (Figure 5.1), which suggest that profits will also reduce by half. For subsistence-oriented farming, utilising orange-fleshed sweet potato as a dual-purpose food crop is suitable, because of the availability of fresh green leafy vegetable during the summer season and after the end of the growing season, the storage roots can be consumed. The benefit of using orange-fleshed sweet potato as a dual-purpose is an improvement in nutritional water productivity, under severe water-stressed conditions. This highlights that nutrient requirements for rural resource-poor households would be met under drought conditions. For example, considering orange-fleshed sweet potato as a dual-purpose food crop required 942 litres per person per day to meet daily-recommended nutrient intakes for iron. In contrast, considering orange-fleshed sweet potato for the storage root only required 3561 litres per person per day to meet the daily-recommended nutrient intake for iron. This demonstrates that there is a scope of utilising orange-fleshed sweet potato as a dual-purpose food crop, especially for rural resource-poor households.

6.2 Reflection and outlook

6.2.1 Generating water productivity and nutritional water productivity database using independent datasets

In Chapter 2, we acknowledged the weakness of the approach we used; generating the nutritional water productivity database using two independent datasets (crop water productivity and nutrient concentration databases). Key findings showed similar water productivity for traditional vegetables and alien vegetables (Chapter 2). This contradicts several literature (Oelofse and Van Averbeke, 2012; Mabhaudhi et al., 2013; Nyathi et al., 2018 a, b; Wenhold et al., 2012) sources which found that traditional vegetables are more productive than alien vegetables in terms of biomass and water productivity. We presume that this was caused by the water use data utilised to compute water productivity. The literature surveyed was not clear whether water use was total seasonal irrigation water applied or crop evapotranspiration. Although Chapter 3 assessed nutritional water productivity of amaranth, spider flower, and Swiss chard, using datasets from the same location, information on nutritional water productivity of selected vegetables benchmarked in Chapter 2 is limited, yet these vegetables can play a major role in supplementing iron, zinc, and β-carotene. In the coming decades, assessment of nutritional water productivity (at global, regional, and national levels) of crops needs to be improved significantly, in order to secure a sustainable food supply for all, including rural resource-poor households. In addition, extreme weather events (low precipitation and higher temperatures) will reduce crop yields (Bastiaanssen and Steduto, 2017; Zwart et al., 2010).

The current food system has to adapt to meet the challenge of improving nutritional food security (food production, food access, food utilization, and food stability), under climate change (Ewert et al., 2015). However, the current food system is not capable of providing highly nutritious food for rural resource-poor households because it lacks dietary diversity. For example, the harvest plus project (https://www.harvestplus.org/) promotes bio-fortification of staple crops (beans, maize, pearl millet, wheat cassava, sweet potato, and rice) with iron, zinc, and β-carotene for improved nutritional food security. Many rural resource-poor households are still experiencing severe micronutrient deficiency (iron, zinc, and vitamin A) in the sub-Saharan Africa region. Therefore, agricultural research and development need to be re-designed by defining a new agenda and setting new objectives that will focus on alleviating nutritional food insecurity of rural resource-poor households (Graef et al., 2014).). This new unity of purpose research should focus on promoting the consumption of vegetables (including traditional vegetables) in sub-Saharan Africa countries through campaigns (local radio stations, TV stations, trade fairs, exhibitions, in-store promotions, outdoor promotions, nutritional walks, and product sampling) (Mwangi and Kimathi, 2006). In addition, it should assess nutritional water productivity of all the vegetables selected in Chapter 2, using datasets from the same experiments and measure other plant parameters (nutritional yield, nutrient concentration, aboveground edible biomass and/or storage organ, and water productivity). This new unity of purpose research should be conducted on a research farm and up-scaled to rural resource-poor households through participatory action approach.

6.2.2 Variation in nutritional values for selected traditional vegetables and conversion from fresh mass to boiled values

In Chapter 2, key findings showed that nutrient concentration (iron, zinc, and β-carotene) of selected vegetables showed a high degree of variability. Uusiku et al. (2010) attributed the variation in nutrient concentration values to several factors [plant variety among species, environment (soil type and pH), harvesting method, climatic conditions, different seasons, and water availability], which play a major role in determining the nutrient concentration of crops. We further argued (Chapters 2 and 3) that nutritionists do not evaluate the effect of environmental factors (climatic conditions, severe drought conditions, soil fertility, and management) on nutrient concentrations of vegetables (Nyathi et al., 2019b). In addition, we suggested that future research should assess the major factors crucial for determining the nutrient concentration of crops (Chapter 2). Chapter 3 assessed the effect of three-water regimes (well-watered, moderate water stress, and severe water stress) on the nutrient concentration of amaranth, spider flower, and Swiss chard. Key findings of Chapter 3 revealed that nutrient concentration differed across irrigation regimes and seasons (Nyathi et al., 2018b). We suspected that different meteorological conditions during the growing seasons caused the variation in nutrient concentration of selected vegetables. Chapter 3 provided an insight that severe water-stressed conditions improved iron and zinc nutrient concentration of selected vegetables, whereas β-carotene concentration was reduced under severe water stress conditions. However, it was not clear how the other factors (plant variety among species, soil type, pH, harvesting method, climatic conditions, and different seasons) affect the nutrient concentration of selected vegetables?

A study by Uusiku et al. (2010) showed that amaranth nutrient concentration (iron, zinc, and β-carotene) vary among the same species and cultivars. Traditional vegetables have not been bio-fortified for high nutrient concentration. We presume that nutrient concentration vary between the same species and cultivars due to crop management (irrigation and fertiliser application) and genetic makeup. Nyathi et al. (2019a) found that no fertiliser application increased iron and zinc concentrations for orange-fleshed sweet potato storage root, whereas zinc concentration of orange-fleshed sweet potato storage root decreased compared to the fertiliser application at the recommended rate. Fageria and Nascente (2014) iterated that plants absorb nutrient from the soil and nutrient availability is determined by soil texture and soil pH. Soil texture affects the ability of soils to hold water; for example, sandy soils are porous; therefore, most essential nutrients are leached beyond the effective rooting depth. At higher or lower pH levels, soil nutrients form solid precipitates that cannot dissolve in water, which makes soil nutrients not to be available for plant absorption. Kader and Lee (2000) averred that climatic factors such as light, temperature, and vapour pressure deficit have a strong influence on nutrient composition of horticultural crops because these factors influence the process of photosynthesis. In addition, the extent of low and high temperatures determines the growth rate and chemical composition of horticultural crops (Kader and Lee, 2000). Nutritional food insecurity is a major problem in sub-Saharan Africa. Therefore, it is prudent to know which factors determine the nutrient concentration of vegetables. This could provide the base for the simulation of nutritional yield and nutritional water productivity of crops. We propose that future research should identify the major factors that determine the nutrient concentration of vegetables.

In Chapters 2 and 3, we used the United States Department of Agriculture nutrient retention factors (USDA, 2007) to convert the fresh aboveground edible biomass (Table A.2.1) to boiled values, so that we can assess the potential contribution of selected vegetables to the daily-recommended nutrient intake for human nutrition requirements. This is not an ideal practice. However, it provided the estimates of the potential contribution of selected vegetables to human nutrition. We propose that future research should consider assessing the entire value chain of vegetables (from production until consumption). In addition, the method of food preparation (boiling, frying, grilling, and baking) play a crucial role in determining whether nutrients are bio-available inside human bodies. A multidisciplinary (including agronomist, irrigation specialists, food scientists, and chefs) research should be conducted to determine the best methods of food preparation such that nutrients are bio-available for human consumption.

6.2.3 Calibrating and validating crop growth models for repeatedly harvested vegetables

In Chapter 4, we iterated that AquaCrop model version 4.0 is not capable of running sequential harvest at a single run. Although we managed to simulate yield response of selected leafy vegetables, the approach we followed is not a practical solution, especially if one has to run large datasets for many seasons. AquaCrop (http://www.fao.org/aquacrop) is freely available software that requires minimal dataset and easy to use in simulating yield response of crops as a function of water productivity under rainfed, deficit, and full irrigation (Mbangiwa et al., 2019). We propose to the developers of the AquaCrop model to consider adding a crop module that can run sequential harvests in a single run simulation. Vanuytrecht et al. (2014) averred that AquaCrop model developers are considering adding alfalfa (*Medicago sativa*) with conservative parameters. Alfalfa is a repeatedly harvested crop during the growing season. Therefore, its crop file can be modified (using experimental data) to simulate yield response of other repeatedly vegetables such as amaranth, spider flower, and Swiss chard. It is crucial to note that crop models have a limitation in that they cannot account for crop-weed interactions and damage by pests and pathogens (Ewert et al., 2015).

We further noted that the database for AquaCrop model caters for mainstream crops (barley, cotton, maize, Irish potato, Quinoa, sorghum, soybean, sugar beet, sugarcane, sunflower, teff, tomato, and wheat) with conservative parameters. The only vegetable, which is available in the model database, is tomato, whereas vegetables play a crucial role in supplementing essential micronutrients and vitamins for improved nutritional food security. To meaningfully address nutritional food security of the rich and the pro-poor, a paradigm shift is needed to support rural resource-poor households (Mabhaudhi et al., 2018). Future projects should focus on developing conservative parameters for a number of vegetables (Table 6.2) that are consumed by rural resource-poor households. These parameters should be used to calibrate and validate several crop growth models [AquaCrop model, the Soil Water Balance Model (SWB), the Agricultural Production System Simulator model (APSIM), the World Food Studies model (WOFOST), and the Decision Support System for Agrotechnology Transfer (DSSAT)]. Calibrated and validated crop growth models can be used directly to investigate the impacts of climate change on crop productivity under extreme weather conditions (Ewert et al., 2015). Although there is already an existing project: the Agricultural Model Intercomparison and Improvement Project (AgMIP). Its main aim is to improve the sustainability of food security due to climate change and enhance adaptation strategies in developing and developed countries (http://www.agmip.org/). However, this project is for mainstream crops (canola, maize, rice, sugarcane, and wheat). The author of this thesis suggests that the AgMIP project should consider extending its scope and consider including highly nutritious vegetables (Table

6.2) as a strategic intervention to address nutritional food security of rural resource-poor households.

Table 6.2 List of vegetables that are consumed in sub-Saharan Africa

Scientific name	Common name	Seasonality
Beta vulgaris	Swiss chard	summer/winter
Brassica oleracea var. italica	broccoli	summer/winter
Beta vulgaris	beetroot leaves	summer/winter
Vigna unguiculata	cowpea leaves	summer
Curcubita pepo	pumpkin leaves	summer
Ipomoea batatas	sweet potato leaves	summer
Bidens pilosa	blackjack	summer
Cleome gynandra	Spider flower	summer
Amaranth spp.	amaranth	summer
Solanum nigrum	nightshade	summer
Sonchus oleraceus	sow thistle	summer
Brassica oleracea	cabbage	summer/winter
Brassica oleracea	cauliflower	summer/winter
Cucumis sativus	cucumber	winter
Solanum melongena	eggplant	summer
Phaseolus vulguris	green beans	summer
Capsicum annuum	green pepper	summer
Lactuca sativa	lettuce	winter
Pisum sativum	peas	summer
Alium cepa	onions	summer/winter
Daucus carota	carrots	summer/winter
Solanum lycopersicum	tomato	winter
Juglans cineria	butternut	summer

6.2.4 Utilising selected vegetables as dual-purpose food crops

The results of Chapter 5 showed that there is a scope of utilising orange-fleshed sweet potato as a dual-purpose food crop for rural resource-poor households (subsistence-oriented farming) because nutritional yield, water productivity, and nutritional water productivity were improved. In Chapter 2, we averred that vegetables such as beetroot, cowpea, pumpkin, and onions could be used as a dual-purpose food crop. We propose that; (1) the effect of vine harvesting should be assessed on other orange-fleshed sweet potato varieties that might respond differently for selected plant parameters (storage root yield, nutrient concentration, water productivity, nutritional yield, and nutritional water productivity). (2) The effect of leaf harvesting should be assessed on other vegetables (beetroot, pumpkin, cowpea, and onions) that have the potential of being used as a dual-purpose food crop.

Another complexity is the frequency of vine harvesting might determine the severity of storage organ reduction. In Chapter 5, we investigated two harvesting frequencies (no vine harvest and vine harvest every 4 weeks during the growing period), which makes it difficult to suggest the allowed harvesting frequency threshold in relation to storage root yield reduction. A study by Gomes and Carr (2001) assessed five vine-harvesting frequencies in relation to sweet potato storage root yield reduction and found that the highest frequency of vine-harvesting reduces sweet potato storage root yield dramatically. However, Gomes and Carr (2001) study focused on storage root yield only. We propose that future research should investigate the frequency of leaf harvesting on all vegetables that could be potentially used as dual-purpose crops and on several plant parameters (storage organ yield, aboveground edible biomass, nutritional yield, and nutritional water productivity). In addition, there are several leaf harvesting methods that can be utilised; this includes branch cutting, leaf picking, and destructive harvesting (Dinssa et al., 2018). We presume that rural resource-poor households might use various leaf harvesting methods, which could affect storage organ yield accumulation. We further suggest that future research should investigate the effect of various methods of leaf harvesting on storage organ yield of all dual-purpose vegetables. To the best of our knowledge, AquaCrop model has not been calibrated and validated for orange-fleshed sweet potato var. Bophelo in South Africa. We propose that field data collected in Chapter 5 should be used to calibrate and validate the AquaCrop model. This will permit the assessment of climate change mitigation strategies for improved nutritional food security.

6.2.5 Re-introduction of traditional vegetables into the food system

Several authors (Afari-Sefa et al., 2012; Chibarabada et al., 2017; Chivenge et al., 2015; Dube and Fanadzo, 2013; Govender et al., 2017; Misselhorn and Hendriks, 2017; Mabhaudhi et al., 2016; Mabhaudhi et al., 2017a) agreed that traditional vegetables can play a major role in supplementing iron, zinc, and β-carotene.. Therefore, traditional vegetables should be promoted for improved nutritional food security of rural resource-poor households. Misselhorn and Hendriks (2017) indicated that food gardens played a positive role in alleviating nutritional food security in that they can provide seasonal fresh produce. A number of studies confirmed that traditional vegetables played a significant role in ensuring the nutritional food security of rural resource-poor households. For example, in Bushbuckridge, 91 % of rural resource-poor households harvest traditional vegetables from the wild and approximately 27 % consume traditional vegetables on a daily basis (Misselhorn and Hendriks, 2017). In Kwazulu Natal, collection of amaranth was the most applied coping strategy in times of hardships and food insecurity (Misselhorn and Hendriks, 2017). This shows that rural resource-poor households rely on traditional vegetables in times of shock and food scarcity.

Given the evidence presented above, we recommend that traditional vegetables (Table 6.2) should be re-introduced into the current food system, to improve the food basket of sub-Saharan Africa (Mabhaudhi et al., 2018). The re-introduction of traditional vegetables should consider following the smallholder value chain model, which utilises a food-based approach to improve nutritional food security of rural resource-poor households (Wiegers et al., 2011) through; (i) production for household consumption, (ii) the sale of agricultural products to generate income, and (iii) local procurement of nutritious food produced locally to be used for food subsistence programs (Figure 1.1). For example, Mwangi and Kimathi (2006) reported that in Kenya, demand for traditional vegetables increased from 31 tonnes to 600 tonnes per month with an average profit margin of US $ 3803 ha^{-1}, double that achieved with alien vegetables. It is crucial to note that traditional vegetables cannot replace mainstream crops, but they can contribute significantly to dietary diversity (Mabhudhi et al., 2019). We conclude that traditional vegetables can play a significant role in improving the nutritional food security of rural resource-poor households, under the stress of climate change.

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Summary

In sub-Saharan Africa, nutritional food insecurity is a major problem, affecting rural resource-poor households. Micronutrients that are deficient in diets of many rural resource-poor households are iron, zinc, and vitamin A (plants produce β-carotene, which is converted into vitamin A when consumed by humans). The world population is predicted to reach 9 billion people by the year 2050 and the major challenge is how to feed this huge number of people with highly nutritious food and meet their nutritional requirements. The current food system is skewed, focusing on increasing productivity of mainstream crops (maize, wheat, and rice). This means that efforts to address nutritional food security of rural resource-poor households often lack consideration. We acknowledge the crucial role played by mainstream crops is meeting protein-energy requirements; however, mainstream crops are deficient in essential micronutrients (iron and zinc) and vitamin A. Therefore, there is a need for a paradigm shift that will focus on delivering highly nutritious food per unit of resources used (land area, fertiliser, water, and agro-chemicals). Different approaches meant to improve nutritional food security in sub-Saharan Africa have been tested; this includes bio-fortification of essential micronutrients (iron, zinc, and β-carotene) through the breeding of staple crops such as maize, cassava, sweet potato, and rice. However, staple crops take a long period to mature when compared to traditional vegetables. The benefits of traditional vegetables over staple crops are; (i) their high nutrient density (iron, zinc, and β-carotene) and more productive in terms of biomass, nutritional yield, and nutritional water productivity, (ii) short crop growth cycle, (iii) the low use of agronomic inputs, their abundance in the ‘‘wild’’ or next to mainstream crops, (iv) their high productivity under sub-optimal conditions, and (v) they can be harvested in small quantities, without the need for storage. This makes traditional vegetables champion species in areas experiencing high levels of nutritional food insecurity; therefore, traditional vegetables can play a significant role in alleviating nutritional food insecurity of rural resource-poor households through dietary diversity. However, information on these benefits has never been tested and proven using data [biomass (aboveground biomass and/or storage organ), nutrient concentration, and evapotranspiration].

The main objective of this thesis was to evaluate nutritional water productivity of traditional vegetables. To address the main objective, the following research questions were formulated: (1) Are traditional vegetables superior to alien vegetables for selected plant parameters (aboveground biomass plus stems and/or storage organ, nutrient concentration, nutritional yield, and nutritional water productivity)? (2) Are traditional vegetables [spider flower (*Cleome gynandra*) and amaranth (*Amaranthus cruentus*)] superior to an alien vegetable [(Swiss chard (*Beta vulgaris*)] in terms of biomass (aboveground edible biomass plus stems), nutrient concentration, nutritional yield, and nutritional water productivity? (3) Can the AquaCrop model be calibrated and validated for repeatedly harvested vegetables such as amaranth, spider flower, and Swiss chard? (4) What is the effect of utilizing orange-fleshed sweet potato (*Ipomoea batatas* var. Bophelo) as a dual-purpose food crop (green leafy vegetable and storage root for human consumption) on the storage root yield?

Chapter 2 assesses nutritional water productivity [NWP = (aboveground edible biomass and/ or storage organ biomass/actual evapotranspiration) × nutritional content of a product] of ten traditional vegetables and compared them with ten alien vegetables. For this purpose, vegetables that are widely utilised by rural resource-poor households were selected. A comprehensive literature search was conducted using databases such as Google Scholar, Scopus, CAB Abstracts, and Web of Science. Data [biomass (aboveground biomass and/ or

storage organ), water use, and nutrient concentration] sourced from the literature were used to compute water productivity, nutritional yield, and nutritional water productivity of selected vegetables. Using the review, we show that alien vegetables are more productive than traditional vegetables in terms of biomass (aboveground biomass and/or storage organ). In addition, we further illustrate that traditional vegetables are superior in nutritional yield (iron and zinc nutritional yields) and nutritional water productivity (iron and zinc nutritional water productivities) of micronutrients. Alien vegetables were rich in β-carotene nutritional yield and β-carotene nutritional water productivity; this is contrary to the anecdotal information. Although data used to generate the nutritional water productivity of selected vegetables came from two independents data sets (crop water productivity and the nutrient concentration databases), both with some level of uncertainty, first-order estimates of nutritional water productivity of selected vegetables were established and they serve as a benchmark.

Chapter 3 evaluates the effect of irrigation three irrigation regimes (well-watered treatment, moderate water stress treatment, and severe water stress treatment) on nutritional water productivity of amaranth (*Amaranthus cruentus*), spider flower (*Cleome gynandra*), and Swiss chard (*Beta vulgaris*). Using the shortfall of assessing nutritional water productivity of selected vegetables using datasets [biomass (aboveground biomass and/ or storage organ), water use or evapotranspiration, and nutrient concentration] sourced from literature (Chapter 2), experiments were conducted under a rain shelter at the Agricultural Research Council, vegetables and ornamental plants, in Pretoria South Africa, during two consecutive seasons (2014/15 and 2014/15). We used the data collected from the experiments to compute nutritional yield and nutritional water productivity of selected leafy vegetables. Our results show that a C_3 plant (Swiss chard) was more efficient than C_4 plants (amaranth and spider flower) in converting intercepted radiation into dry matter, contrary as suggested by the literature. We presume that more energy was required to produce total aboveground biomass (lignified stems and leaves) for amaranth and spider flower when compared to Swiss chard. In Chapter 3, we demonstrate that amaranth and spider flower are more nutrient dense (iron, zinc, and β-carotene) than Swiss chard. However, higher nutrient denseness did not translate to superior nutritional yield. Swiss chard exhibited higher iron and zinc nutritional yields, whereas amaranth displayed higher β-carotene nutritional yield. Similarly, Swiss chard was the most productive leafy vegetable per unit of water used to produce iron and zinc, whereas amaranth was the most productive vegetables to produce β-carotene per unit of water used. The added advantage of Swiss chard over amaranth and spider flower for higher nutritional yields and nutritional water productivities for micronutrients is its higher harvest index. Using the findings of Chapter 3, we show that there may be an opportunity to improve nutritional water productivity under drought conditions.

In Chapter 4, we calibrated and validated the AquaCrop model version 4.0 for repeatedly leafy vegetables (amaranth, spider flower, and Swiss chard) using field experiments data (Chapter 3). The AquaCrop model (version 4.0) is not capable of running sequential harvests in a single run to simulate yield response of repeatedly harvested vegetables during the growing period. In this Chapter, we show that it is possible to calibrate and validate AquaCrop model by assuming that after each harvest; approximately 1-2 % of canopy cover is left on the plot, which becomes the initial canopy cover for the subsequent cover. The AquaCrop model was calibrated and validated for canopy cover, aboveground biomass, soil water content, evapotranspiration, and water productivity. We compared the model output with measured plant parameters. In Chapter 4, we show that there was a good fit ($0.60 < R^2 < 0.99$, $0.94 < RMSE < 5.44$, and $0.04 < RSR < 0.79$) between measured and simulated values for the well-water treatment. However, the fit for the water-stressed treatment was not good as for the well-watered treatment for canopy cover, soil water content, evapotranspiration, and water productivity. We further demonstrate that water productivity of C_4 leafy vegetables (amaranth and spider flower) was superior to the water productivity of a C_3 leafy vegetable (Swiss chard). In Chapter 3, we noted that the AquaCrop model caters for mainstream crops, neglecting dark green leafy vegetables, which play a major role in supplementing essential micronutrients. Although we managed to calibrate and validate the AquaCrop model for repeatedly harvested leafy vegetables, the procedure is not practical, especially when there is a need to simulate yield response of huge dataset and for many seasons, for repeatedly harvested vegetables. We proposed that the model developers should consider adding a crop module that will run sequential harvests in a single run.

In Chapter 5, we assessed the potential of utilising orange-fleshed sweet potato var. Bophelo as a dual-purpose food crop; green leafy vegetable and the storage root. In South Africa, the practice of consuming the aboveground edible biomass as a green leafy vegetable, additional to the storage root is not common, whereas nutritional food insecurity is pervasive, affecting rural resource-poor households. In the decades to come, the world population is predicted to increase, therefore, coping strategies to balance nutritional food security of rural resource-poor households will be needed. We conducted field experiments assessing the effect of two vine harvest (no vine harvesting and vine harvesting every four weeks), irrigation regimes (well-watered and supplemental irrigation), and soil fertilisation (well-fertilised and no fertiliser application) on selected plant parameters (water productivity, leaf and storage root nutrient concentration, nutritional yield, and nutritional water productivity). In this Chapter, we show that utilising orange-fleshed sweet potato (var. Bophelo) is not an ideal practice for market-oriented farming, because of the marketable storage root yield decrease by approximately half. However, for subsistence-oriented farming (rural resource-poor households), utilising orange-fleshed sweet potato as a dual purpose food crop makes more sense, as the aboveground edible biomass is available for human consumption during the growing season. At the end of the growing season (winter period in South Africa), the storage roots can be consumed. This spreads food availability over two seasons, hence an improvement in nutritional food security of rural resource-poor households. In addition, utilising orange-fleshed sweet potato as a dual-purpose food crop improved nutritional yield and nutritional water productivity of selected nutrients (iron, zinc, and β-carotene). In this Chapter, we show that there is an opportunity of using orange-fleshed sweet potato as a dual-purpose food crop for rural resource-poor households. Therefore, we encourage rural resource-poor households to produce orange-fleshed sweet potato for their own consumption and the surplus could be sold at a local market.

Chapter 6 discusses the main findings of this thesis. In this Chapter, we draw conclusions about the main research findings in each of the research questions addressed for the four main Chapters. We benchmarked the nutritional water productivity of selected vegetables using datasets from different literature sources and field experiments. In addition, we calibrated and validated the AquaCrop model to make the results of this thesis generic and show that orange-fleshed sweet potato can be used as a dual-purpose food crop. Lastly, we discuss additional steps that have to be undertaken in order to improve the nutritional food security of rural resource-poor households and propose that traditional vegetables should be ‘‘re-introduced" to the current food system for dietary diversity of rural resource-poor households.

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A PhD is like engaging in a journey, which requires intrinsic motivation, respect, humbleness, and teamwork. Let me share with you the journey of my PhD ; from the start up to finishing. I thank all the people who supported me during the last six years of my PhD trajectory.

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Gerardo, I remember showing up at your office in 2011, to discuss the possibility of you becoming the supervisor of my MSc. Thesis; calibrating and validating AquaCrop model for Swiss chard. You showed enthusiasm and immediately suggested that you know someone at the University of Pretoria (Prof. John Annadale) who can assist with hosting the research in South Africa. You immediately sent him an email and everything became well organised. Before I could finish my MSc. you suggested that I should consider doing a PhD, which was already in my mind. We immediately applied for the WASS scholarship award and got a rejection. Thereafter, we applied for the NUFFIC grant and got a rejection. You never gave up on me and we strategised that I should study at the University of Pretoria and go to Wageningen University as a visiting student. While I was sitting at work (the Agricultural Research Council), I received an email from you stating that the NUFFIC scholarship has become available; I needed to make an immediate decision to accept it. At first, I could not believe it, but I said yes to the opportunity. That is how I ended up with the water Resource Management Group, at Wageningen University. You have been a good mentor to me through your research ideas, which sometimes confused me, but we managed to strike a balance.

Prof. John Annandale, we met through Gerardo and you suggested that I should conduct my field experiments at the Agricultural Research Council, Vegetables and Ornamental Plants, Pretoria, South Africa. At first, I was a little bit sceptical about this suggestion because I did not know anyone there. Little did I knew that it was the best suggestion, because I ended up being employed by the Agricultural Research Council. Through you, I met Dr Beletse who became my mentor at the Agricultural Research Council. You further took me under your wings when we discussed about the possibility of pursuing my PhD at the University of Pretoria by paying for my modules (advanced statistics, research methodology, and environmental biophysics). It was through you that I met Dr Backeberg (former agricultural water management research manager at the Water Research Commission of South Africa). Little did I knew that the Water Research Commission was going to play an important role in funding my PhD research through their project, which needed a student for capacity building. They entrusted me with running the project through the Agricultural Research Council. Your critical feedback on the four manuscripts I wrote and submitted to the Agricultural Water Management Journal groomed me to be an independent scientist. Thank you Prof. Annandale, I look forward to future collaborations to come.

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Melvin Nyathi

Wageningen, 01 August 2019

Publications

<u>Peer-reviewed journals:</u>

Nyathi, M.K., Mabhaudhi, T., Van Halsema, G.E., Annandale, J.G., Struik, P.C., 2019b. Benchmarking nutritional water productivity for twenty vegetables- A review. Agric. Water Manag. 221, 248–259. https://doi.org/10.1016/j.agwat.2019.05.008

Nyathi, M.K., Van Halsema, G.E., Beletse, Y.G., Annandale, J.G., Struik, P.C., 2018b. Nutritional water productivity of selected leafy vegetables. Agric. Water Manag. 209, 111–122. doi:10.1016/j.agwat.2018.07.025

Nyathi, M.K., Halsema, G.E. Van, Annandale, J.G., Struik, P.C., 2018a. Calibration and validation of the AquaCrop model for repeatedly harvested leafy vegetables grown under di ff erent irrigation regimes. Agric. Water Manag. 208, 107–119. doi:10.1016/j.agwat.2018.06.012

Nyathi, M.K., Plooy, C.P. Du, Halsema, G.E. Van, Stomph, T.J., Annandale, J.G., Struik, P.C., 2019a. The dual-purpose use of orange-fleshed sweet potato (Ipomoea batatas var . Bophelo) for improved nutritional food security. Agric. Water Manag. 217, 23–37. doi:10.1016/j.agwat.2019.02.029

<u>Other publications:</u>

Nyathi, M.K., Annandale, J.G., Beletse, Y.G., Beukes, D.J., Du Plooy, C.P., Pretorius, B., Van Halsema, G.E., 2016. Nutritional Water Productivity of Traditional Vegetable Crops. Water Research Commission (WRC 2171/1/16), Pretoria, South Africa. ISBN:978-1-4312-40-1. www.wrc.org.za.

<u>Conference proceedings/ posters/ talks and contributions:</u>

Nyathi, M.K.**,** Beletse, Y.G. , Du Plooy, C.P., Van Halsema, G.E., Annandale, J.G., Buekes, D.J., Pretorius, B. 2016. Nutritional water productivity of traditional vegetable crops. World nutrition conference, University of Western Cape, 30 August- 2 September 2016.

Nyathi, M.K**.,** Beletse, Y.G., Du Plooy, C.P., Van Halsema, G.E., Annandale, J.G., Buekes, D.J., Pretorius, B. 2016. Nutritional water productivity of traditional vegetable crops. African Association of Agricultural Economists, Addis Ababa, 23 - 26 September 2016.

Nyathi, M.K., Beletse, Y.G., Du Plooy, C.P., Van Halsema, G.E. 2014. Nutritional water productivity of orange fleshed sweet potato (*bophelo*) for selected micronutrients (iron and zinc) and β-carotene. International Horticultural Conference, Brisbane, Australia, 17-22 August.

Nyathi, M.K**.**, Beletse, Y.G., Du Plooy, C.P., Van Halsema, G.E. 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.

Nyathi, M.K., Beletse, Y.G., Du Plooy, C.P. 2013. Water productivity of selected traditional leafy vegetables. A poster presented at the 3rd Global Conference on Agriculture, Food and Nutrition Security and Climate Change. Johannesburg, South Africa, 3 – 5 December.

Nyathi, M.K**.**, Beletse, Y.G., Du Plooy, C.P., Van Halsema, G.E., Nembudane, S. 2013. Water productivity of Spider Plant (*Cleome gynandra L.*). A poster presented at the Global Food Security Conference, The Netherlands, 29 September – 03 October.

Nyathi, M.K., Beletse, Y.G., Du Plooy, C.P., Van Halsema, G.E., Annandale, J.G., Buekes, D.J., Pretorius, B. 2016. Water use and food security-A nutritional water productivity perspective. SANCID symposium, Worcester, Cape Town, 11-13 October.

Nyathi, M.K., Annandale, J.G., Wenhold, F., Steyn, J.M., Van der Laan, M. 2012. Nutritional water productivity: An emerging approach for tackling malnutrition in South Africa, SANCID 2012 Symposium, Alpine, Drakensberg, 20-23 November 2012.

Nyathi, M.K., Beletse, Y.G., Du Plooy, C.P. 2012. Nutritional Water productivity of Traditional leafy vegetables: A Review presented at the Combined Conference, University of KwaZulu-Natal, Westville Campus, Durban, 21-24 January.

Nyathi, M.K., Beletse, Y.G., Du Plooy, C.P., Van Halsema, G.E. 2014. Effects of water and fertility stresses on nutritional yield of two traditional leafy vegetables. ASSAf conference, 14-16 October.

Nyathi, M.K., Fessehazion, MK, Du Plooy, C.P., Molopo, K., Van Halsema, G.E. 2016. Water productivity of traditional leafy vegetables. Combined Conference University of Free state, Bloemfontein, South Africa, 23-27 January.

Nyathi, M.K, Fessehazion, M.K., Du Plooy, C.P., Molopo, K., Van Halsema, G.E. 2016. Tackling hidden hunger with orange-fleshed sweet potato leaves. A poster presented at the Combined Conference, University of Free State, Bloemfontein, South Africa, 23-27 January.

Nyathi, M.K., Fessehazion, M.K., Du Plooy, C.P., Khoza, J., Van Halsema, G.E. 2016. Nutritional yield of Amaranth and Spider flower. A poster presented at the first African young water professional, CSIR, Pretoria, South Africa, 16-18 November.

Nyathi, M.K., Du Plooy, C.P., Van Halsema, G.E., Stomph, T.J,. Annandale, J.G., Struik, P.C. 2019. The dual-use of orange-fleshed sweet potato for improved nutritional food security, Combined Congress, Bloemfontein, South Africa, 20-23 January.

Short biography

Melvin Kudu Nyathi was born on 6 March 1984 in Xanthia, Bushbuckridge, South Africa. When he was very young, his mother took him to Swaziland, where he stayed with his grandparents. From 1988 to 1995, he attended his primary education at Good Shepherd primary school, which was approximately 4 km from his homestead. After school, Melvin Kudu Nyathi enjoyed heading cattle with his mates, hunting birds using a catapult, and fetching water from the nearby ground water source. These activities groomed him as a young boy and taught him responsibility. He was always achieving the highest marks in mathematics, natural science, and home economics. From 1996 to 1998, Melvin Nyathi attended his secondary school at Good Shepherd High School, where he continued to do well in his studies. Unfortunately, his mother lost her job when he accomplished his secondary education level, passing with a first class. His stepmother (Zodwa Dlamini) took him to a town called Matsapha, where he enrolled at Swazi National High School and accomplished his high O'level in 2000.

Thereafter, Melvin obtained the Swazi Government scholarship, which paid for his studies at the University of Swaziland, Luyengo campus, to pursue a Diploma in Agricultural Sciences. After graduating with his Diploma in Agricultural Sciences (2005), he immediately pursued a Bachelor of Sciences in Land and Water Management with the same University and Graduated (2007) with a first class. Thereafter, he went back to Bushbuckridge and got a job as a teacher at Mzila High School where he was teaching Mathematics, Life Sciences, and Agricultural Sciences at FET level. His passion was to further his studies; while he was pursuing his Bachelor, Melvin used to tell his friends that he would pursue his Masters overseas. His dream came true when he Googled and the Masters in Land and Water Management and Wageningen University came on top of the Google search. Melvin Nyathi immediately applied and got an admission within two weeks. His Programme was starting in August 2008. However, he did not have a scholarship to pay for his Master's Programme. Melvin Nyathi applied for the prestigious Ford Foundation, which granted him an award to pursue his Masters, which happened between 2009 and 2011. The Agricultural Research Council, Vegetables and Ornamental Plants, in Pretoria, employed Melvin Nyathi as a researcher immediately after graduating. In 2013, he was awarded a grant by NUFFIC to pursue his PhD in Water Resources management, under the supervision of Prof. Paul Struik, Dr Gerardo Van Halsema, and Prof. John Annandale. His PhD provided him with many opportunities to travel the world and presenting his initial results in five international conferences. Melvin's current research interests are related to nutritional water productivity of crops, climate change, crop modelling, remote sensing, and human nutrition.

Melvin Kudu Nyathi
Wageningen School of Social Sciences (WASS)
Completed Training and Supervision Plan

Name of the learning activity	Department/Institute	Year	ECTS*
A) Project related competences			
Environmental biophysics	Plant and soil Science, University of Pretoria	2013	3
Scientific communication	Plant and soil Science, University of Pretoria	2013	6
Research Methodology	Plant and soil Science, University of Pretoria	2013	3
Writing a research proposal	WRM, Wageningen University	2013	3
'Assessment of nutritional water productivity & improvement strategies for traditional leafy vegetables in South Africa'	WRM, Wageningen University	2013	1.5
B) General research related competences			
WASS introduction course	WASS	2013	1
Techniques for writing and presenting a scientific paper	WGS	2014	1.2
Reviewing a scientific paper	WGS	2014	0.1
Elsevier publishing (Preparing your manuscript, structuring your manuscript, using proper scientific language, grant proposals)	Elsevier academy	2015	1
Advanced statistical modules (Linear models, mixed linear models, generalized linear models & Introduction to R statistical analysis)	PE&RC, Wageningen	2013-2015	2.7
Scientific writing and communication	ACP-EU	2015	3
C) Career related competences/personal development			
Supervision of students	ARC, South Africa	2013-2016	3.4
Information literacy	WGS, Wageningen University	2013	0.6
Hunger defeated long term Dynamics of global food security	PE&RC, Wageningen University	2013	2
'Nutritional water productivity of traditional vegetable crops'	World Nutrition Conference, South Africa	2016	1
'Nutrional water productivity of orange fleshed sweet potato (Bophelo) for selected micronutrients (iron and zinc) and ß-Carotene'	29th Int. Horticultural Conference, Brisbane, Australia	2014	2
Simulating yield and water use of selected African Leafy vegatables'			
'Effects of abiotic stresses and leaf harvesting on nutritional yield of sweet potato'	Nat. conference on global change, Port Elizabeth, South Africa	2014	1

'Nutritional yield of amaranth and spider flower'	1st Young Water professionals conference, Pretoria, South Africa	2015	1
'Water productivity of Spider Plant (Cleome gynandra L.)'	Global Food security Conference, The Netherlands	2013	1
Business Management and entrepreurship	ALISON	2015	0.75
Human Resources	ALISON	2015	0.6
Teaching skills for educators	ALISON	2015	0.6
Total			**39.45**

*One credit according to ECTS is on average equivalent to 28 hours of study load

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