ESTIMATION OF THE VOLUMETRIC WATER FOOTPRINT OF CARROT (*DAUCUS CAROTA* L.) AND SWISS CHARD (*BETA VULGARIS* L.) GROWN IN GAUTENG PROVINCE, SOUTH AFRICA

by

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Agronomy in the Department of Plant and Soil Sciences
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DECLARATION

I hereby declare that the dissertation submitted by me for the qualification Masters in Agriculture degree at the University of Pretoria is my own independent work and has not previously been submitted by me at another University/faculty for a degree either in its entirety or in part.

Signed: Matlala Matswatswe Nosey

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ABBREVIATIONS

CWR	Crop Water Requirement
D	Drainage
ET	Evapotranspiration
FW	Fresh weight
IR	Irrigation requirement
IS	Irrigation scheduling
LCA	Life cycle assessment
PET	Potential evapotranspiration
R	Runoff
RSA	Republic of South Africa
SWB	Soil water balance
VWC	Volumetric water content
WF	Water footprint
WFD	Wetting front detectors
WFN	Water Footprint Network
WP	Water productivity
WUE	Water use efficiency

ABSTRACT

This study estimated the total volumetric water footprint (WF) of two vegetable crops, a root vegetable crop (carrot) and a leafy vegetable crop (Swiss chard) grown in Gauteng Province, South Africa. South Africa is a water scarce country and demands for food have increased due to population growth, and hence more water is required to ensure sufficient production or more efficient production methods. However, this is unlikely with dwindling water resources and the increased production of high value horticultural crops that are dependent on irrigation to ensure sufficient and profitable yields. To date, irrigation water efficiencies are often low, and there is still a lack of information on the long-term sustainability of water for current and future food production. WF accounting can potentially provide better information on the impact of human activity, such as crop production under irrigation, on water resources and to guide a more sustainable management of these resources.

The Soil Water Balance (SWB-Sci) model was used together with field trials to estimate crop evapotranspiration (ET) and the volumetric blue water footprint (WF_{blue}) and green water footprint (WF_{green}) of carrot (*Daucus carota L*.) and Swiss chard (*Beta vulgaris L*.) grown at different planting dates in different locations in Gauteng Province, South Africa. The volumetric grey water footprint (WF_{grey}) was estimated separately from WF_{blue} and WF_{green} because of the difference in methodology. Field trials were established at the UP Hatfield Experimental Farm and Greenway Farms in Tarlton to monitor carrot and Swiss chard (Hatfield only) growth and water use over two seasons (summer, autumn). For Swiss chard, the volumetric WF_{blue} and WF_{green} was measured at three harvest interval dates in each of the two seasons (summer and autumn).

At the different planting dates, seasonal ET of carrot grown at Tarlton was relatively lower than seasonal ET of carrot grown at Hatfield in the summer growing season and relatively higher than for autumn growing seasons. High crop yields obtained at Tarlton reduced the total volumetric WF of carrot, which was relatively lower than for carrots grown at Hatfield in autumn and summer. There were differences in the ratio of blue/green water use in addition to the volumetric WF_{blue} and WF_{green} throughout the different growing seasons. During the summer growing season at Hatfield, the

crop water requirements were met by green water even though blue water was used as a supplement. However, in autumn crop water requirements were met only by blue water resources as the autumn season is categorised by cool and dry weather conditions with the absence of rainfall. As a result of different agronomic practices at the two locations, WF_{grey} in Tarlton was relatively higher than the WF_{grey} for Hatfield in summer and autumn. On average, the volumetric WF of carrot was less than 200 L kg^{-1} for all growing seasons, with the highest carrot volumetric WF obtained for the summer growing season at Hatfield (182 L kg^{-1}) , followed by autumn grown carrot crop at Hatfield (179 L kg^{-1}) and then carrots grown for the autumn growing season at Tarlton (155 L kg^{-1}). The difference in planting dates, crop management, weather conditions and environmental characteristics influenced the total water use and volumetric WF of carrot at different planting dates for the two locations.

Swiss chard was grown in the two growing seasons with the average yield measured at three harvest intervals because Swiss chard has the ability to re-grow, thus several harvests can be made for one sowing date. Therefore, it was hypothesized that Swiss chard would have a relatively lower WF than other similar crops which cannot be harvested multiple times. For the summer growing season, water use was met by both blue and green water resources, with high crop water requirements observed for the first harvest, followed by the 3rd harvest and then the 2nd harvest. The same trend was observed for the autumn growing season even though crop water requirements were met using blue water resources exclusively. During the summer growing season, the highest Swiss chard yield was observed during the 1st harvest, with the 2nd and 3rd harvest yields. Similar trends were also observed for autumn growing season with the reduction in plant size.

Swiss chard consumptive WFs for different harvests were observed to decrease following the first harvest, potentially due to the fact that the crop had already established a root system. The WF_{grey} of Swiss chard grown in autumn was slightly higher than in summer due to differences in crop yield and nitrogen (N) leaching. For the two growing seasons, autumn-grown Swiss chard had higher total volumetric WF of 222 L kg^{-1}, while the summer Swiss chard had a total volumetric WF of 140 L kg^{-1}. The variation in the summer and autumn production results from different weather conditions where high temperatures in the summer season increased crop water use, driven by the higher atmospheric evaporative demand, while cooler temperatures in autumn led to a longer growing season.

Although vegetable production is dependent on irrigation water, green water clearly remains to be an essential component in ensuring food security in Gauteng Province. Thus, effective use of rainwater can help reduce the use of blue water resources and decrease pressure on scarce freshwater resources, especially in semi-arid regions. However, optimal management to ensure high crop water use efficiency and yield may contribute significantly to reducing blue water use in food production. Most importantly, the results illustrate the importance of separating blue and green water use in order to get reliable results on how production influences water availability thus ensuring sustainability. For future research it is important to consider the possibility of growing each crop in a season where it is more efficient, and to focus on the reduction of blue water resources for each of the different study sites.

GENERAL INTRODUCTION

Water is a natural resource which plays an essential role in ecosystems and all human activities, most importantly, food production (Fereres et al., 2011). It is a scarce resource in many parts of the world and is continuously under pressure due to population growth, climate change and competition among the agricultural, domestic and industrial sectors (Oki and Kanae, 2006). According to Postel (1998), the change in food preferences in a rapidly growing population will increase demand on water resources, which is predicted to exceed supply by the year 2050, especially in regions already experiencing high water stress.

Climate change is expected to reduce food production as a result of increased temperatures, modified rainfall intensities and drought (Mukheibir and Sparks, 2006, Quezada et al., 2011). The impact of these factors will not only affect food production but also catchment hydrology and the availability of water resources needed for the continual growth of the different sectors. The reallocation of agricultural water to other users is also expected to increase in future due to the intensification in water scarcity, thus affecting a range of production systems, and raising the importance of using water more efficiently (Fereres et al., 2003, Speelman et al., 2008).

In previous decades, challenges of water scarcity and improving food production were partly addressed by the expansion of irrigation land, but further potential increases are constrained due to limited water resources for existing irrigation schemes (Yang and Zehnder, 2002). The production of food in water limiting areas is reported to be particularly unstable in water scarce countries where local production must be supplemented by importing food products from elsewhere. Among the different scopes that influence food security issues, water availability for food production has become the most critical (Fereres et al., 2011). This includes sub-Saharan African countries and South Asia where water scarcity has already been experienced (Kamara and Sally, 2003).

Agriculture is the largest user of freshwater and accounts for 70% consumption of the world's freshwater (Hoogeveen et al., 2009, Deurer et al., 2011). In addition to being the largest user, agriculture is considered to be one of the leading sectors that contribute to water pollution (Herath et al., 2013). Dabrowski et al. (2009) reported that intensive agriculture's use of water and agrochemicals potentially have a negative impact on the environment due to salt accumulation and water pollution that result in degradation of water resources. This does not only put pressure on the availability of water resources in general, but also poses threat on future sustainability of irrigated agriculture and therefore food production.

A shift of production from cereal crops to high-value horticultural crops has also increased the intensity of water scarcity, as the latter has large water requirements to ensure high yields (Clothier, 2010). Even with cereal production expected to increase by 40% in the next decade, cultivation of high-value horticultural crops is also set to increase because of their potential to provide high financial returns, especially during dry seasons (Gawel and Bernsen, 2013). In South Africa (RSA), 90% of fruit and vegetable crops rely on irrigation as a result of low erratic rainfall patterns that are unevenly distributed throughout the seasons (Annandale et al., 1999, Speelman et al., 2008). Furthermore, the effect of climate change on environmental factors, particularly droughts, erratic rainfall patterns and increased temperatures provide a potential risk of depleting freshwater resources.

In irrigated agriculture water is mainly lost through transpiration, which is a productive loss, while the key three unproductive losses are evaporation, runoff and deep percolation (Fereres et al., 2003, De Pascale et al., 2011). Therefore, it is important to monitor different water losses and manage accordingly in order to maximize production while using less water. This will not only help in minimizing water loses, but it will also improve the knowledge on water productivity (WP) of the specific cropping systems. Raising WP in irrigated agriculture will help increase the net water savings that can be diverted to the domestic and industrial sectors. As reported by Verstraeten et al. (2008), evapotranspiration (ET) differs in magnitude for different crop species and growing locations. Thus improving WP in both irrigated and rain-fed agriculture will play an essential role in addressing increasing water scarcity.

In order to account for weather variability, different crop models have been used to better understand crop water use and identify knowledge gaps, allowing improved efficiency and targeted research planning (Oteng-Darko et al., 2013). These models have also been used with the aim to monitor crop growth, crop yield predictions, field management recommendations, agricultural production potential evaluation and climate change impact evaluation (Murthy, 2004). Although these models simulate the current agricultural issues, conditions change with time. Mechanistic models that are based on sound physiological data are usually best able to support extrapolation to alternative cropping cycles and locations, thus permitting the quantification of temporal and spatial variability (Lobell et al., 2006).

In order to account for water challenges the water footprint (WF) concept was developed to serve as a metric that indicates freshwater use and impact as a result of human activities (Hoekstra and Chapagain, 2007b, Herath et al., 2013). It is a research tool that enhances understanding and addresses concerns in the context of water shortages and pollution (Lassche, 2013). Furthermore, WF accounting does not only monitor consumption volumes, but also specifies the sources of the water used together with the location and timing (Jefferies et al., 2012). It may also one day have the potential to support product labelling, especially of food products to provide consumer awareness on water use, particularly under irrigation (Herath et al., 2013). It can also be estimated for an individual, goods or services, a town or nation, taking into consideration the amount of freshwater resources available, thus being able to indicate impact on freshwater systems, potentially informing strategic plans to reduce this impact (Jefferies et al., 2012).

According to Hoekstra (2013), the total WF is made up of blue, green and grey WF components. The WF_{blue} refers to the volume of surface water and groundwater consumed during the production of a good or service. Consumption is defined as the volume of freshwater that is used and lost through evaporation, transpiration or is incorporated into a product. The WF_{green} refers to the volume of green water resources that are consumed via ET during the production process (rainwater that is stored in the soil). The WF_{grey} refers to the volume of freshwater that is needed to dilute pollutant loads to ambient water standards (Aldaya et al., 2012). Using the WF concept, several studies have been completed and many more are underway (Hoekstra and Hung, 2002, Chapagain et al., 2006, Chapagain and Hoekstra, 2007, Hoekstra and Chapagain, 2007a, Hoekstra and Chapagain, 2007b, Chapagain and Orr, 2009, Aldaya et al., 2010, Mekonnen and Hoekstra, 2011a, Gerbens-Leenes et al., 2013, Chouchane et al., 2015, Pahlow et al., 2015). These include the estimation of the WF for a nation, region or product. Many of these studies focussed on the estimation of the WF on large scales, which according to Aldaya et al. (2012), are essentially to provide awareness. However, with the continued deterioration of groundwater resources, drying of rivers and worsening of pollution, site-specific studies have shown to be more informative than when using a wider location like a catchment, river basin or nation where more than one activity occur (Multsch et al., 2013). These are supported by Chapagain and Orr (2009), who indicated that site specific studies particularly at field scales, show a more meaningful value of the WF, as the impacts of all crops or a single crop on a farm can more easily be addressed. Transparency of water use by a single product can create a better understanding on the available water resources at local scales. The difference in the value of the WF for a single product is, however, strongly influenced by geographic variation and site-specific conditions, crop characteristics and different managements systems (Kongboon and Sampattagul, 2012).

To date, irrigation efficiencies have been shown to be low for many regions around the world and there is still lack of information on the long-term sustainability of water for current and future food production (Kang et al., 2009). WF accounting can potentially provide better information on the impact of a human activity, such as crop production under irrigation, on local water resources and to guide a more sustainable management of these resources.

The objectives of this study are to:

(i) Improve understanding of the impact of planting date as influenced by different growing seasons, management practice and growing location on the volumetric water footprint of carrot grown in Gauteng Province, as Greenway farms in Tarlton are major carrot producers in South Africa,

(ii) Estimate the volumetric blue and green WFs of Swiss chard (which is an easily grown leafy vegetable crop that has the ability to re-grow for one sowing date) and assessing the impact of planting date and 1st, 2nd or 3rd harvest event,

(iii) Estimate and compare the grey volumetric WF of carrot and Swiss chard grown in Gauteng Province, South Africa.

Hypotheses of this study include:

(i). On commercial farms, excess water and agrochemical are used to ensure production and profitable yields, whereas on small research trials, water and agrochemicals are easily controlled, thus the sum of WF_{blue} and WF_{green} are expected to be higher in Tarlton than in Hatfield,

(ii). In summer growing season, the average temperatures are high, which increases atmospheric evaporative demand thus the frequency of irrigation and therefore, the sum of WF_{blue} and WF_{green}. In autumn, the average temperatures are lower, which reduces the atmospheric evaporative demand thus the frequency of irrigation and therefore, the sum of WF_{blue} and WF_{green}.

(iii). The growth and development of carrot is longer than that of Swiss chard thus higher water footprint values are expected for carrot.

(iv). Nitrogen is easily leached down the root zone, especially in cases of excess water, that is more likely to occur during the rainfall season, therefore, WF_{grey} is more likely to be higher in summer than in autumn.

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Literature review

1.1. The water footprint (WF) concept

1.1.1. Background

The water footprint (WF) concept builds on the virtual water concept that was developed in the early 1990's to study the impact of imported products as compared to those produced domestically in a country with limited water resources (Wiedemann and McGahan, 2010). The virtual water concept is defined as the volume of water used to produce a product, measured at the place of origin (Hoekstra, 2008a). The term 'virtual' indicates that most of the water used to produce the product is not contained in the product. The real water content is generally a negligible component of the virtual water content. Early work was done by Allan (1998) to describe water needed to produce traded commodities such as food products, especially in water-stressed economies, such as those commonly found in the Middle East. This concept provides an understanding of virtual water trading (particularly imports) where water is 'transferred' from one country to another, for example, indicating freshwater use (irrigation water) of one commodity grown in a water rich country, while saving water in a region with limited water resources (Chapagain and Orr, 2009).

Unlike the virtual water concept that quantifies only the amount of water consumed by the product during production, the WF is defined on the basis of actual water use in the country of origin per unit of product produced (Hoekstra et al., 2009). It serves as a multidimensional indicator that calculates the volume of water used by a product and also indicates the location, sources of water used and impact on local freshwater resources (Holcomb, 2011). The WF can be used to understand water used by a product, a consumer (e.g. individual or family, community, town or province) or other entity (e.g. public organisation, private sector or the whole economic sector) (Galli et al., 2012). This is done by quantifying the effect of water consumption and pollution due to a specific human activity, making it a potentially useful tool for integrated water resources management where it can assist in decision making and policy actions (Hoekstra and Mekonnen, 2012).

Traditionally, water resources were managed by focusing on measuring water withdrawals for the domestic, agricultural and industrial sectors by satisfying water users (Neubauer, 2012). The WF concept aims to correct this by providing a broader perspective of water use which measures both the direct and indirect water use (Figure 1.1) (Hoekstra, 2013). It shows the consumptive water use where water evaporates, is incorporated into a product or does not return to the same catchment in the same period (e.g. it is withdrawn in the dry season and returned during the rain period) (Aldaya et al., 2012). It can also measure the total water appropriation of goods and services by integrating the water consumption and pollution over a complete production and supply chain. By adopting the supply chain perspective, the WF differentiates the use of local versus global water resources by the product produced (Hoekstra, 2008a).

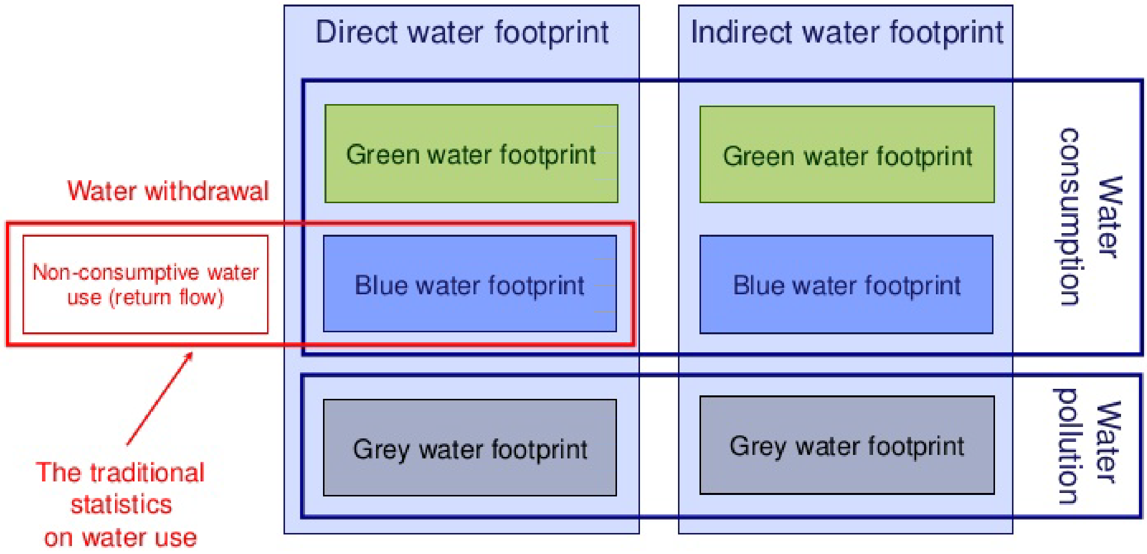

Figure 1.1: Schematic diagram showing the three components of the water footprint that contributes to water consumption and pollution. This includes the blue, green and the grey water footprints. The water withdrawal component does not form part of the water footprint (Hoekstra et al., 2009).

As shown in Figure1.1, the WF is an indicator of both direct and indirect water use. The direct water use refers to freshwater resources used and polluted in association to water use by consumer or producer. The indirect water use is the summation of freshwater consumption and pollution of all products (for example, the final food product, good or service) a consumer or producer uses when a product is being consumed or produced (Hoekstra, 2008b). In addition, the total WF (whether direct or indirect) of a consumer or producer is separated into three water colour components that are used through the whole life cycle of a product. These include the WF_{green}, WF_{blue} and WF_{grey}. WF_{blue} is the total amount of freshwater resources that is evaporated or incorporated into a product from the surface and groundwater bodies to produce a commodity or service. It excludes the non-consumptive water that is withdrawn from surface water or groundwater bodies that returns to the system before it could be used or is returned to the system after it has been consumed. The WF_{green} is the total amount of rainwater that is stored in the soil as soil moisture and available for plant uptake.

The differentiation of WF_{blue} and WF_{green} is useful as green water is only available dependent on the occurrence of rainfall in a specific area of production (Ridoutt and Pfister, 2010). According to Berger and Finkbeiner (2010) the total amount of green water (rainwater) received during production does not necessarily represent the WF_{green} as some of the water is lost as runoff or drains down the root zone into surface and sub-surface water bodies where the water is regarded as blue water. This then indicates that the WF_{green} is only dependent on effective rainfall.

The WF_{grey} is associated with water pollution as a result of human activity, thus the WF_{grey} is defined as the volume of freshwater that is required to dilute pollutants to ambient water quality standards (Hoekstra, 2008a). WF_{grey} is calculated separate from WF_{green} and WF_{blue} as it requires different data inputs to quantify available water resources.

1.2. Water footprint accounting methodology

Water footprint assessment can be conducted according to three main methodologies that have been proposed over the years, including the consumptive approach of the water footprint network (WFN), life cycle assessment (LCA) approach (Jeswani and Azapagic, 2011), and the hydrological approach which considers all the hydrological flows (net water balance) (Clothier et al., 2014). For the scope of this study, the WFN approach will be focused on.

1.2.1. Water footprint network approach

The assessment of a WF is described using four phases: (i) setting goals and scope, (ii) WF accounting, (iii) WF sustainability assessment, and (iv) response formulation (Hoekstra et al., 2009). This study focuses exclusively on the WF accounting which is used to calculate the blue, green and grey WFs of two important and different vegetable crops in South Africa (root versus leafy vegetable).

1.2.2. Calculating the blue and green water footprints of a crop

The WF_{blue} and WF_{green} of a crop is calculated by estimating the crop water use divided by crop yield and expressed in litres/kg (L kg^{-1}) or cubic meters per ton (m^3 $tonne^{-1}$) (Lassche, 2013). There are two approaches used in calculating the WF of a crop based on: (i) Crop Water Requirement (CWR) option and (ii) Irrigation Schedule (IS) option. Both of these approaches require the use of crop growth models to account for the evaporative demand of the atmosphere, simulation of actual crop ET (ET_c) and separation of ET into ET_{blue} and ET_{green}.

(i) Crop water requirement (CWR) option

The CWR estimates ET under ideal conditions (well-watered, disease-free, nutrient non-limiting, good soil conditions under given climate conditions). This option can be run using weather and crop data only. It is calculated from the accumulated ET_c (in mm d^{-1}) over a complete growing period at a specific location and time (Kongboon and Sampattagul, 2012). The ET_c is calculated by multiplying the reference ET_c (ET_o) by the crop coefficient (K_c):

$$ET_c = K_c \times ET_o \quad (1)$$

ET_o is calculated as the rate of ET from a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed crop surface resistance of 70 s m^{-1} and an albedo of 0.23. It is calculated based on the FAO Penman-Monteith equation (Allen et al., 1998), using weather variables that include maximum and minimum temperature (°C) and relative humidity (%), solar radiation (MJ m^{-2}) and wind speed (m s^{-1}) (Chapagain and Orr, 2009, Wu et al., 2012).

(ii) Irrigation scheduling (IS) option

With the irrigation scheduling option, crop evapotranspiration is calculated based on both optimal and water-stressed conditions. This option shows greater accuracy than the CWR approach where only weather data is considered (Aldaya et al., 2012). It also considers the applied irrigation practices but effective rainfall is not considered in favour of the soil water balance which keeps track of the soil water that is used on a daily basis. The total ET_c is calculated using a water stress coefficient (K_s), where $K_s<1$ is under soil water limiting conditions and $K_s=1$ is when there is no soil water stress.

$$ET_c = K_s \times K_c \times ET_o \quad (2)$$

The irrigation scheduling options uses climate, crop and soil data to estimate green and blue evapotranspiration (ET_{green} and ET_{blue}).

The crop coefficient is a value that indicates different crop characteristics as per crop type, crop age and it differs with the growing period. Therefore, the crop growing period is divided into four key stages including initial, developing, middle and late stage (See Figure: 1.2). K_c of different crops is also influenced by crop varieties, crop growth stages, weather patterns and growing conditions.

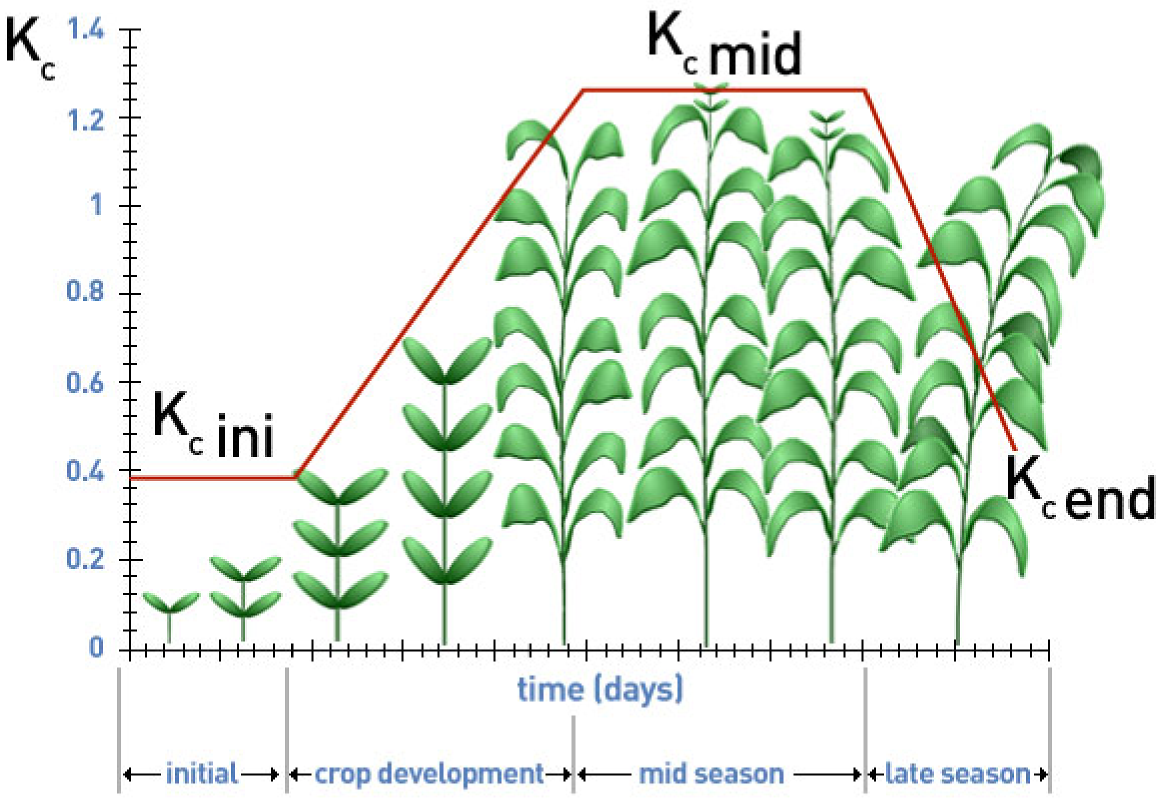

Figure 1.2: Different development stages of computing the crop coefficient (K_c) (Kort, 2010)

The volumetric WF_{blue} is the minimum between crop ET and irrigation requirement (IR) divided by fresh weight (FW):

$$WF_{blue}\ \left(\frac{\text{litres}}{\text{kg}}\right) = \frac{\min(\text{crop ET,IR})}{\text{FW}} \tag{3}$$

The volumetric WF_{green} is the difference between Crop ET and the min of Crop ET and IR, divided by FW:

$$WF_{green}\ \left(\frac{\text{litres}}{\text{kg}}\right) = \frac{\text{crop ET} - \min(\text{crop ET,IR})}{\text{FW}} \tag{4}$$

WF_{green} and WF_{blue} for both options CWR and IS are calculated similar to equations (3) and (4). The estimated crop ET in mm is converted to L by multiplying with the factor 10.

1.2.3. Calculating the grey water footprint

WF_{grey} is calculated following as:

$$\text{WFgrey} = \frac{L}{C_{max} - C_{nat}} \tag{5}$$

Where, L = load of pollutant released to the water source

C_{max} = maximum concentration of pollutant at ambient water quality standards (mg L^{-1})

C_{nat} = natural concentration of the pollutant in the receiving water source (mg L^{-1}).

C_{max} and C_{nat} are different in all regions of the world therefore the grey WF can be different from one region to another even for similar pollutant loads. As with the blue and green WF, the grey volumetric WF is divided by crop yield to give units in volume of water per mass of crop yield (Aldaya et al., 2012).

1.3. The water footprint of a product

Currently, in South Africa water demands exceed water supply hence water management is necessary, especially in the competing agricultural, domestic and industrial sectors (Walter et al., 2011). Water management is no longer just an issue affecting local regions but also international bodies that contribute in ensuring food security at global scale. In previous studies, the WF of products was measured mainly at national level to measure product effects on national water resources (Chapagain and Hoekstra, 2004). However, the WF has gained popularity to better understand the total water used for consumer products in a form of food, beverages and clothes (Hoekstra, 2008b, SABMiller, 2009, Mekonnen and Hoekstra, 2011b).

In estimating the WF of a product, the production system that consists of different process steps is taken into consideration so that water use can be accounted for all production process steps of a product's supply chain. For example, in the production of a bottle of wine, different production steps are shown in Figure 1.3. The production steps include the cultivation of grapes where the WF is calculated based on water used to grow the crop (irrigation), water used in fertilisation, pesticide application and that related to farm operations. Post-harvest processes include washing and cleaning of harvested grapes, water used for making bottles of wine and packaging (includes caps and bottle labelling). The WF in this case does not include the water used in the production of machinery and/or equipment (e.g. irrigation systems and machinery used for harvesting and applying fertilisers and pesticides).

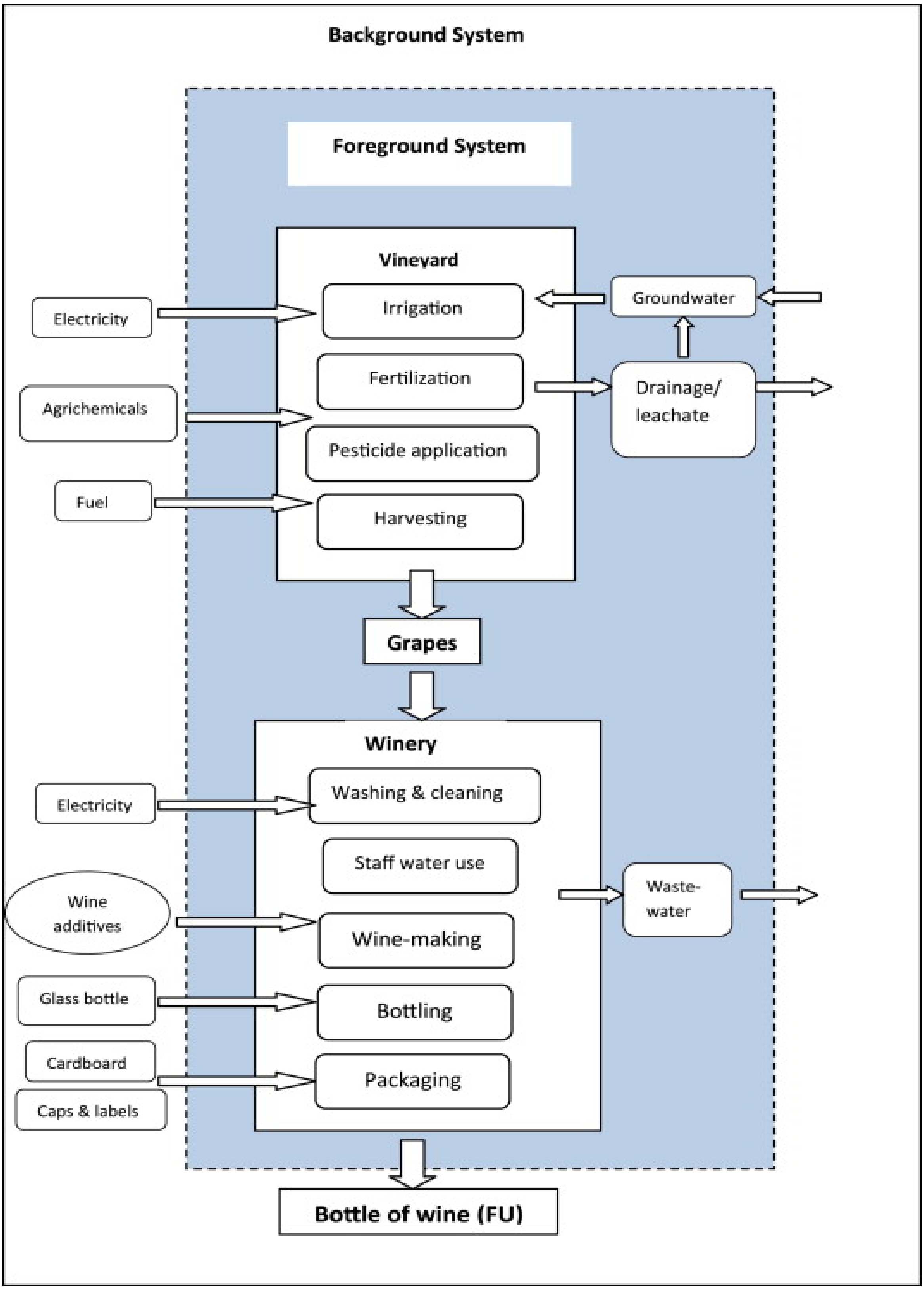

Figure 1.3: Schematic diagram of the major production steps required to produce a bottle of wine (Herath et al., 2013).

1.4. Application of the water footprint accounting in agriculture

Within the agricultural sector, Mekonnen and Hoekstra (2011a) have studied the WF of several common products providing a wide picture of the global WF averages of different crops including sugar crops at 200 m^3 $tonne^{-1}$, vegetable crops 300 m^3 $tonne^{-1}$, root and tuber crops 400 m^3 $tonne^{-1}$, fruits 1000 m^3 $tonne^{-1}$, cereals 1600 m^3 $tonne^{-1}$, oil crops 2400 m^3 $tonne^{-1}$, pulses 4000 m^3 $tonne^{-1}$. The WF of the different crops varies in each crop category and per production region. However, when considering the amount of moisture contained in each crop, vegetable crops have been reported to contain high levels of moisture (80-90%) as compared to other, particularly cereal crops with moisture of 12% (Richard et al., 1998). However, when calculating the WF of vegetable crops, these crops have a lower WF as compared to cereal crops. In addition, Huang et al. (2014) reported that the volumetric WF of vegetable crops is relatively lower than cereal crops even though vegetable crops contain high moisture level than cereal crops. Therefore, it is recommended that vegetable crops be used to achieve better water use efficiency.

Even though a product can potentially have a lower or higher WF, there are different factors that contribute to the final WF of product that may include processes that are presented above. For example, the WF of grapes can be lower as compared to the WF of a bottle of wine. Some products are eaten raw while others are further processed into different products which may potentially require more water, thus the higher WF. For example, in the production of chocolate, the extent of processing resulted in a higher WF because of the different ingredients used in production (Hoekstra, 2008b). This is supported by Ruini et al. (2013), indicating that processed food has a larger WF, as it has more production steps than raw products.

Table 1.1 shows the WF of several common food products measured in L kg^{-1} as estimated by Hoekstra (2008b). These include several fruits, vegetables, grains, meat and beverages. For example, in beef production, 200 kg boneless beef has been reported to have used about 15,500 litres of water at different process steps of the production chain. However, the total amount of water used is mostly during cultivation of feeds that may include wheat, oats, barley, maize, dry peas, soybean meal, pastures, dry hay and silage, drinking water and the additional services that contribute to the final product in the development of the animal. Chapagain and

Hoekstra (2004) also reported that it takes a period of three years before an animal is slaughtered, so the volume of water used is accounted for over the three year duration. Most of the fruits have average WF below 1000 L, while vegetable crops are less than 500 (Mekonnen and Hoekstra, 2010). Most of the processes foods have large WF values such as bread at 1300 L kg^{-1} and chocolate at 24 000 L kg^{-1}.

Table 1.1: Global water footprint (WF) of common food products (Hoekstra, 2008b)

Food product	Unit	Global average WF (litres)
Apple or pear	1kg	700
Banana	1kg	860
Beef	1kg	15,500
Bread (from wheat)	1kg	1,300
Cabbage	1kg	200
Chicken	1kg	3,900
Chocolate	1kg	24,000
Cucumber or pumpkin	1kg	240
Groundnuts (in shell)	1kg	3,100
Lettuce	1kg	130
Maize	1kg	900
Mango	1kg	1,600
Oranges	1kg	460
Potato	1kg	250
Rice	1kg	3,400
Sugar (from sugar cane)	1kg	1,500
Tea	1 cup of 125 ml	30
Tomato	1kg	180
Wine	1 glass of 250 ml	120

The size of the products WF potentially has different implications in different countries of varying water resources. Many regions around the world produce beef using green water resources, even though these are different for water scarce countries where production is dependent on both rain-fed and irrigated agriculture.

The information on water resources in different regions can potentially provide awareness to consumers regarding the impact of the goods and services they consume (Clothier et al., 2010). This could potentially help when consumers decide what product to purchase and creates responsibility for consumption patterns in the country of origin. It can also address the public concern about the WF of common crops and as a result this can lead to the development of labels, particularly for food products (Hoekstra, 2008a).

More detailed studies include the WF of tea and coffee (Chapagain and Hoekstra, 2007), tomatoes (Chapagain and Orr, 2009), cotton (Chapagain et al., 2006), sugar cane and cassava (Kongboon and Sampattagul, 2012). Other products with higher WFs include tobacco, nuts, fibre (processed from cotton) and spices as a result of all the process steps occurring during production. The type of commodity does not necessarily determine the WF, as these crops are produced in different environments with site-specific conditions. Factors such as soil characteristics, weather conditions and available water resources contribute significantly to the WF that may differ within one region or country. Thus regional water studies will be more useful to provide accurate and reliable WF results.

1.5. Reduction of the water footprint by changing production and consumption patterns

Blue water resources are often scarcer than the green water resources as blue water is available to multiple users. Blue water also has higher opportunity cost and thus more focus is placed on this resource. Green water availability is directly linked to seasonal rainfall patterns that differ from one location to another and between seasons (for example, in South Africa rainfall is mainly received in the summer season, even though a small portion is received in winter). Even though more focus is placed on the blue water resources, green water resources are now recognised to be extremely important in agricultural food production because it effectively irrigates vegetation and refill the surface and ground water bodies (Falkenmark and Rockström, 2006).

Many reports have shown that increasing water productivity can be part of the resolution of reducing the WF. WP is defined generally as the amount of biomass produced per cubic metre of water consumed. However, the WF cannot be reduced by improving water productivity alone as there are existing production and consumption patterns that carry an inherent dependency on water that cannot easily be addressed by increasing efficiency alone. According to Wichelns (2010), water is a local rather than an international resource as water availability and/or stress are measured at local levels, thus knowing the temporal and spatial distribution of the WF help provide information essential to evaluate sustainability or manage risks within a geographic area. Water use is also affected by climate which shows the temporal variability that influences growth in different areas and between seasons. Clothier et al. (2010) indicates that water can be saved by using more efficient techniques (tillage, mulching, etc.) that will ensure sustainability. Different products have varied WFs, so it is essential to evaluate the water footprint of all activities within a confined area (Chapagain and Orr, 2009).

According to Ridoutt and Pfister (2010), a product with a lower volumetric WF can be more damaging to the environment than a product with higher volumetric WF depending on where the water was sourced. This is supported by Chapagain and Hoekstra (2004), indicating that a larger WF of a product does not show the extent of water scarcity but indicates the potential impact of water used as opposed to water availability, for example, the water that remains after production to sustain the ecosystem. Therefore, even in water limited countries such as South Africa, the WF of a product can be more damaging dependent on water available in the confined area, where drier areas with low erratic rainfall patterns are more likely to be affected by producing products with higher WF.

Several studies have been done quantifying the WF of products using local and international water resources by comparing the water requirements of crop and livestock products world-wide (Chapagain and Hoekstra, 2004, Chapagain and Hoekstra, 2007, Aldaya and Llamas, 2008, Chapagain and Orr, 2008, Chapagain and Orr, 2009, Bulsink et al., 2009). These studies calculated the WF based on the volume of consumption (related to countries gross income), consumption pattern (i.e. supply versus demand of a commodity, for example, high and low consumption of meat), climate (growth conditions) and agricultural practices (for example, management to improve water use efficiency). Rainfed agriculture remains the dominant crop and forage production system throughout the world, however, as a result of drought conditions, several countries have limited water resources. Therefore, in such water scarce countries, different agricultural practices have been used to improve water efficiencies. These includes the use of both rainfed and irrigated agriculture, reducing tillage, mulching, harvesting of rainwater, irrigation scheduling, integrating farming practices and improving efficiency of on-farm irrigation application (Tilman et al., 2002). Efficient and sustainable agricultural productions require the continuation to strive under such systems. Analyses of these studies are based on the country or region's water scarcity, water self-sufficiency and water import dependency (Chapagain and Hoekstra, 2003).

In these studies, the variation in products WF at different production levels have been shown as a result of varied climate patterns, agricultural practices and the amount of water used to produce single or different commodities across a wide spectrum (Bulsink et al., 2009). However, in the different regions, more emphasis is placed on saving blue water resources that contribute to maintaining biodiversity and other purposes, unlike the green water resources which are the most effective way of irrigating. Therefore, the efficient use of rainfall, particularly in rain-fed and irrigated areas can improve WP.

Since water is a more local resource than an international resource, product's WFs should be measured on smaller scales (regional or field levels) so that the levels of water scarcity are shown, especially if commodities are produced in areas with high levels of rainfall or where the WF of those particular products is low (Liu and Savenije, 2008). When the pressure on the natural resources increase and water becomes scarcer, trade in virtual water can help save water and reduce pressure on local water resources and assure a high level of food self-sufficiency (Hoekstra and Chapagain, 2007b). However, in order to ensure true self-sufficiency, especially in the agricultural sector, higher efficiencies need to be attained when possible in producing these products.

Trading of goods among countries does not necessarily mean that countries should import products to save water, as international trading is based on different factors including trading advantages, comparative strategies and economic considerations. According to Hoekstra and Chapagain (2007a), international trading of agricultural products depends on the availability of land, labour, knowledge and capital, competition in certain types of production and import taxes. Therefore, trading of products cannot always be explained simply in terms of water availability alone. However, many producers in countries of limited water resources participate in the exportation of agri-foods for financial gain, especially in the dry season (Wichelns, 2011b). Trading particularly of agri-food products are supported by the idea that water-scarce countries will save water with the importation of goods and services with higher virtual WFs (Suh et al., 2011). Gerbens-Leenes et al. (2009) stated that reducing the production of the most water-intensive crops such as coffee, tea, and others will help reduce the total WF of different commodities. Other suggestions include changing of diets, especially by reducing the consumption of meat and dairy products that use relatively high levels of water for production. Hoekstra and Mekonnen (2012) suggest that the high levels of meat be replaced with vegetarian or light meat (for example, chicken and pork) meals to potentially help lower the WF.

1.6. Limitations and uncertainty of the water footprint

The WF has been developed to assess the use of freshwater resources that have reached their limit in different parts of the world, particularly arid and semi-arid regions. The calculation of the WF has shown its limitations in assessing the total water use as it only considers water used for human activities (Galli et al., 2012). Even though more work needs to be done on the environmental indicator component of the WF, the social and economic indicators also need to be addressed to ensure sustainability of the WF assessment (Aldaya et al., 2012). Flooding and drought conditions that may arise are not addressed in the calculation of the WF, which indicates that water management and policy planning may need other indicative tools to make conducive decisions.

The WF plays an important role in the analysis of water resources in international trading. This serves as a solution to save and measure water losses in water scarce countries. Therefore, it is suggested that countries with limited water resources should not produce or export water-intensive crops in order to reduce pressure on available water (Dabrowski et al., 2009). However, trading of products remains to be questionable as international trading is a rather complex market that involves different issues that are not considered in the WF. Even so, producers in water scarce countries prefer to produce water intensive products (for example, producing high-value horticultural crops over cereal crops) in order to get good financial returns. Therefore, as a result, the production of these products poses threats to countrie's water resources, which could have been avoided by importing. Even though importing may be a solution in these water limited countries, other challenges such as producers income, livelihood and job creation arise (Wichelns, 2010).

Water scarcity and quality conditions have different implications in different parts of the world, and there is lack of information that indicates net benefits of production and consumption activities. For example, for the occurrence of rainfall, water is lost in different forms most importantly as runoff or through drainage, However, when the water reaches the surface and /or sub-surface water bodies, it is no longer referred to as green water but blue water that is allocated for irrigation and other purposes (Wichelns, 2011a). Concerns are also shown in the calculation of the WF_{grey} that relies heavily on a number of assumptions. The WF_{grey} is assumed to represent the total amount of water required to assimilate pollutants to ambient water quality standard, however, this component does not show the true reflection of pollution as the volume of the freshwater in which the pollutant is leached into is unknown (Galli et al., 2012). Therefore, information of the WF_{grey} can provide misleading information (Hastings and Pegram, 2011).

1.7. Water productivity

WP is defined generally as crop yield per cubic meter of water consumption that includes green water (effective rainfall), particularly in rain-fed areas and both green water and blue water (diverted water from water systems) in irrigated areas (Fereres et al., 2003). The concept of WP varies greatly from region to region, field to field and is also dependent on a number of factors, including crop growing conditions, weather conditions, irrigation technologies, inputs (for example; fertilisers and machinery) and field management. All these factors are dependent of the availability of the green water and blue water resources of a specific area. Rainfall plays an important role in food production (Mekonnen and Hoekstra, 2010). It has the potential to reduce water scarcity, particularly in water abundant countries, its efficient use can reduce the use of irrigation water (blue water). This is different in arid and semi-arid region, where rainfall is low, thus irrigation is needed to attain reasonable yields (Mekonnen and Hoekstra, 2011a). This then affects the blue/ green ratio of water use that may differ across different environmental areas.

Demand of water for future food production is dependent on limited water resources, thus there is a necessity to emphasise the concept of WP in both irrigated and rain-fed agriculture (Rockström et al., 2003). This concept strongly indicates the efficiency of water use, particularly at local scale as it clearly shows the economic value of producing a product (Kumar et al., 2009). Even though some users confuse WP for water use efficiency (WUE), in agriculture the two concepts are explained differently. WP is based on "more crop per drop" or "producing more food from the same water resources" or "producing the same amount of food with less water" (Van Dam and Malik, 2003) while WUE does not dwell on economic values but only measures actual ET based on the total water used in crop production (Kumar et al., 2006). WUE, particularly in agriculture is complex since crop production involves multiple and interacting factors that cannot be described by a simple input/output system. This includes a broad range of disciplines, including plant physiology, agronomy, and engineering. In this case, efficiency means transpiration efficiency to physiologists, irrigation efficiency to agronomists, and water application efficiency to engineers (Annandale et al., 2011). Also, the units used to measure efficiency are not always easy to compare. However, in semiarid environments, the fulfilment of leaching requirements significantly limits the possibility of applying deficit irrigation criteria and reduces the WUE in irrigated vegetable production. Higher yields, improved WUE, and higher produce quality have been reported for drip irrigation systems compared with other irrigation methods for different vegetable crops. However, the choice of the proper irrigation technology is highly site-specific, reflecting regional (field characteristics and climate), technical (water supply and crop characteristics), and market factors (De Pascale et al., 2011).

Water productivity improvements can effectively address food insecurity and poverty alleviation. There is a large potential to improve water productivity through improved and known water management practices. Management practices that increase agricultural yields also improve water productivity. The greatest potential to increase yields and water productivity is in areas where agricultural productivity is currently low (Kijne et al., 2009). Such areas include low input rainfed agriculture in Sub-

Saharan Africa and South Asia, which provides the food for most of the poorest in the world, in regions where water resources often are considered scarce and where future water demands for food grow fastest due to population growth and development needs. Major opportunities to improve water productivity are found in water management practices along the continuum from rainfed to partially and fully irrigated farming systems (Molden et al., 2010).

Increasing WP particularly in the agricultural sector will potentially reduce competition for water resources, thus allowing more food to be produced with less water, thus making water available to other sectors and the ecosystem. The environmental factor play an essential role in water use as influenced by the atmospheric evaporative demand, where in drier climates, ET is higher than in humid climates. Different factors such as crop type, agronomic management techniques and soil condition also play an essential role in improving WP (Molden et al., 2003). The following equation is used to calculate WP:

$$\mathrm{WP} = \frac{\mathrm{Y_a}}{\mathrm{ET_a}} \quad (6)$$

Where Y_a represents the actual marketable crop yield (kg ha^{-1}) and ET_a is the actual seasonal crop evapotranspiration (mm).

1.8. Review of selected vegetable crops

1.8.1. Carrots (*Daucus carota* L.) and its importance in South Africa

Carrot (*Daucus carota*) is one of the major root vegetable crops grown throughout the world (Rubatzky et al., 1999). It originated from Europe and Asia (particularly Afghanistan) where numerous varieties are currently found. Carrots are distinguished into different types that include wild carrot which was initially used as a medicinal plant, the white to yellow varieties which through domestication have been used to develop the strong taproot orange carrot and the red or purple carrot that are still being grown around the world. Usually carrot is grown for its thick roots, although the leaves are also edible. Carrot is a rich source of β- carotene and contains other vitamins, like thiamine, riboflavin, vitamin B-complex and minerals. Garcia and Barrett (2002) reported that carrot can be consumed raw, as a juice and in salad and cooked vegetable dishes. Large quantities are also processed, either alone or in mixture with other vegetables, by canning, freezing or dehydration.

Predominantly, carrot was cultivated as a temperate plant which has now spread into Tropical and Sub-tropical regions including Africa (Rubatzky et al., 1999). In the past 30 years carrot production in both Africa and South America slowly increased whereas production in Asia (primarily China) showed a very rapid increase in 1997 to replace Europe as the leading production area. Current carrot world annual production is 27 million tonnes, with the leading producing countries including China, Russia, and USA. These countries produce about 45% of World output, with South Africa contributing as a minor exporter to several African countries (FAO, 2008).

Carrot is a temperate cool season crop that performs well under cooler weather of 10 to 25°C (Manosa, 2011). With the availability of different cultivars with varied characteristics, carrots can withstand summer and winter conditions, even though this crop grows best in the cooler season. Although there are available varieties that accommodate different weather conditions, this crop does not tolerate extreme cold in cases of frost and very high temperatures result in poor plant stand (Rubatzky et al., 1999). South Africa is a subtropical region with climate conditions from temperate to Mediterranean, thus carrot can be cultivated easily across the country (Leff et al., 2004). The country is also known for its limited water resources and low erratic rainfall patterns, thus carrot production is mainly dependent on irrigation to ensure proper growth, high yield and good quality (Van Averbeke et al., 2011). Due to high water demand, this crop requires frequent water supply particularly during the root development stage (Nagaz et al., 2012). Thus proper irrigation scheduling can ensure maximum yield. Carrots have average yields ranging between 30-40 tonnes ha^{-1} while more successful yields are 60 tonnes ha^{-1} or more (Mehedi et al., 2012). In South Africa, carrot is one of the most important root vegetable crops and is widely cultivated throughout the country. South Africa is a country heavily influenced by varietal differences and geographic location. The commonly grown carrot varieties in South Africa include Cape Market, Chantenay Karoo, Chantenay Royal, Flacora, Ithaca, Kuroda, Senior, Star 3006 and Sugar Snax. Most carrots cultivars are grown for 150 days after planting, even though other have shorter periods of 120 days after planting.

1.8.2. Swiss chard (*Beta vulgaris* L.) and its importance in South Africa

Swiss chard (*Beta vulgaris L.*) is an annual to biennial plant that belongs to the family of beets Chenopodiaceae. It originated from Europe and Western Asia (Shannon and Grieve, 1998). Swiss chard has been cultivated since 300 B.C. and roots of the wild chard were used as medicine. The wild form is found in the Canary Islands, Mediterranean region, and east to southern Asia. The first records of Swiss chard cultivation suggest the Mediterranean area, perhaps Italy, as the centre of origin. The commonly known names for Swiss chard include chard, white beet, strawberry spinach, seakale beet, leaf beet, Sicilian beet, spinach beet, Chilian beet, Roman kale, and silverbeet. Swiss chard is characterized by large ovate leaves with armoured edges; the colour varies according to the cultivar from dark green to light green, and has creamy or white coloured petioles (Echer et al., 2012). It is popular for its nutritional properties as the green, white or sometimes reddish leaves are rich in vitamin A and vitamin C. It contains minerals such as potassium (379 mg 100 g^{-1}), sodium (213 mg 100 g^{-1}) and iron (1.80 mg 100 g^{-1}) (Maboko and Du Plooy, 2013). It also has natural antioxidants and anti-acetylcholinesterase that are essential to human health and preventing chronic diseases.

Swiss chard is a temperate climate plant, which grows best in warm weather, with temperatures ranging between 18 and 25°C (Echer et al., 2012). It is also grown as an annual crop that is adaptable to cool weather, but due to its adaptability to warm temperatures, it can be grown throughout the year (Kasim and Kasim, 2012). Unlike other green leafy vegetables, Swiss chard tolerates moderate frost even though very low temperatures can result in bolting.

Swiss chard allows multiple harvests of the outer leaves as it is able to re-grow from the younger, inner leaves. Maruo et al. (2002) stated that leafy vegetables have the potential to re-grow and supply several harvests for months. The supply of several harvests indicates the plant is able to regenerate leaves and shoots from one sowing time, thus accumulating higher yields with less area. The regeneration of leaves and shoots are mostly observed in the production of Swiss chard where the crop can reproduce leaves when the cutting level is above the lateral growing point. Swiss chard average yields range from 8 -10 tonnes ha^{-1} to maximum yields of 15 tonnes ha^{-1} per harvest. Common cultivars of Swiss chard grown in South Africa include

Fordhook Gaint and Star 1801 (Maboko and Du Plooy, 2013). Most Swiss chard cultivars are grown for 60 days after planting before the first harvest, while harvesting is done at 2-3 weeks intervals.

1.9. The Soil Water Balance (SWB-Sci) model

The Soil Water Balance (SWB-Sci) model is a real-time, mechanistic, multi-layer, daily time step, soil water-salt balance, as well as generic crop growth model (Annandale et al., 1999, Annandale et al., 2001, Jovanovic et al., 2001, Annandale et al., 2004). It provides a detailed-description of the Soil-Plant-Atmosphere continuum by making use of weather, soil and crop units. The soil unit in SWB-Sci uses a cascading soil water balance approach when canopy interception and the surface runoff have been accounted for (Annandale et al., 2011). Potential evapotranspiration (PET) consists of two components, including the potential evaporation (E), which is the water lost from the soil surface, and the potential transpiration (T), which is the water lost through the crop canopy. PET is estimated using weather data that includes minimum and maximum air temperature (°C) and relative humidity (%), solar radiation (MJ m^{-2}) and wind speed (m s^{-1}) using the Penman-Monteith method (Allen et al., 1998). As SWB-Sci allows the separation of potential evaporation and transpiration this solves the problems of taking into account the irrigation frequencies that occur during production (Jovanovic et al., 2000).

The crop unit of SWB-Sci calculates the accumulation of dry matter that is directly proportional to transpiration corrected for vapour pressure deficit. It also estimates radiation-limited growth and takes the lesser of the two. Dry matter is partitioned into roots, stem, leaves and grain or fruit, depending on the type of crop (Jovanovic et al., 2002). Partitioning depends on phenology calculated with thermal time and modified by water stress. The input data that is required includes planting date, latitude, altitude, rainfall and irrigation water amounts, daily maximum and minimum temperatures, initial water contents of the soil layers and two points on the water release curve, usually field capacity and wilting point (Annandale et al., 1999). The model includes a database of parameters for a number of crops including field crops, vegetables, pastures and fruits (Jovanovic et al., 1999, Jovanovic et al., 2001, Beletse et al., 2008, Annandale et al., 2011). For crops with multiple harvest (i.e.

Lucerne, Swiss chard), this model also accounts for the re-growth (Jovanovic et al., 2001). The model can also use a FAO-type crop factor coefficient approach in the absence of specific crop growth parameters to take into account crops with limited parameters (Annandale et al., 2011). In this study only the mechanistic crop growth model is used, thus the FAO model is not described.

Chapter 2 Impact of planting date, management practice and location on the volumetric water footprint of carrot

2.1. Introduction

Carrot (*Daucus carota L.*) is a root crop that originated in South Asia (Afghanistan, Iran and Pakistan) (Rubatzky et al., 1999, Abdel-Mawly, 2004). Today it is recognised as one of the top ten most important vegetable crops that are grown throughout the world in terms of market value, high nutritional value and production area (Manosa, 2011). In South Africa, this crop is considered one of the major consumed vegetables which are rich in vitamins C, B1 and B2, and particularly rich in carotene (pro-vitamin A). Carrots can be consumed in salads, cooked and eaten raw, or added to soups, stews and other dishes. Large quantities are processed, either separately or with other vegetables, in canning, freezing or dehydration (da Silva Dias, 2014b).

Globally, carrots are grown in large quantities and the leading producers include China, Russia, United States, Poland and Uzbekistan (Sharma et al., 2012). South Africa is among the minor producers, however, carrots are grown in most parts of the country with total production increasing on an annual basis (Louw et al., 2008). South Africa's annual carrot production sufficiently supplies all domestic markets, leaving a surplus that is exported to other African countries (Dolan and Humphrey, 2000). Even though production of this crop currently satisfies the domestic market, issues of sustainability are being questioned in order to ensure continued production. Currently, water scarcity is considered as one of the major constraints that threatens current and future food production as irrigated agriculture is known to play a major role in ensuring food security (Fereres et al., 2003). Therefore, irrigation management under water scarce conditions needs to be carried out as efficiently as possible.

In water stressed countries up to 70-80% of freshwater resources are allocated for irrigation (Chapagain and Orr, 2009). In South Africa horticultural crops (fruits and vegetables) have been reported to use the majority of the water allocated for irrigation, as a result of low erratic rainfall patterns that are unevenly distributed and the high value of these crops (Hassan and Thurlow, 2011). Furthermore, increased droughts are exerting more pressure on water availability and indirectly on food security (Fereres et al., 2003). The water footprint (WF) has been developed with the aim of addressing challenges in water scarcity and quality issues. The WF concept quantifies water consumption and the impact on water quality by human activities on freshwater resources (Lassche, 2013). It potentially enables strategic management that can better address the problems of water scarcity (drought, changing rainfall patterns or overexploitation of water resources) and increased pollution that are related to crop production. The WF is measured based on the amount of water used and/or polluted per unit yield (Wu et al., 2012).

The WF has three water components that distinguish the type of water used in crop production. These include the WF_{blue} which refers to consumption of surface and/or groundwater resources (irrigation), WF_{green} which refers to rainfall stored in the soil, and the WF_{grey} which is associated with water pollution and represents the freshwater required to assimilate the pollutant loads to existing ambient water quality standards (Aldaya et al., 2012). The objective of this study was to investigate the impact of planting date, management practices and location on the consumptive WF (WF_{blue} and WF_{green}) of a carrot crop. Two carrot crops were planted on the Hatfield Experimental Farm and values were also benchmarked against a commercial crop grown in Tarlton, North West Province. For this purpose, reference evapotranspiration (ET_o), air temperature and vapour pressure deficits were compared for the respective growing seasons.

2.2. Materials and methods

2.2.1. Site description and trial management

Field experiments were conducted in two areas in the Highveld Region of Gauteng Province, South Africa. These included the University of Pretoria's Hatfield Experimental Farm, and the commercial Greenway Farms in Tarlton near Krugersdorp, North West Province. The Hatfield Experimental Farm is situated at an altitude of 1327 m above sea level with latitude of 25°45'S and longitude of 28°16'E. This area receives an average rainfall of 670 mm per annum. Average minimum and maximum air temperatures range between 1.5°C in winter (June) and 35°C in summer (January) and the soils have a sandy clay loam texture. The Greenway Farms is situated at an altitude of 1588 m above sea level, with latitude 26°08'S and longitude of 27°35'E. It receives an average rainfall of 700 mm per annum with average minimum and maximum air temperatures ranging from 1 - 31°C. The soils have a sandy loam texture.

Hatfield Experimental Farm

The experimental layout was based on a randomised complete design replicated three times. Carrot (cv. Kuroda) was planted on three replicated plots of 2 × 2 m. Carrots were planted directly from seed which were broadcasted in each plot. Thinning was done two to three weeks after emergence to obtain the desired planting density for each plot (1875 000 plants ha^{-1}). In the cropping area of 4 m^2 fifteen rows of carrots were planted at a spacing of 0.15 m between rows and 0.15 m between plants. Carrots were grown over two growing seasons, summer and autumn. In the summer growing season, carrots were planted on the 30th October 2013, while in the autumn growing season, carrots were planted on the 12th March 2014. Carrots were harvested at three weeks intervals throughout the growing season after six weeks of planting. Soil samples were collected before planting and analysed to determine required fertiliser applications and the trial site soil was regarded as nutrient non-limiting. Before planting, 400 kg ha^{-1} of 2:3:4 fertilisers (6.7% N, 10%P, and 13.3% K) were applied to the cropping area. This is equivalent to 24 kg N ha^{-1}, 40 kg P ha^{-1} and 52 kg K ha^{-1}. In total, 200 kg N ha^{-1} was applied throughout the growing seasons. During the growing season, weeds were controlled by hand weeding.

Watering cans were initially used to irrigate the crop until it was well established. This was then replaced by high-density drip irrigation system with the volume of water applied measured using a water flow meter (Netafim (Pty) Ltd, model Arad IRT-80, South Africa). The spacing between dripper lines was 0.3 m and the spacing between drippers in the line was also 0.3 m. Irrigation scheduling was applied using two tensiometers (Irrometer Company Inc. California, USA) were installed in between rows at depths of 0.25 m and 0.5 m. Irrigation was applied when the tensiometer gauge at depth 0.25 m read above -50 kPa. Two wetting front detectors (WFD) (Agriplas (Pty) Ltd, South Africa) were installed in between rows in each plot at two different depths of 0.25 m and 0.5 m. The rising of the 'flag' of the WFD indicates that a wetting front due to irrigation/rainfall has reached the specific depth.

Soil volumetric water content (VWC) was measured using Decagon ECH2O 10HS sensors (Decagon Devices Inc. Washington, USA) linked to an EM 50 logger (Decagon Devices Inc. Washington, USA) and installed at depths of 0.25 and 0.5 m. The ECH2O 10HS probes were set to monitor and record VWC every 60 minutes. These measurements were replicated three times at 0.25 and 0.5 m depths (one per plot). One additional ECH20 10HS sensor was installed at 0.9 m for each plot.

Greenway Farms (Tarlton)

This experiment focused on monitoring and measuring crop variables within a commercial field in the Tarlton region. Thus, as a commercial farm, the farmer only uses preferred cultivars for their specific market. Carrot (cv. Dordoigne, also known as Soprano) seeds were planted in two rows on each ridge with both inter and intra-row spacing of 0.1 m on an area of 10.4 hectares. Carrots were planted on the 3rd January 2014. Carrots were harvested at three weeks intervals throughout the growing season. A centre pivot was used to irrigate the crop. The fertiliser application rates of carrot were dependent on the farmer. The volume of water applied was determined by the pivot speed (as percentage of maximum) and irrigation scheduling was determined by the commercial farmer. Soil VWC was measured using ECH2O 10HS sensors which were installed at depths of 0.20, 0.40 and 0.60 m on ridges and 0.20 and 0.40 m in the furrow. The sensors were connected to EM50 data loggers set to monitor and record VWC every 60 minutes. This array of sensors was replicated twice within the field.

2.2.2. Data collection

Hatfield Experimental Farm

The aboveground parts together with the roots were destructively harvested from an area of 0.6 x 0.3 m^2 from each plot. From the harvested samples, plants were separated into leaves, shoots and roots. Growth analyses were done at two to three week intervals with six plants removed per harvest. The fresh and dry matter yield of each part was determined. Harvestable fresh mass was measured immediately after sampling while the dry matter was measured after oven drying at 65 °C for a period of five days (until constant mass). Leaf area was measured destructively using a LI 3100C belt-driven leaf area meter (LiCor, Lincoln, Nebraska, USA) and leaf area index (LAI) was calculated from the data. Fractional interception (FI) of photosynthetically active radiation (PAR) was measured using a Sunfleck ceptometer (AccuPAR LP-80, Decagon Devices, Washington, USA), which is a non-destructive method. Three readings were taken above and six below the canopy in close proximity to the water sensors. Readings were taken between 11h00 to 12h00 and only when there were clear skies.

Greenway Farms (Tarlton)

Growth analyses were done every second week by randomly harvesting plant material from three rows per ridge with an area of 1 m^2 in close proximity to the water sensors. A total of three samples were randomly harvested to check for variation across the field. Plant samples were separated into leaves, shoots and roots and the fresh and dry mass of each part was determined, as described in the section above. Leaf area, LAI and FI were also measured/ calculated in the same way as for the Hatfield trial.

2.2.3. SWB-Sci model parameterisation

The SWB-Sci model local parameters are presented in Appendix I and II (Table 1 and 2). To run the simulation, field data collected during the different planting dates at Hatfield Experimental Farm and Tarlton Greenway Farm were used for comparison purposes (measured and simulated). These include LAI, top dry matter yields and harvestable dry matter yields.

2.2.3.1. Weather data

Weather data including rainfall, daily maximum and minimum air temperatures, solar radiation, wind speed, and minimum and maximum relative humidity were collected by an automatic weather station. For the Hatfield trial, the automatic weather station was located approximately 30 m away from the field trial and the weather variables were measured at a height of 2 m. In Tarlton, the automatic weather station was located approximately 500 m away from the field trial and the weather variables were measured at a height of 2 m. Meteorological data for both the representative sites were used to calculate crop evapotranspiration (ET) using the FAO Penman-Monteith method (Allen et al., 1998).

2.2.3.2. Soil parameterisation

The soil module in the SWBSci model uses a cascading soil water balance approach and also accounts for canopy interception and surface runoff which does not infiltrate into the soil. Potential ET (PET) consists of potential evaporation which is the water lost from the soil surface and the potential transpiration which is the water evaporated through the crop canopy. SWB estimates actual evaporation and transpiration based on crop canopy size, soil moisture status and atmospheric evaporative demand. The separation of evaporation and transpiration allows consideration of the effect irrigation frequency has on unproductive evaporation losses (Jovanovic et al., 2000).

Each of the 11 soil layers in SWB-Sci is assumed to fill to saturation if sufficient infiltrating water is available, and then passes on a fraction of the water above field capacity to the layer below, as determined by a user defined 'drainage factor' (0-1). Any water that passes beyond the bottom layer, moderated by a user defined 'drainage rate' parameter, is assumed lost to deep percolation. Input data related to crop management includes starting date of simulation, planting date, irrigation timing options and irrigation system type. Soil parameters required per layer include soil layer thickness (m), volumetric water content at field capacity and permanent wilting point (m^3 m^{-3}), initial volumetric water content (m^3 m^{-3}) and bulk density (kg m^{-3}) (Appendix I).

2.2.3.3. Crop parameter calibration/ model application

The crop module of SWB estimates the accumulation of dry matter as being proportional to transpiration. It also estimates radiation-limited growth and takes the lesser of the two on a daily time-step. The dry matter is partitioned to roots, stem, leaves and grain or fruit depending on the type of crop stimulated (Jovanovic et al., 2002). The maximum soil depth was set at 0.6 m because carrots have relatively shallow root system.

2.2.3.4. ET calculation in SWB

The SWB model calculates ET using the following equation (7):

$$\mathrm{ET} = \mathrm{P} + \mathrm{I} - \mathrm{R} - \mathrm{Dr} - \Delta \mathrm{S} \quad (7)$$

Where ET is crop evapotranspiration, R is rainfall, I is irrigation, Dr is drainage and Δ S is the change in soil water storage. All the terms are expressed in mm.

2.2.4. Calculating the volumetric blue and green water footprints according to the Water Footprint Network approach

The total WF for a cultivated crop is the sum of three water footprint (WF) components (WF_{blue}, WF_{green} and WF_{grey}) as shown in equation 8:

$$\mathrm{WF_{total}} = \mathrm{WF_{blue}} + \mathrm{WF_{green}} + \mathrm{WF_{grey}} \quad (8)$$

Where, the WF is expressed in litres of water used and/or polluted per unit crop. The consumptive water use (blue and green WF) was calculated based on the Water Footprint Network approach (Aldaya et al., 2012). The WF_{blue} and WF_{green} were presented in Chapter 1.

The WF_{grey} was calculated based on the Franke et al. (2013) Tier 1 approach using N as the critical pollutant. The WF_{grey} was calculated as shown in equation 11:

$$\mathrm{WF_{grey}}\left(\frac{\mathrm{L}}{\mathrm{kg}}\right) = \left(\frac{\alpha * \mathrm{AR}}{\mathrm{C_{max}} - \mathrm{C_{nat}}}\right) \times \left(\frac{1}{\mathrm{Y}}\right) \quad (9)$$

Where, the WF_{grey} (L kg^{-1}) was calculated by multiplying the fraction of N that is estimated to leach (α, %) by the local N application rate (AR, kg ha^{-1}) and dividing this by the difference between the maximum acceptable concentration of nitrogen (C_{max}, mg L^{-1}) and the natural concentration of N in the receiving water body (C_{nat}, mg L^{-1}) and finally divided by the actual yields (kg).

2.3. Results

2.3.1. Simulated and measured data of carrots planted at different dates at Hatfield and Tarlton

Figure 2.1 – 2.3 presents the SWB-sci model simulated and measured data output (root depth, LAI, above-ground dry matter yield (TDM) and soil water deficit) for carrots in Hatfield and Tarlton. However, no measurements were made for root depth and soil water deficit as this study was non-limiting. The statistical indicators are given at the top right corner of the graphs to show the status of the model calibration. All the statistical indicators of LAI, TDM and HDM are 0 except for N (number of items) and MAE during the summer growing season. N was one for LAI, TDM and HDM because the crop was only harvested once because of its poor plant

stand. However, N for Hatfield-autumn and Tarlton-autumn was more than one, thus all the statistical indicators are shown. Simulation of carrot for both Hatfield and Tarlton was not in agreement with the measured data for all parameters during model calibration. All the statistical parameters (r2 and D > 0.8 and MAE < 20%) imply that calibration of the model was not in agreement with the measured data.

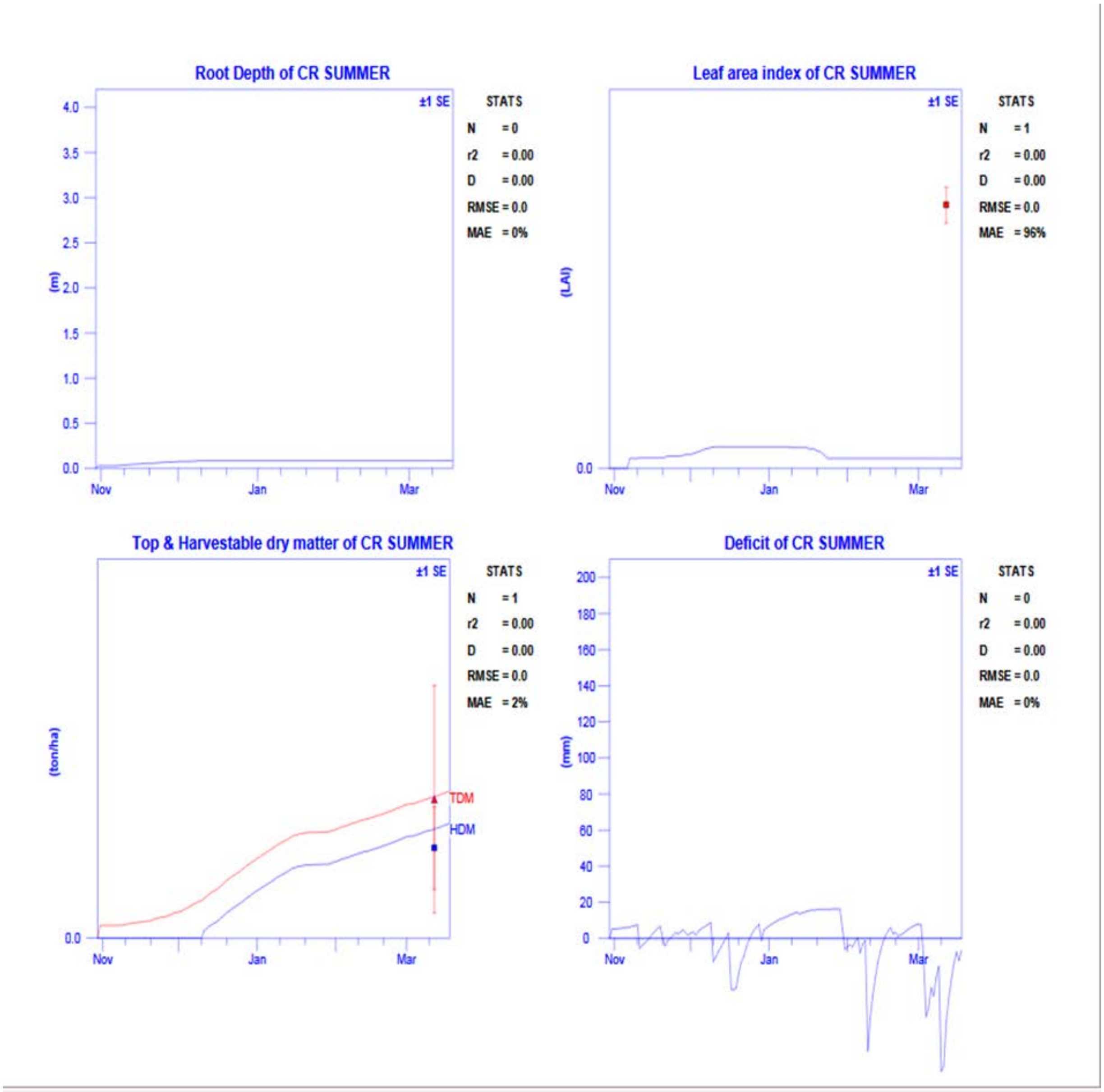

Figure 2.1: Simulated (lines) and measured (dots) LAI and yield for carrots grown during the summer growing season at Hatfield.

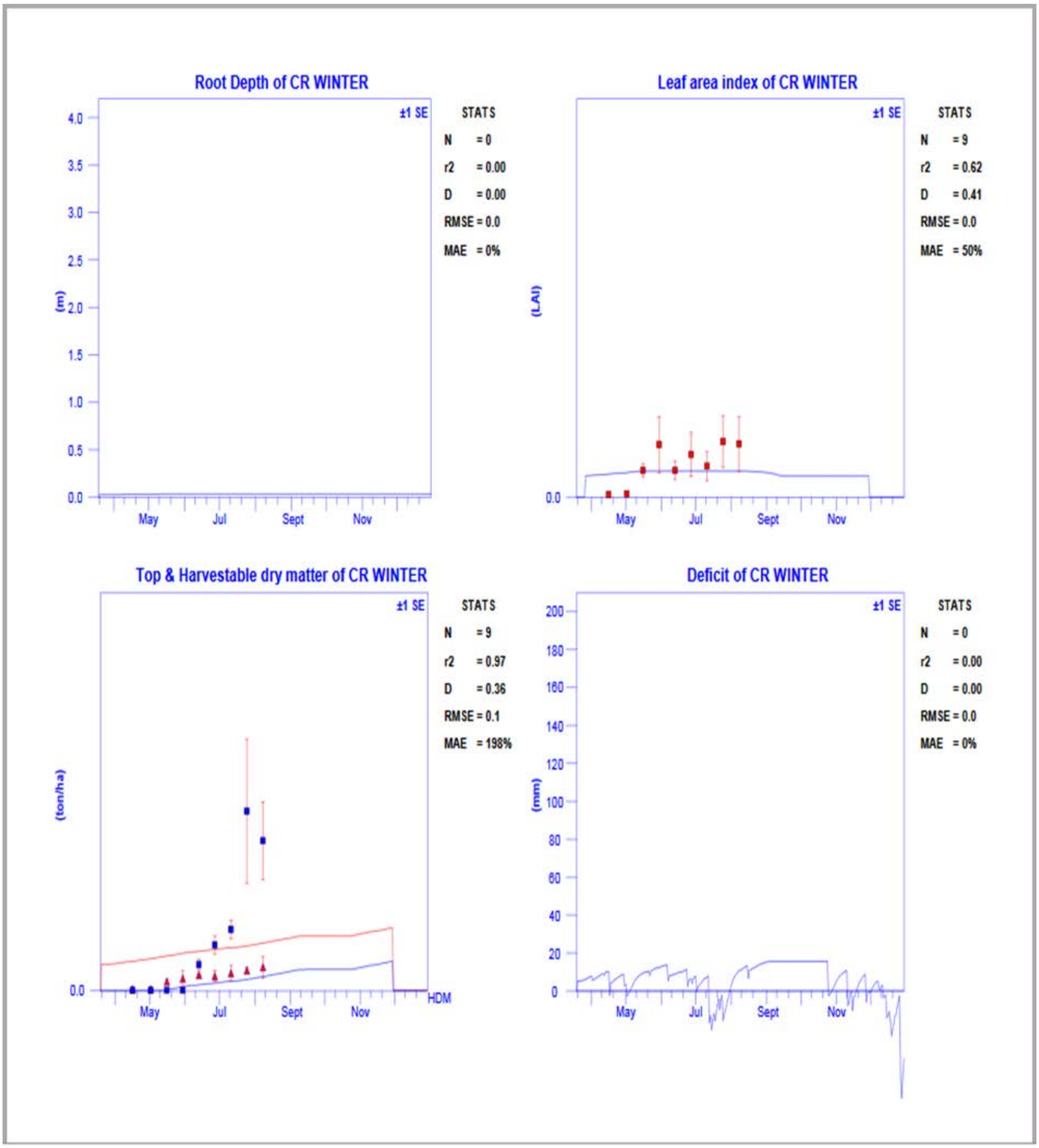

Figure 2.2: Simulated (lines) and measured (dots) LAI and yield for carrots grown during the autumn growing season at Hatfield.

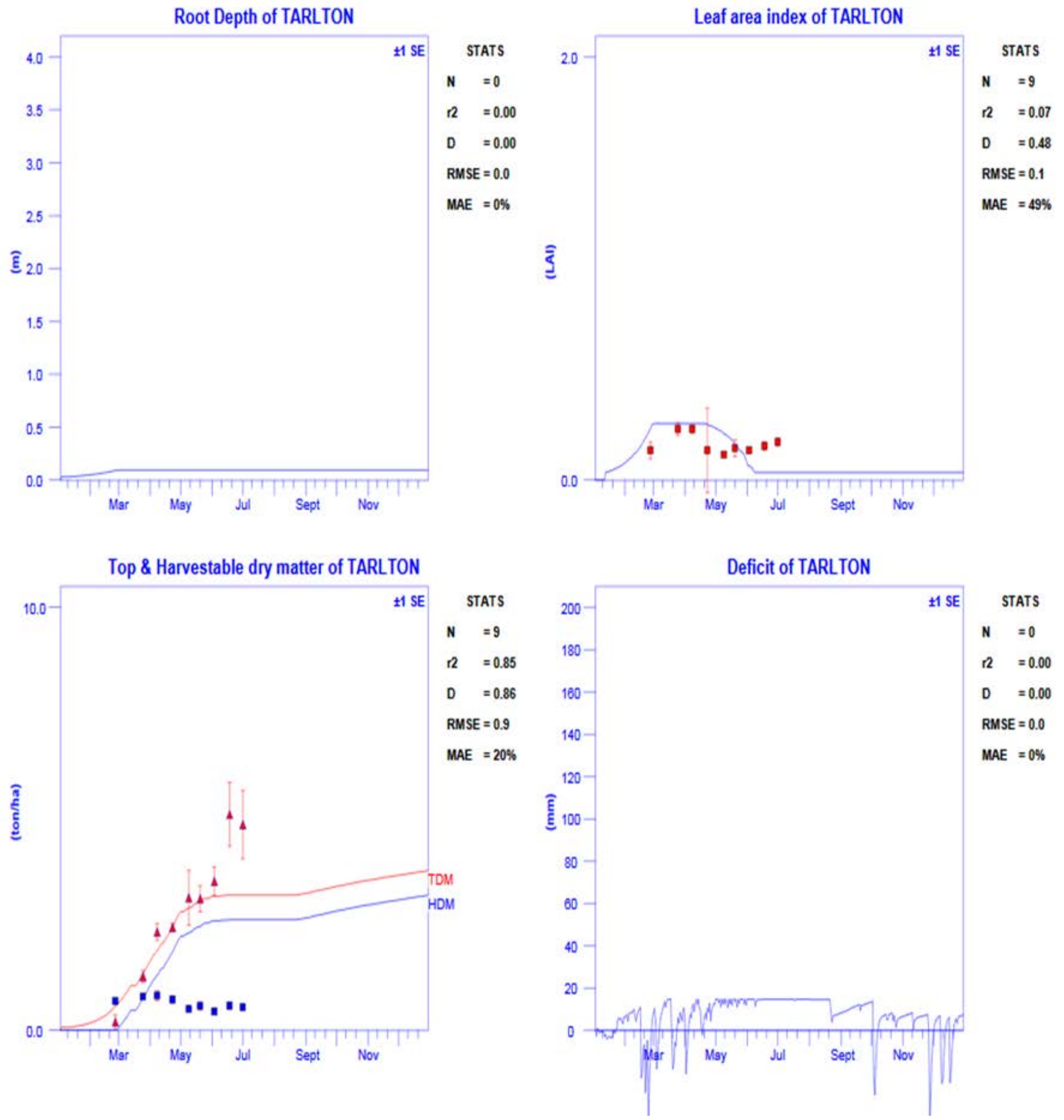

Figure 2.3: Simulated (lines) and measured (dots) LAI and yield for carrots grown during the autumn growing season at Tarlton

2.3.2. The consumptive WFs of carrots planted on different dates

Table 2.1 provides a summary of carrot planting dates, harvest dates, seasonal rainfall and irrigation, drainage, runoff, green water use (ET_{green}) and blue water use (ET_{blue}), and cumulative crop evapotranspiration (ET_c). For the three planting dates, the highest ET_c was observed at Hatfield during the summer season at 547 mm with ET_{blue} of 71 mm lower than ET_{green} of 476 mm as a result of high rainfall during the growing season. However, for both Tarlton and Hatfield during the autumn season, the production of carrot was dominated by the use of blue water resources. Even so, the seasonal water use for Tarlton (433 mm) was relatively higher than Hatfield-autumn with the lowest seasonal ET_c of 383 mm. For both Hatfield (autumn season) and Tarlton, the amount of green water used was lower than blue water for autumn-planted crops as a result of lower rainfall during autumn and winter. The use of both blue and green water resources in crop production is common in many arid and semi-arid regions as a result of erratic rainfall patterns.

Table 2.1: Seasonal rainfall, irrigation applied, drainage, runoff and crop evapotranspiration of carrots planted at different dates at Hatfield and Tarlton.

Location	Planting date	Harvest date	Rainfall	Irrigation applied	Drainage*	Runoff*	ET_{green}*	ET_{blue}*	ET_c*
			mm						
Hatfield	30/10/ 2013	12/03/2014 summer	674	71	198	0	476	71	547
Hatfield	19/03/ 2014	08/08/ 2014 autumn	31	417	65	0	31	352	383
Tarlton	03/01/ 2014	01/07/ 2014 autumn	254	391	212	0	42	391	433

*** Estimated using SWB**

The yields and consumptive (blue plus green) WF of carrots grown on the Hatfield Experimental Farm (summer and autumn season) and Tarlton Greenway Farms are shown in Table 2.2. The total consumptive WF of carrots at both Hatfield (for the two growing seasons) and Tarlton (for one growing season) showed a variation for different planting dates. The variation of WF_{blue} and WF_{green} may be as a result of the different weather conditions thus the accumulation of ET_o that occurred across specific locations and growing seasons. Seasonal differences in environment are common in South Africa, where the summer growing season is characterised by higher temperatures and occurrences of rainfall, while the autumn growing season is characterised by lower temperatures and usually with no rainfall. Therefore, the availability of rainfall in the summer season influences the ratio of blue: green WF. The amount of water used during the growing season does not necessarily inform the total average yield of carrots at different planting dates. Weather conditions of a specific location and growing season as well as the management practices, especially at Hatfield during the summer growing season may have influenced the average yields measured. Tarlton and Hatfield have different weather conditions that could easily influence the accumulation of biomass and water use through the changes in leaf area index, which changes interception, transpiration and evaporation. In addition, the irrigation management, row spacing arrangement and method of cultivation also influenced water use, thus the WF of carrot.

There were also major differences in the ratio of blue/green water use for carrots grown in different growing seasons. The seasonal consumptive WF of carrots produced at Hatfield (summer season) had relatively higher WF_{green} during the growing season as a result of higher rainfall throughout the growing season. However, for both Hatfield-autumn and Tarlton-autumn, the total consumptive WF of carrot was relatively lower than the summer values. Therefore, WF_{green} for the two autumn planting dates was 0 L kg^{-1} as the crop water requirement was met by only the blue water resources that are considered as scarce and under pressure.

Even though carrots grown in Tarlton during the autumn season used higher amounts of water as compared to Hatfield-autumn, the seasonal consumptive WF of 75 L kg^{-1} was relatively lower than for Hatfield in both seasons as a result of higher seasonal yields. The results in Table 2.2 indicate that in order to produce carrots planted at different dates and growing seasons, crop water requirements may differ.

Table 2.2: Crop water use, Yield and the consumptive water footprint of carrots planted in different seasons

Location	Season	Yield	WF_{blue}	WF_{green}	$WF_{blue\&green}$
		t ha^{-1}	l kg^{-1}		
Hatfield	(summer)	37	19	109	128
Hatfield	(autumn)	31	114	0	114
Tarlton	(autumn)	52	75	0	75

2.3.3. Average reference evapotranspiration (ET_o) values for three carrot cropping periods

Higher ET_o values were observed for Hatfield during the summer months when the atmospheric evaporative demand was high (Figure 2.1). The values declined towards the end of the summer season with the beginning of the cooler season, thus resulting in lower ET_o values for autumn. In autumn, ET_o values were above 4 mm at the beginning of the season and decreased towards the winter season as the days grew colder. The decrease of ET_o in autumn and winter season was also shown for Tarlton even though the values were higher as a result of varied weather conditions. In the summer season ET_o reached values of up to 8 mm per day while the lowest values of less than 2 mm per day were observed in the winter season.

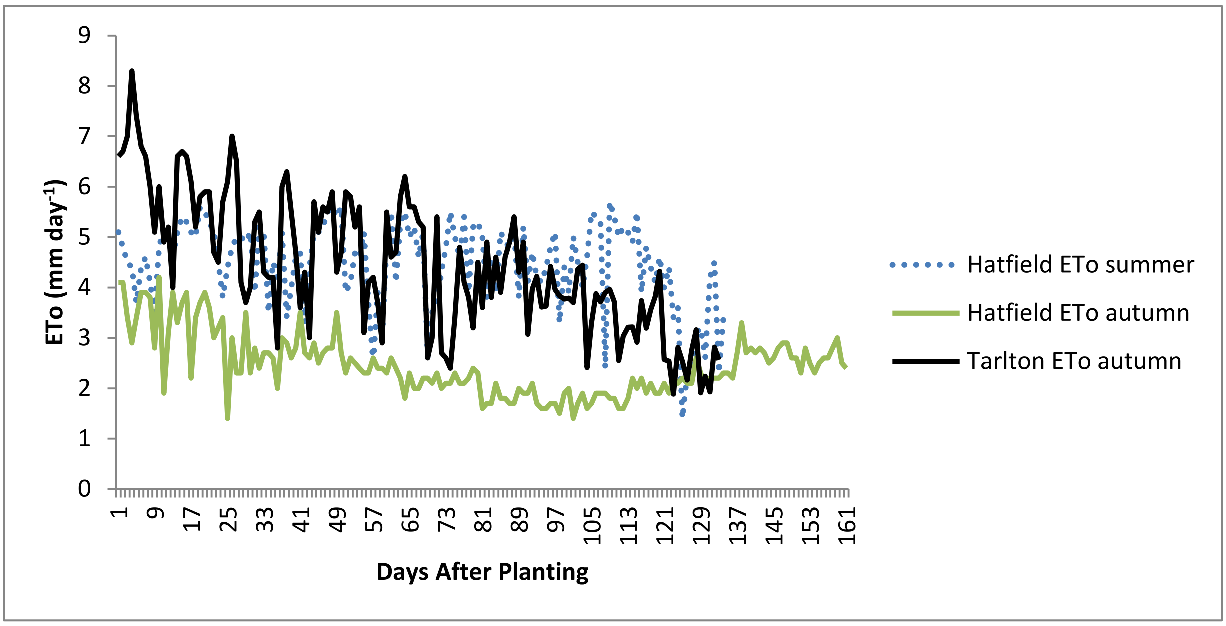

Figure 2.4: Daily reference evapotranspiration (ET_o) for three carrots cropping periods at Hatfield and Tarlton

2.3.4. Average vapour pressure deficit values for three carrot cropping periods

Vapour pressure deficit is tightly linked to temperature and relative humidity, thus as temperature increases so does the value of VPD. As expected and shown in Figure 2.2, VPD values are higher in the summer season at Hatfield when air temperatures were also high as opposed to autumn when air temperatures are lower. VPD is also dependent of the relative humidity (RH) in the growing environment, where RH greater than 85% impacts the VPD gradient lelow the leaf and the atmosphere. At Tarlton, VPD values were high (about 2.1 kPa) at the beginning of the growing season, however, these decreased in autumn and winter (to a minimum value of approximately 0.25 kPa). The same applies for Hatfield during the autumn season, where lower values were observed through autumn and winter season even though increases are shown towards the end of the growing season at Hatfield when spring begins. The highest VPD value observed for the different growing seasons was 2.9 kPa, whilst the lowest value was 0.25 kPa in Tarlton.

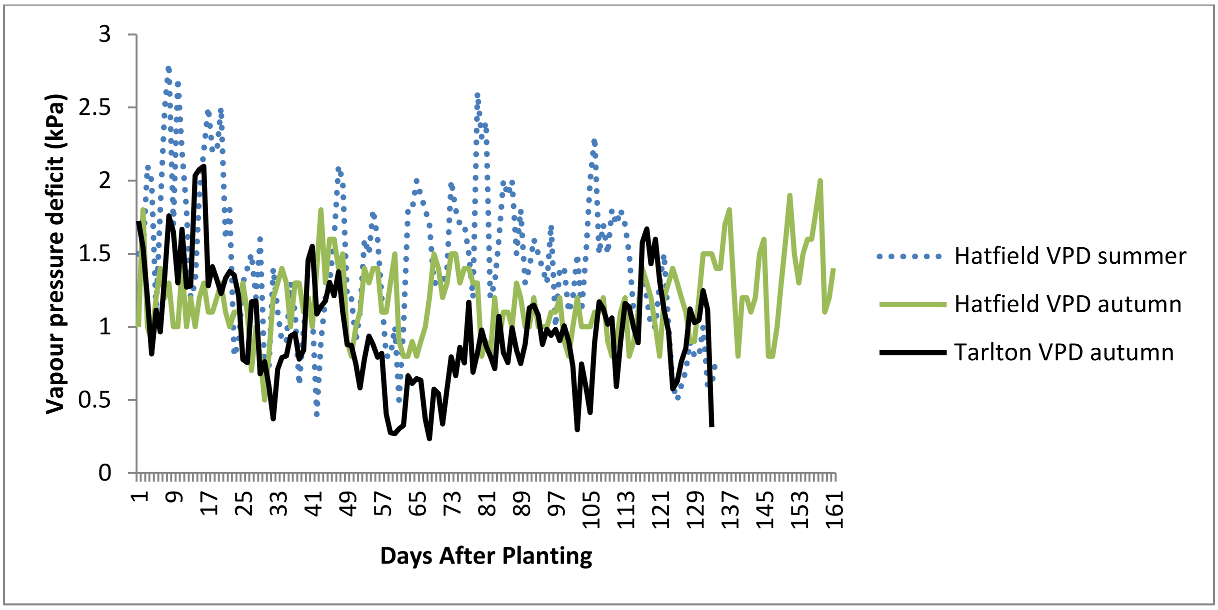

Figure 2.5: Average daily vapour pressure deficit (VPD) values for three carrots cropping periods at Hatfield and Tarlton

2.3.5. Average minimum and maximum air temperatures for three carrot cropping periods

The average maximum and minimum air temperatures for Hatfield and Tarlton are presented in Figures 2.3 and Figure 2.4. The highest daily maximum air temperature (of 32.8 °C) was observed at Hatfield during the summer months, whilst the lowest daily average air temperature was less than 12.4 °C. For Hatfield during the autumn growing season, the highest average daily air temperatures were at the beginning of the season at (± 32 °C), while the lowest minimum value was observed in June (± 0.6 °C). At Tarlton, the highest average air temperature during the carrot production season were also observed at the beginning of the season (31 °C), while the lowest average daily minimum value was also observed in June (1.52 °C). Minimum and maximum air temperatures indicate that Tarlton is much colder as compared to Hatfield in autumn and winter. In addition, minimum and maximum air temperatures also influence the rate of crop growth and development provided there is optimal water availability. The increase in temperature also increases ETo and VPD thus increasing the rate of crop growth and development.

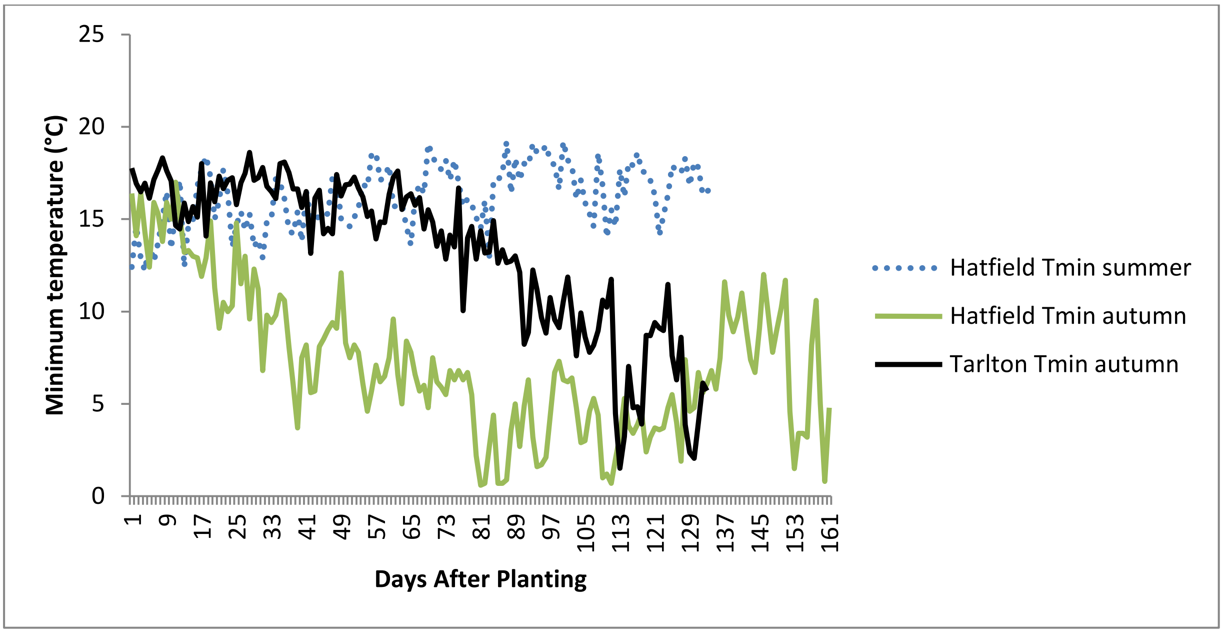

Figure 2.6: Daily minimum air temperatures for three carrots cropping periods at Hatfield and Tarlton

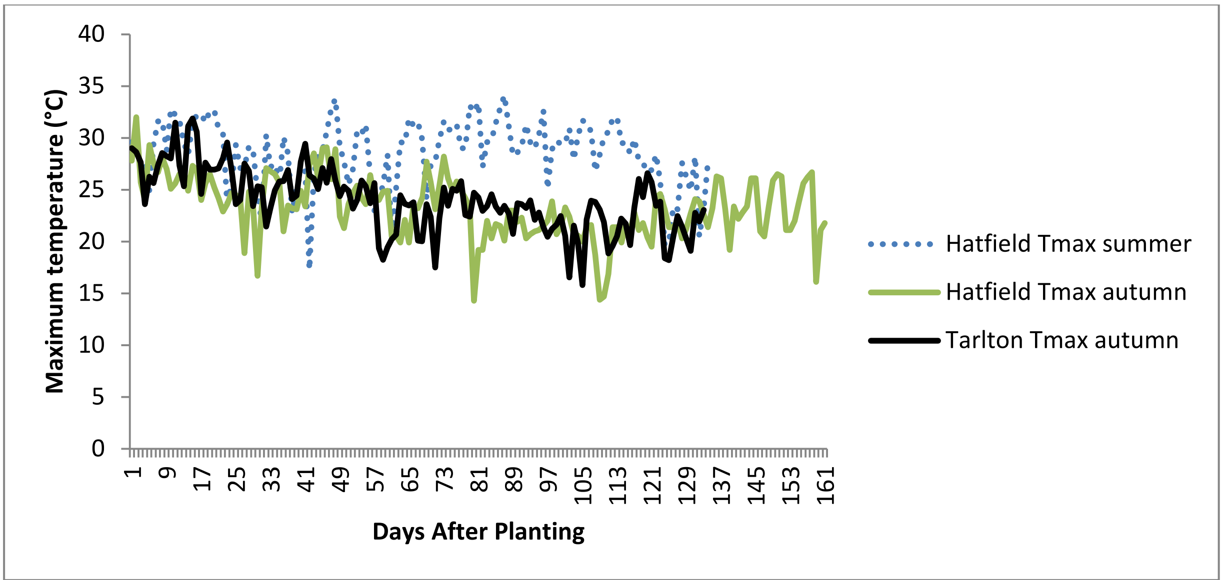

Figure 2.7: Daily air maximum temperatures for three carrots cropping periods at Hatfield and Tarlton

2.4. Discussion

Vegetable crops are usually grown in the cooler growing season because of their adaptability, however, with the development of new cultivars these crops are grown throughout the year (da Silva Dias, 2014a). Even with different cultivars used in this study, the effect of crop cultivar on crop water use and yield, thus the effect on

WF_{blue} and WF_{green} was not measured. Different cultivars of the same crop can easily influence seasonal crop yields as these varieties have different characteristics adaptable to different environmental conditions. As shown in this study, the average yields of carrots varied in the two locations over different planting dates. On the commercial farm (Tarlton), large average yield above 50 tonnes ha^{-1} were obtained during the growing season while lower yields were obtained in the research trial on small scale. Both the summer and autumn average yields were lower than 40 tonnes ha^{-1}. As indicated by Manosa (2011), average carrot yields between 30 and 40 tonnes ha^{-1} are regarded as good even though potential yields for carrot in South Africa were recorded above 60 tonnes ha^{-1} especially on commercial farms. South Africa is a country with diverse environmental conditions that differ from one area to the other (Mahadea and Pillay, 2008). The variation in weather conditions across a wide geographic area influence plant growth and development, thus yield (Bita and Gerats, 2013).

In different growing seasons, weather conditions play a crucial role for crop water use, especially in Gauteng Province where the autumn growing season is dry in the absence of rainfall (Jovanovic et al., 1999). In South Africa, the summer months are categorised with high average temperatures with occurrences of rainfall while the autumn months have lower temperatures with fewer or no rainfall, therefore, influencing the blue: green water used at different seasons. The availability of green water resources during the summer growing season plays an important role in carrot production, as supported by Aldaya et al. (2012), stating that use of green water resources in food production prominently influences water scarcity especially in water limiting countries and reduces pressure on available water. The use of green water resources during production has shown to influence the amount of blue water used. Pahlow et al. (2015) also reported that the wide geographic variation across SA leads to high variable distribution of green water resources which can potentially contribute largely to the total WF of crops in all provinces. This indicates that crop production during the summer growing season has potential to use green water more efficiently while saving blue water resources available for multiple other purposes and ensuring food security for future production.

According to Hatfield and Prueger (2015), vegetative development of plants increases as temperature rises even though carrot is susceptive to extreme hot regions. During the summer growing season there is an increased rate of development when temperatures are high, therefore, crop maturity occurs over a shorter period (Hatfield and Prueger, 2015). The occurrence of crop maturity over a shorter period was shown in this study, where the summer growing season had a shorter growing season as compared to the autumn growing season in both Hatfield and Tarlton. As air temperatures decrease, crop growth also slows down thus development of the crop takes longer even though less water is lost as a result of reduced air temperatures that reduce ET_o and VPD (Laker et al., 2012). This indicates that temperature is an important climatic factor that influences crop growth and yield that will vary across different weather conditions and planting date. Even so, the amount of water used during the growing season does not necessarily indicate higher WF even if there is sufficient water supply in a specific region. Crops with higher WFs in a specific region with limited water resources are usually advised to be grown in water abundant regions.

Temperature is the most important climate factor affecting carrot production. It has an effect on plant growth that is considered to be the accumulation of biomass and influences water use through changes in leaf area index, which changes interception, transpiration and evapotranspiration through its life cycle from germination to emergence, to flowering and maturity. As shown in the study, simulated and measured data outputs of carrot in both Hatfield and Tarlton have not performed well. The poor performance of model calibration could have influenced ET, thus the average WF_{blue} and WF_{green} of carrot. The atmospheric evaporative demand of a growing season is also dependent on the climatic factors of a region, which determines the natural volume of water needed to grow crops. The atmospheric evaporative demand is the driving force of crop water use that is expected to be relatively higher in warmer regions/seasons. However, climate is not the sole determinant of crop WF. Therefore, areas with high evaporative demands do not automatically have high WF. Other factors that influence the WF include, yield, food consumption volumes, diet of people and the ratio of imports versus domestic production and others (Chapagain and Hoekstra, 2004).

According to Tilman et al. (2002), there are different factors that could improve water use in crop production. This includes reducing tillage and mulching in agricultural fields. However, mulching can be challenging on large field. However, different factors affecting water use and yield, thus WF_{blue} and WF_{green} are shown in this study, where Tarlton management practices differ from Hatfield. The irrigation system, row spacing arrangement, cultivation methods, and soil type and soil texture with addition to weather condition could have greatly influenced the average WF of carrot at different planting dates in the two locations. The use of ridges in Tarlton during the growing season could have improved the soil moisture storage as compared to a flat surface where water can easily evaporate thus requiring frequent irrigation. However, the drip irrigation only irrigates a small portion of the soil surface while the centre pivot irrigates the entire surface, increasing water loss through evaporation. This indicates the importance of measuring the different management practices that can easily influence water efficiency and reducing crop WF.

Many studies have evaluated the consumptive WF of different crops around the world, however, there are limited studies that reported on the WF_{blue} and WF_{green} of carrots grown in specific locations and in different growing seasons. The consumptive WF of carrots varied relatively among different growing seasons and specific areas due to differences in planting dates, management practices and environmental factors. The influence of space and time are shown in this study where carrots grown in Tarlton had the lowest consumptive WF as compared to those in Hatfield in both seasons as a result of higher carrots yields and lower ET_o and VPD throughout the growing seasons. Even so, at Hatfield during the summer growing season, the consumptive WF of carrots was relatively higher as a result of lower crop yields that were also measured in the autumn growing season at Hatfield. Higher yields obtained at Tarlton have shown to sufficiently reduced the WF as influenced by the growing seasons which affect the WF_{blue} and WF_{green}. The results of this study supports the findings of Ridoutt and Pfister (2010), stating that the volumetric WF is weather specific which indicated that the different weather conditions in relation to water use greatly influences the WF. Mekonnen and Hoekstra (2011a) also concluded that the consumptive WF of different vegetables varies as a result of different crop characteristics that differ in spatial frequency and length of growing period for cultivated and irrigated area. However, only the WF of carrot was measured in present study.

There are several authors that have evaluated the consumptive WF of vegetable crops in different locations all around the world, including South Africa. Le Roux et al. (2016) studied the total volumetric WF of several vegetable crops including carrot in the Steenkoppies region in Tarlton, South Africa which is the same area as in this study. The average consumptive WF of carrot was measured over four growing seasons where the total carrot WF_{blue} and WF_{green} was 116 L kg^{-1}, which was relatively higher than for carrot grown at Tarlton in this study. The average consumptive WF of carrots at the four growing seasons also differed in every season, as a result of different ET_o. The variation in total consumptive WF of carrot grown in the same area may be influenced by planting and harvesting dates as some crop are grown earlier in the season before the market is saturated.

In a study done by Multsch et al. (2013) in Saudi Arabia (hot and dry environment), the WFs of vegetable crops varied from 167 L kg^{-1} for cucumber to 7026 L kg^{-1} of sesame. In general, all produced vegetable crops had an average WF lower than 500 L kg^{-1}, which correlates with the average global WF of vegetable crops as reported by Mekonnen and Hoekstra (2011a). This is in agreement with the present study, where the consumptive WFs of carrot were lower than 300 L kg^{-1}. Jordaan and Grové (2012) also evaluated the consumptive WF of carrots produced on Zanyokwe vegetable farms in East London, South Africa. The total consumptive WF of carrot was 273 L kg^{-1}. Another important factor that influences the amount of water consumed includes the length of the growing season which is dependent on the weather conditions that notably increase/decrease water use depending on the season, thus WF_{blue} and WF_{green} (Chico and Botín, 2010).

Even with the relatively lower WFs attained in this study, it is still important to reduce the crop WF where possible. Reducing crop WF can be done by considering the timing of production in respect to water availability, which is closely linked to growing season (Schyns and Hoekstra, 2014). Growing crops in the summer season when green water is available can help reduce the use of blue water resources that can become available for multi-purpose activities. In addition, measuring the WF of crop under improved management practices in a specific region with known available water resources, can help reduce the WF as a different production method such as conservation tillage can increases water infiltration and reduces runoff and ET through its mulching effect. In many cases, farmers select the type of crops to grow, however, advisory services especially from extension officers can help reduce water use by providing advice on the WF of different vegetable crops. The crop type and length of growing period largely influences the final WF. Even so, the availability of genetically improved crop cultivars for warmer temperatures also encourages the use of green water resources that can help improve water productivity and reduce the use of blue water resources (Fan et al., 2011).

2.5. Conclusions

Evapotranspiration varies widely across geographical regions and between different seasons that are influenced by landscape and topography, weather conditions, cultivar, nutritional and soil status and agronomic management practices. It is evident that the two locations had different weather conditions, therefore, the WF would differ. Even so, climate is not the only factor influencing the WF. Other factors that potentially influenced the WF of carrot at the two locations, include, the different irrigation systems, row spacing arrangement, cultivation methods and soil type and texture. At different planting dates, the atmospheric evaporative demand is the driving force of plant water use, where warmers temperatures had high atmospheric evaporative demands that facilitate the processes of respiration and photosynthesis, this transpiration. Even so, in extreme temperature, the plant closes its stomata to prevent water loss that could damage the plant cells. Furthermore, the closure of the stomata reduces photosynthesis that is directly linked to the production of biomass. However, the closure of the stomata does not determine average production yields of a crop. Therefore, the amount of water used throughout the growing season does not necessarily determine yield.

Vegetables have high crop water requirements which greatly influences the amount of water irrigated during the growing season, and ultimately determines the final yield. Yield plays an important role in reducing the WF, thus the choice of cultivar should be evaluated to investigate the influence of crop yields and thus the WF. Higher yields were obtained in the autumn growing season at Tarlton while notably lower yields were measured in Hatfield as higher yields are measured in commercial farms. The variation in consumptive WF of carrot at different growing seasons is greatly influenced by yield. Therefore, comparison in crop management and ultimately yield is necessary to reduce the WF and improve water use efficiency. This clearly shows that for the same crop, the consumptive WF can differ in similar or different locations even with similar or different growing seasons.

In this study, the consumptive WF of carrot grown at different sites and planting dates showed a large variation in the total amount of water consumed, thus the variation of WF_{blue} and WF_{green}. In the summer growing season, carrot production was dependent on green water resources, even though blue water resources were used as a supplement which is common in semi-arid regions like South Africa. However, in the autumn growing season, production was met only by blue water resources as a result of lower or no rainfall. However, the use of green water resources in the summer rainy season has shown to reduce blue water resources that are limited and scarce as influenced by climate change and variability. Therefore, the efficient use of green water resources in the rainy season may reduce pressure on available water resources even though many farmers grow vegetable crops in the dry seasons for financial returns.

Chapter 3 Estimating the volumetric blue and green water footprints of Swiss chard and assessing the impact of planting date

3.1. Introduction

Swiss chard (*Beta vulgaris L.*) is one of the popular dark green leafy vegetable crops that has gained economic importance amongst other leafy vegetables because of its nutritional properties (Miceli and Miceli, 2014). In South Africa, this crop is widely cultivated in home gardens, on subsistence farms as well as large commercial farms because of its adaptability to varied environmental conditions allowing all year production (Pokluda and Kuben, 2002). In many parts of the country Swiss chard is grown under irrigation for its large ovate light green to dark green edible leaves that differ in colour depending on cultivar (Palmero et al., 2012). This crop is often wrongfully referred to as spinach (*Spinacia oleracea L.*), and has largely substituted spinach as many farmers prefer it because it is more vigorous and easier to grow. It is a highly nutritious vegetable that is rich in antioxidants, phytonutrients, vitamins, iron, fibre, folate, protein and magnesium (Maboko and Du Plooy, 2013).

Swiss chard is a cool season crop that is usually grown as an annual crop. It has a relatively high tolerance for cold and low tolerance for heat (Love et al., 2009). Depending on location, this crop is also abundantly grown in spring and summer (Kasim and Kasim, 2012). Unlike other green leafy vegetables, Swiss chard tolerates moderate frost but very low temperatures can result in bolting (Love et al., 2009). It allows multiple harvests of the outer leaves as it is able to re-grow from the younger, inner leaves. Maruo et al. (2002) stated that leafy vegetables such as Swiss chard have the potential to increase yields with one sowing time due to the continuous growth and harvesting of leaves that result in higher yields on less area.

Dark green vegetable crops are recognised as one of the most important dietary components in many countries, including South Africa. These crops were introduced to reduce health problems (such as malnutrition) that were mostly experienced by people in developing countries. In arid and semi-arid regions, both water and nitrogen (N) are most often the limiting factors for crop production. In these areas vegetables are mostly dependent on irrigation water, thus N potentially becomes the only limiting factor (Qawasmi et al., 1999). The availability of freshwater is scarce in many regions, thus the need for proper management is essential.

The water footprint (WF) concept has been introduced to indicate water use and impact of production systems on water resources, quantified as the total amount of water used to produce a product (Hoekstra and Hung, 2002). The Water Footprint Network (WFN) approach divides a WF into three water components namely, blue, green and grey water that are measured in terms of water volumes consumed and polluted as a function of space and time. The WF_{green} is the volume of rainwater stored in the soil that is used during the production of a product. The WF_{blue} refers to the volume of freshwater that evaporates from blue water resources to produce a good or service. The WF_{grey} represents pollution and is defined as the volume of freshwater required to dilute pollutant loads based on the existing ambient water quality standards (Aldaya et al., 2012). The objective of this chapter was to estimate the blue and green volumetric water footprints of Swiss chard, including the impact of planting date on the size and constitution of the WF.

3.2. Materials and methods

3.2.1. Study site and trial management

Field experiments were conducted during summer 2013 and autumn 2014 seasons at Hatfield Experimental Farm of the University of Pretoria, South Africa. The farm is located at an altitude of 1327 meters above sea level (masl), latitude of 25°45’ S and a longitude of 28°16’ E. It receives an average rainfall of 670 mm per year and has dry mild winters and wet summers. The highest mean maximum and lowest mean minimum air temperatures are 35°C (January) and 1.5°C (June), respectively. The soil is a Hutton form with a sandy clay loam texture and an average soil pH of 5.4 (Group, 1991).

Trial management

The experimental layout was based on a Randomised Complete design replicated three times. Swiss chard (cv. Fordhook Giant) was planted in three plots of 2×2 m. Within the cropping area of 4 m^2 seven rows of the crop were planted at a spacing of 0.3 m between rows and 0.3 m between plants. Therefore, the plant population on the total area was 40 000 plants per hectare. In the summer growing season, Swiss chard was planted on the 19th September 2013 and harvested on 03 December 2013, 07 January 2014 and 14 February 2014, while for autumn growing season, Swiss chard was planted on the 12th April 2014 and harvested on 12 September 2014, 03 October 2014 and 24 October 2014. Swiss chard seedlings were first grown in seedling trays in a nearby glasshouse using Hygromix growing medium. Two seeds were placed per hole (at a depth of 0.01 m) and thereafter, transplanted at a depth of 0.1 m five to six weeks after emergence. The seedling trays were first sterilised (with Jik) to prevent harmful fungi or plant diseases. Watering cans of 2.5 mm were used three times a week to establish the crop until it was ready to be transplanted. Soil analyses were done before planting to determine nutrient requirements. Nutrients at a rate of 200 kg ha^{-1} N, 100 kg ha^{-1} P and 150 kg ha^{-1} K were applied using split application (with 50% applied before planting and 25% split between the 1st, 2nd and 3rd harvest). The fertilisers were manually incorporated into the soil using a spade. During the growing season, weeds were controlled by hand weeding. Water use and the equipment to measure volumetric soil moisture of Swiss chard after transplanting were the same as described in Chapter 2 for the Hatfield trial.

Growth analysis

Growth analysis of Swiss chard was done by frequently harvesting six plants that were randomly selected per plot. The above ground parts were separated into leaves and shoots. Analysis was done at two to three weeks intervals when four to five leaves were removed per harvest, leaving the younger central leaves to continue developing. Harvestable fresh mass was measured immediately after sampling while dry matter was measured after oven drying the samples at 65°C for a period of five days or until plant dry matter yields remained constant. Leaf area, LAI and FI were also measured/ calculated in the same way as for the Hatfield trial in Chapter 2.

3.2.2. SWB-Sci model parameterisation

The SWB-Sci model local parameters for Swiss chard at Hatfield are presented in Appendix I, II (Table 1 and 2).

3.2.2.1. Weather

Information on weather data is presented in Chapter 2.

3.2.2.2. Soil

Information on soil data is presented in Chapter 2.

3.2.2.3. Crop parameter calibration and model application

Measured data collected during the summer 2013/2014 and autumn 2014 growing season of Swiss chard were used for comparison purposes (measured and simulated). These include LAI and top dry matter yields. The initial soil water content at planting for all the layers was set at field capacity. This assumption can be supported by the high rainfall received during the summer growing season and the fact that the trial was irrigated (Figure 3.1).

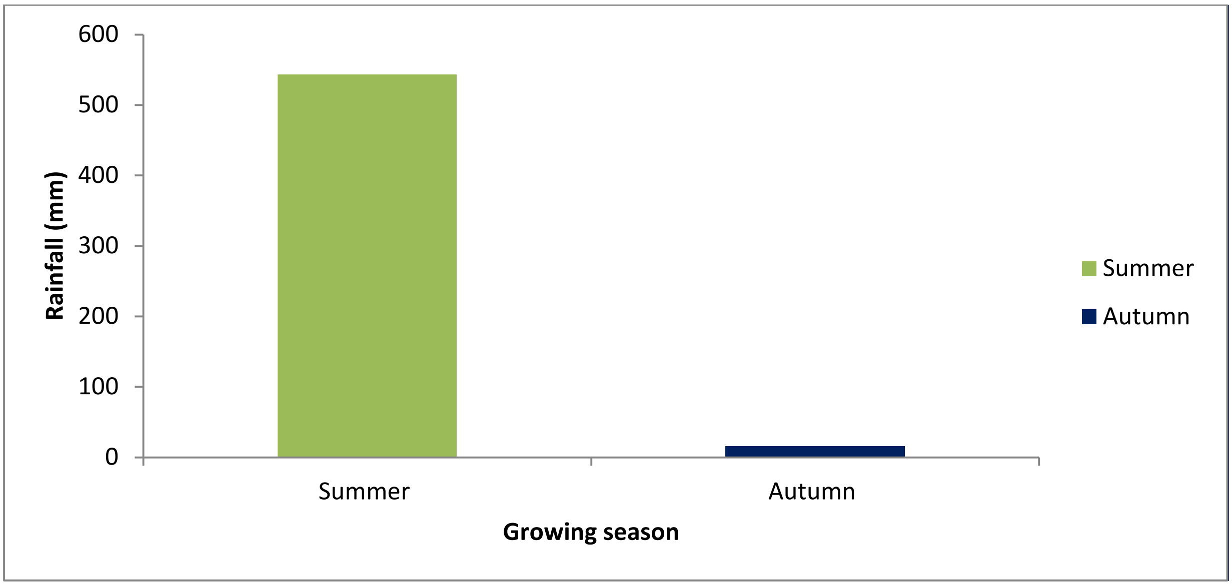

Figure 3.1: Rainfall received during two different Swiss chard growing seasons

3.2.2.4. ET calculation in SWB

Information on calculation of cumulative evapotranspiration (ET) is presented in Chapter 2.

3.3.3. Calculating the blue and green volumetric water footprints of Swiss chard

The calculations of the volumetric water footprint of a crop were presented in Chapter 2.

3.3. Results

3.3.1. Simulated and measured data of Swiss chard grown over two growing seasons at Hatfield

The SWB-sci model simulated and measured data output (root depth, LAI, above-ground dry matter yield (TDM) and soil water deficit) for swiss chard at two growing seasons (summer and autumn) are presented in Figure 3.1 and 3.2. However, no measurements were made for root depth and soil water deficit as this study was non-limiting. The statistical indicators are given at the top right corner of the graphs to show the status of the model calibration. Simulation generally was in agreement with the measured data for all parameters during model calibration as all statistical parameters r2 and D were greater than 0.8 and MAE was less than 20%.

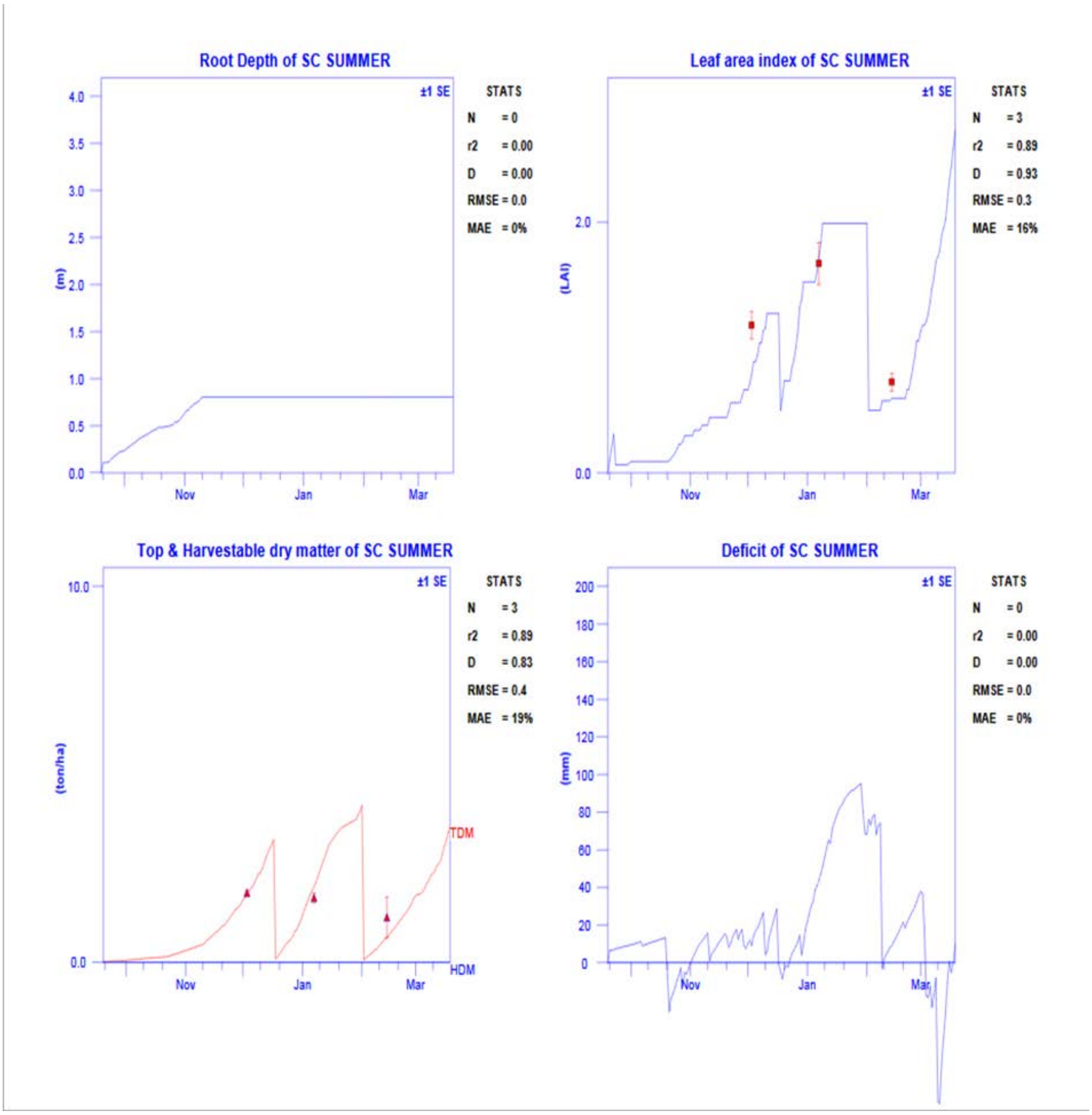

Figure 3.2: Simulated (lines) and measured (dots) LAI and yield for Swiss chard grown during the summer growing season at Hatfield.

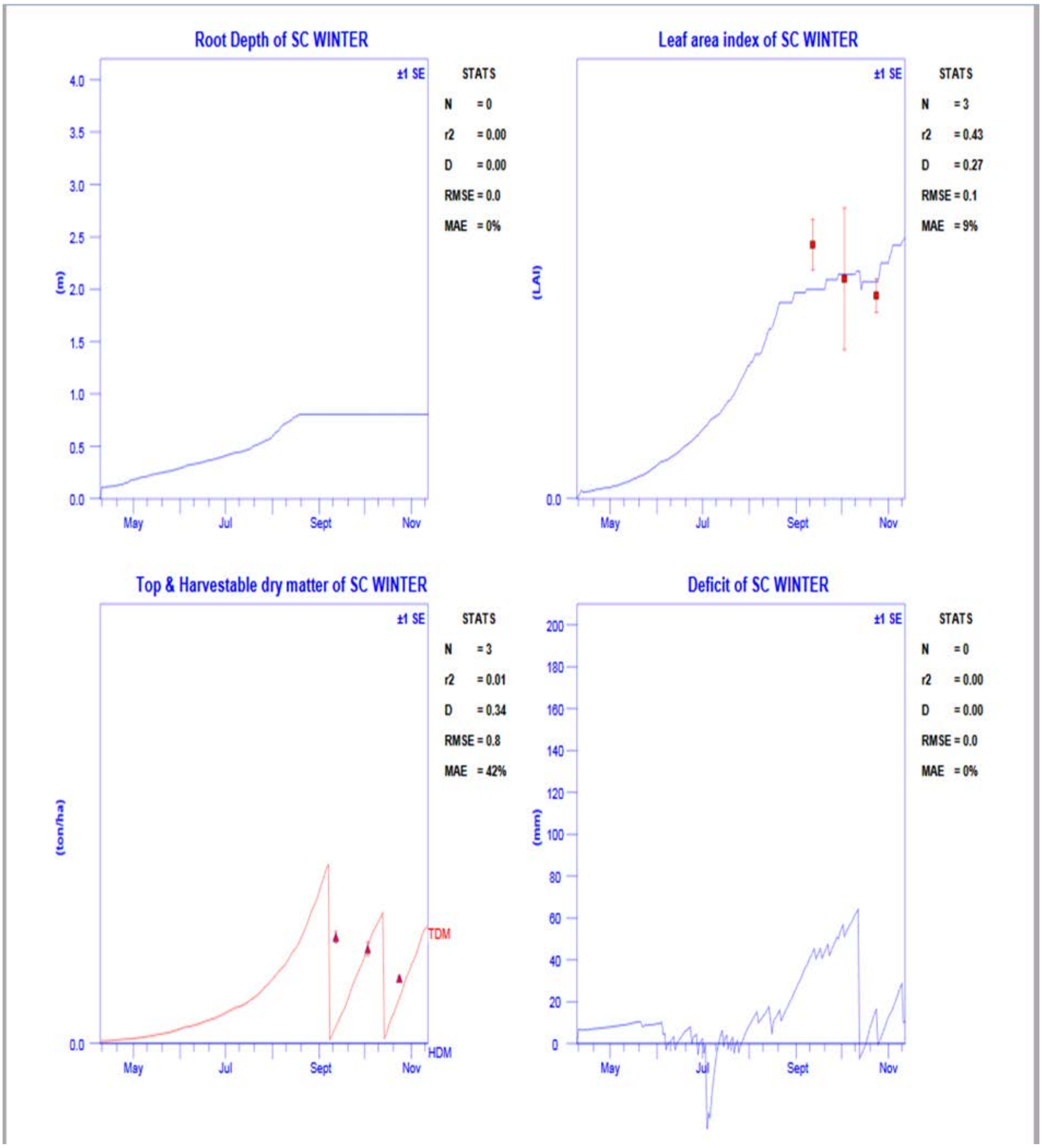

Figure 3.3: Simulated (lines) and measured (dots) LAI and yield for Swiss chard grown during the autumn growing season at Hatfield.

3.3.2. The blue and green WFs of Swiss chard grown in different seasons

Table 3.1 provides a summary of the planting dates, harvest dates, seasonal rainfall and irrigation, drainage, runoff, blue water use (ET_{blue}) and green water use (ET_{green}) over two growing seasons (summer, autumn) at Hatfield. For the summer growing season, rainfall use (ET_{green}) was higher than the use of irrigation (ET_{blue}) throughout the whole growing season. However, this was different in the autumn season, where the use of blue water resources was higher than that of green water in the absence of rainfall. Even so, there were a few occurrences of rainfall (17 mm) that were recorded during the autumn/ winter growing season.

For the summer growing season, Swiss chard seedlings were planted on the 19th September 2013 and the 1st harvest occurred on the 3rd December 2013, which is 36 days from the transplanting date. However, during the autumn growing season as a result of low temperatures, the crop took a longer period to establish, thus the time to the 1st harvest only took place 113 days after transplanting. The slower growth in the autumn growing season partly be due to the cold weather that reduced plant growth. Even so, Swiss chard like many other vegetable crops is a cool season crop grown in the winter months. The highest ET_c was observed for the 1st harvest for both the summer and the autumn growing season, followed by the 2nd harvest and then the 3rd harvest. The high ET_c at the beginning of the growing seasons may be as a result of more water used for the establishment of the seedlings, especially the root system that is needed for effective water uptake.

Table 3.1: Seasonal rainfall, irrigation applied, drainage, runoff, and crop evapotranspiration of Swiss chard planted at different dates at Hatfield.

Season	Planting date (s)	Harvest date (s)	Harvest number	Rainfall (mm)	Irrigation (mm)	Drainage (mm)*	Runoff (mm)*	ET_{green} (mm)*	ET_{blue} (mm)*	ET_c (mm)*
		03/12/2013	1	125	90	45	0	125	90	215
		07/01/2014	2	143	19	59	0	84	19	103
summer	19/09/2013	14/02/2014	3	58	21	11	0	47	21	68
		12/09/2014	1	17	505	78	0	0	353	353
		03/10/ 2014	2	0	78	0	0	0	78	78
Autumn	09/04/2014	24/10/ 2014	3	0	116	6	0	0	67	67

*** Estimated by SWB**

A summary of consumptive WFs of Swiss chard grown in two seasons are provided in Table 3.2. The relationship between seasonal crop water use and crop yields are shown to greatly affect the total consumptive WF of Swiss chard for three harvest events in the two different growing seasons, as influenced by weather conditions. For the summer growing season, Swiss chard average yields for the three harvest intervals were slightly higher than those during autumn. In both growing seasons, Swiss chard yields decreased incrementally for successive harvests. The decline in Swiss chard yields for successive harvests may have been as a result of changing weather condition from autumn to winter and spring. The Swiss chard cultivar as well as the rate of renewal of growth may have also influenced average yields, as different cultivars are adaptable to different weather conditions.

The WF_{blue} and WF_{green} of the Swiss chard crops are also shown in Table 3.2. In the growing seasons, WF_{blue} and WF_{green} differed greatly in terms of crops water use and yield at the three harvest intervals during the two growing seasons. For the summer growing season, the consumptive WF of Swiss chard was highest for the 1st harvest at 34 L kg^{-1}, followed by the 2nd harvest at 27 L kg^{-1} and then the 3rd harvest at 18 L kg^{-1}. The same was applicable during the autumn growing season even though WF_{blue} and WF_{green} of Swiss chard for the 2nd and 3rd harvest had similar values. Similar consumptive WFs at different harvest intervals may be as a result of the changes of weather conditions towards the end of the season. During the summer growing season, Swiss chard production was dominated by the use of green water resources, thus higher WF_{green} as opposed to the autumn growing season that depended mostly on the use of blue water resources with WF_{green} of zero.

Table 3.2: The consumptive water footprint (WF) of Swiss chard over two different growing seasons

Season	Harvest intervals	Yield t ha^{-1}	WF_{green}	WF_{blue} L kg^{-1}	$WF_{green\&blue}$
Summer	1st	39	9	23	32
	2nd	31	21	6	27
	3rd	26	10	8	18
Autumn	1st	38	0	93	93
	2nd	26	0	30	30
	3rd	22	0	30	30

3.3.3. Average reference evapotranspiration values recorded for two different Swiss chard growing seasons

Figure 3.2 shows daily variation of ET_o that fluctuated largely between summer and autumn. In the summer season, ET_o values increased gradually at the beginning of the growing season, levelled off in the middle of the season and then declined as temperatures decreased towards the end of the growing season. For the autumn growing season, ET_o was lower at the beginning of the growing season, with values declining in the middle and then increasing towards the end of the growing season in spring. During the autumn season, the highest ET_o value estimated was 5.5 mm day^{-1} while the lowest value was 1.4 mm day^{-1} (at the beginning of the growing season). The highest ET_o value was estimated in the summer growing season at 5.6 mm day^{-1}, with the lowest value estimated at 1.9 mm day^{-1}. The length of growing season for autumn grown Swiss chard was longer than the summer grown swiss chard, thus more water was required during the autumn growing season even through the cumulative ET in autumn was generally lower than in summer.

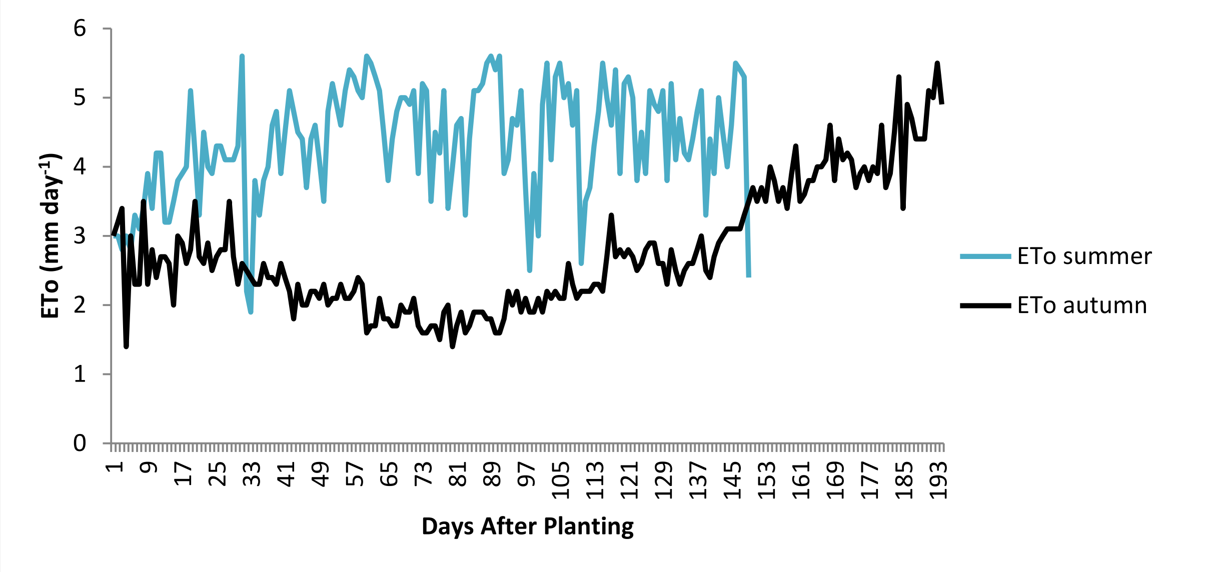

Figure 3.4: Daily reference evapotranspiration of Swiss chard over two growing seasons (summer & autumn) in Hatfield

3.3.4. Average vapour pressure deficit values during two Swiss chard growing seasons

The influence of temperature on VPD is shown in Figure 3.3, where the highest VPD values were observed throughout the summer growing season when average air temperatures were high and relatively low during autumn when average air temperatures were lower. For the summer growing season, the highest VPD values were observed at the beginning of the growing season (around 2.9 kPa), while the lowest value of 0.3 kPa was also observed at the beginning of the growing season on a rainy day when temperatures were low and RH was high. During the autumn growing season, VPD values were higher towards the end of the growing season (± 3.1 kPa) while the lowest VPD of 0.5 kPa was observed at the beginning of the growing season. High VPD values indicate potential water losses when the stomata open to absorb CO_2 from the air, thus photosynthesis occur to increase dry matter.

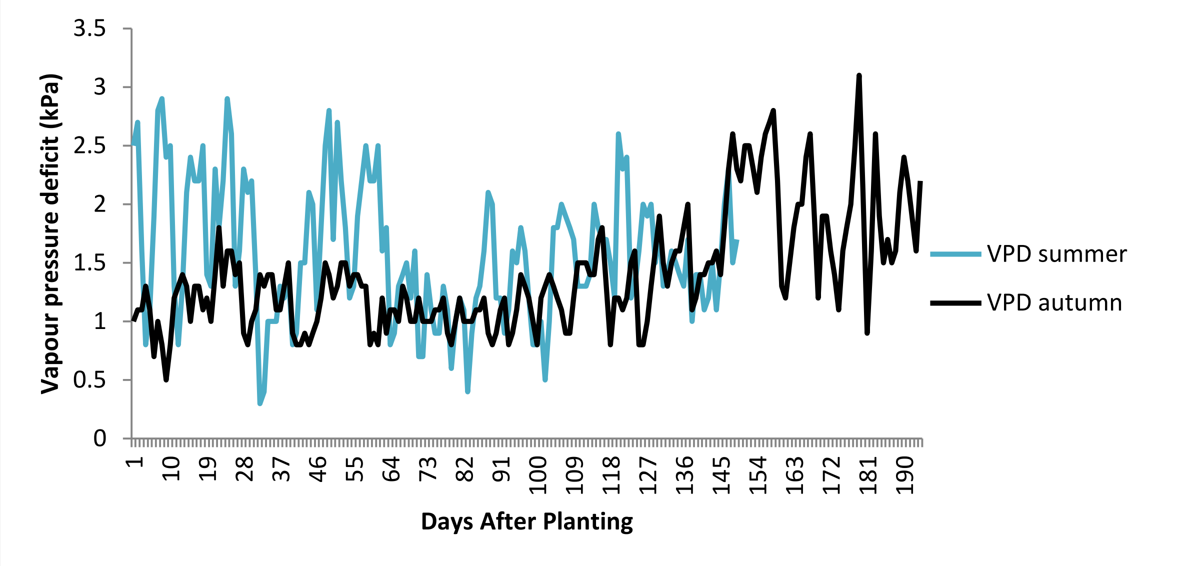

Figure 3.5: Daily vapour pressure deficit (VPD) of Swiss chard over two growing seasons (summer & autumn) in Hatfield

3.3.5. Average minimum and maximum air temperatures during two growing seasons

Figure 3.4 and 3.5 show daily minimum and maximum air temperatures during two Swiss chard growing seasons (summer and autumn). These weather variables show clear variation throughout the different growing seasons. Maximum temperatures in the early autumn growing season showed a gradual decrease while the highest maximum temperature was reached towards the end of the season. The highest maximum temperature was 34.2 °C, with the lowest being 14.3 °C. In the summer months, the highest minimum daily temperatures were measured towards the end of the growing season at 19.2°C, while the lowest value of 0.7°C was also observed at the beginning of the of the growing season. In the summer season with gradual increases in temperatures, Swiss chard grew vigorously over a short period of time, resulting in a relatively short growing period, while in autumn the crop's growing season was longer as a result of lower temperatures which, slowed down crop growth and the growth stages to reach maturity.

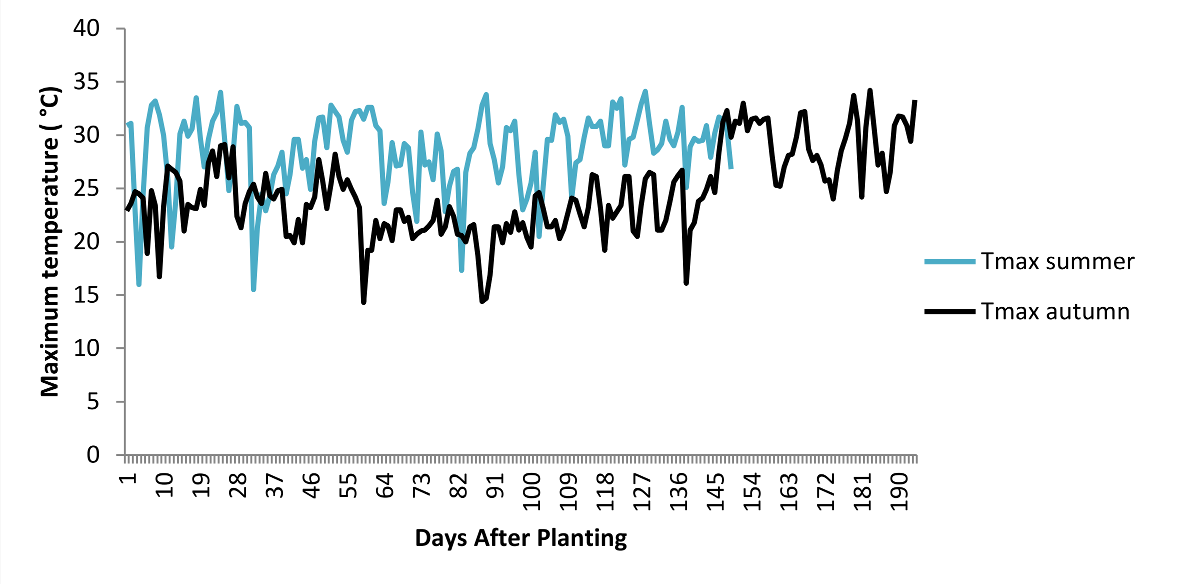

Figure 3.6: Daily maximum air temperatures of Swiss chard over two growing seasons (summer & autumn) in Hatfield

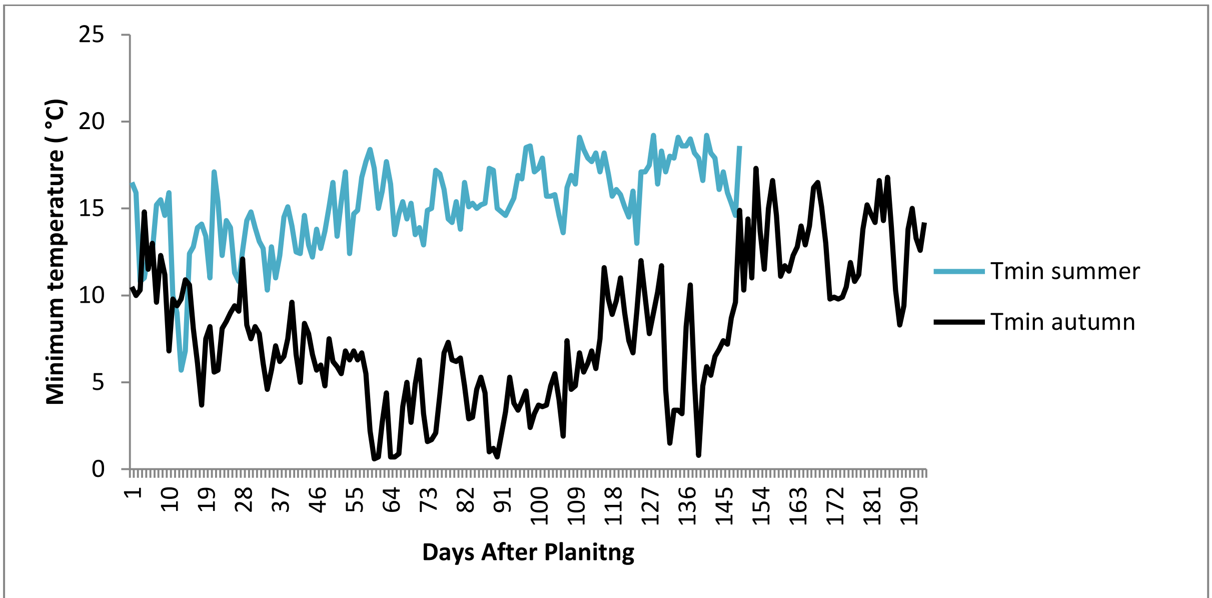

Figure 3.7: Daily minimum air temperatures of Swiss chard at two growing seasons (summer & autumn) in Hatfield

3.4. Discussion

Vegetable cultivation varies across different crop categories, depending on the parts consumed as food. In this case, Swiss chard ss a dark green leafy vegetable crop that is grown for its edible stems and leaves. This crop was grown at one sowing date and harvested at intervals over several months during the summer and autumn growing season. Swiss chard crop can be marketed from as early as two months after transplanting when the crop has reached a harvestable stage (when the outer leaves have reached full size). For this reason, new leaves develop from the growing point, thus leaf harvesting can be repeated when the outer leaves are ready, while the growing point is left to generate new leaves. In the different growing seasons, the growth of Swiss chard was slower with the removal of the older leaves as they supplied nutrients and amino acids to the younger leaves when the crop was fully developed. In addition, the removing the older leaves reduces the storage capacity while that of the younger leaves remains the same.

On average the expected yields of Swiss chard have been reported to range from 20 to 30 tonnes ha^{-1} per season, with highest yield recorded at 50 tonnes ha^{-1} per season (Pokluda and Kuben, 2002). However, in this study the average yields of Swiss chard ranged from 30 to 40 tonnes ha^{-1}. The simulated and measured data outputs showed that Swiss chard performed well as shown by the statistical indicators. This shows that the value ET was estimated objectively, thus the WF. The length of the harvesting intervals as well as the total number of harvest play an important role in determining the average yields harvested. Since Swiss chard was harvested at three intervals, the WF was measured at the intervals. Higher yields were obtained in the 1st harvest and declined from the 2nd to the 3rd harvest. The decline is average yields in the three intervals shows that the plant lost nutrients as the older leaves were harvested thus delaying growth. There are several factors influencing the re-growth, including several environmental factors and management practices. In this study, during the two growing seasons (summer and autumn), Swiss chard was managed using similar techniques, thus the management factors did not influence the total average yields. Therefore, the environmental factors played a great role in influencing the average yield of Swiss chard in the summer and autumn growing seasons.

The influence of crop biomass on the total WF was reported by Nyambo and Wakindiki (2015), where low crop yields resulted in higher consumptive WFs. This was also recorded in the present study, where higher yields observed during the summer growing season, resulted in lower consumptive WF of Swiss chard, while lower yields measured during the autumn growing season resulted in higher WFs.

The average yield of 31 t ha^{-1} achieved in the present study was similar to that reported by Kolota et al. (2010), indicating that Swiss chard grown in the autumn season have lower average yield. This is mainly as a result of rapid growth caused by high temperatures that increase transpiration and thus crop biomass production. According to Maboko and Du Plooy (2013), crop cultivar also influences the average yield harvested per growing season, however, since only one cultivar was used in the two growing seasons, crop cultivar was not a factor in the present study. Even so, higher yields do not necessarily mean lower WF as there are numerous factors that contribute to the WF.

Temperature plays a crucial role in crop production and it is closely linked to both VPD and ET (Manosa, 2011). However, the effect of VPD in crop production combines both the effect of temperature and relative humidity. VPD values increase with the rise in temperature and fall in RH, while VPD values decline with a decrease in temperature and rise in RH (Ray et al., 2002). In the summer growing season when average air temperatures are high, vapour pressure deficit also increase creating variation in air saturation inside and outside the leaf. This in turn encourages the opening and closure of the stomata, facilitating transpiration that directly influence the amount of water that is rapidly lost into the atmosphere. When the stoma opens, CO_2 enters the plant to facilitate photosynthesis. Yield is linearly related to transpiration when compensated for VPD. Therefore, the high VPD observed during the summer growing season, when average air temperatures were high, with low RH, produce less yield, while increasing water use. However, at low VPD and moderate air temperatures when the air is closer to saturation, less water evaporates when the stomata opens, allowing for the absorption of carbon dioxide (CO2) (Tanner and Sinclair, 1983), for photosynthesis, thus improving efficiency and crop yields (Wang et al., 2009).

In this study, large amounts of water were lost during the autumn growing season as influenced by the length of the growing season, (longer in autumn than in summer). The shorter summer growing season was as a result of rapid growth that caused vigorous growth of Swiss chard, and thus shorter harvest intervals. The amount of water used throughout the growing seasons for the specific crop is mostly dependent on both weather conditions and the length of the growing season. According to

Rockström et al. (2007), the consumptive WF of crops is largely determined by agricultural management. However, during the summer growing season, more water was required to meet the crop's water requirements, which are dependent on the atmospheric evaporative demand, which were higher during the summer months and lower in autumn as a result of cumulative ETo for the different growing seasons (Barnett et al., 2005).

The dominant use of blue water resources during the autumn growing season influences water availability especially in areas with limited water where higher WFs can negatively affect water sustainability if water resources are not managed well. In the present study the use of green water resources are dominated in the summer season when rainfall is highest making up to 75% of the consumptive WF. This thus highlights the importance of green water resources to food production. The importance of green water resources are reported by Aldaya et al. (2012) on global food production to contribute 78% to WF_{green}. These findings were supported by Schyns (2013), indicating that food production especially the cultivation of animal feed contributes about 77% of WF_{green} in Morocco during the rainy season. Even though global food production is dominated by the use of green water resources, arid and semi-arid countries such as South Africa are mostly dependent on irrigation to ensure optimal vegetable crop production and profitability as a result of low erratic rainfall patterns that occur in the summer season.

The highest consumptive WF of Swiss chard in both seasons was observed in the first interval during the establishment of the crop's root system. These results are supported by Simonne et al. (2004) who reported that vegetable crops take longer periods to establish the root system that is important in water and nutrient absorption during crop growth. Therefore, the high water levels recorded during the 1st harvest are accounted for. However, the high WF_{blue} of Swiss chard in the autumn season indicates the importance of using green water resources more efficiently and thus save blue water resources. In addition, planting date also play an important role as rainfall only occurs in the summer season of the four seasons in the year.

3.5. Conclusions

The consumptive (blue and green) WF of Swiss chard varied between the two growing seasons, with varied weather conditions that influenced seasonal water use and crop yields. In the summer season, green water was used to meet the crop water requirements of Swiss chard during the growing season, even though as a result of uneven distribution of rainfall, blue water was used as a supplement. However, in the autumn growing season, only blue water is used to meet the crop water requirements, even with less or no rainfall. Crop yields play an essential role in determining the consumptive WF of Swiss chard at different harvest intervals. The ability of Swiss chard to re-grow after each harvest has the potential to improve crop yields, however, at different harvest intervals yield reduces successively for the 1st, 2nd and 3rd harvest, as influenced by factors including the reduction of plant size, the effect of growing season on crop cultivar and the influence of weather conditions at different harvests.

The study indicates the importance of planting dates in affecting crop water demands, depending on water availability of an area. Thus, careful selection of the planting date should be considered, especially in the summer rainy season where lower consumptive WFs were achieved with increased crops yields and the use of green water resources. This will help reduce the use of blue water resources that are at risk of depletion if not well managed. With the intensity of water scarcity, there is a growing interest in improving crops WF, especially of high value crops with large water requirements to ensure food security with limited freshwater resources. Therefore, the challenge is to produce more crops with limited water, thus, reducing the WF per unit of crop produced. This study shows the importance of using green water resources efficiently to help save the blue water resources that are scarcer and more expensive. The results of this study can be used to serve as guideline to farmers to reduce the WF of their crops to reasonable levels, and thus to use green water more efficiently.

Chapter 4 Estimating the volumetric grey water footprint of carrot and Swiss chard grown in Gauteng Province, South Africa

4.1. Introduction

The world population is increasing, leading to increased food demand which is exerting pressure on freshwater resources. Furthermore, projections are made that in the next 30 years the socio-economic growth levels will add even more pressure on the freshwater resources while water pollution and water quality degradation will become one of the key issues in many regions around the world. The challenges of water scarcity and degrading water quality are emerging worldwide at all levels (from local farms to the international - level) (Hedden and Cilliers, 2014). These crises occur across different regions as well as within individual countries such as South Africa (SA). SA is a water scarce country that is among the top 30 driest countries in the world (Postel, 1997). It has an average annual rainfall of 470 mm, well below the world average of 860 mm. Currently, about 65% of fresh water is allocated to irrigated agriculture while approximately 98% of SA's freshwater resources are allocated for human activities (Annandale et al., 1999, Postel, 2000).

Agriculture is a key component that contributes to the world's economy and ensures food security which is a major priority as a result of population growth (Hazell and Wood, 2008). In addition, agriculture has been reported to be the largest overall contributor to water pollution (Herath et al., 2013). Water pollution (in agriculture) is the contamination of water bodies when pollutants are directly or indirectly discharged into surface and/or water ground bodies (Chapman and Organization, 1996). A pollutant refers to a substance or condition that pollutes water or the atmosphere. In crop cultivation, the types of pollutants causing pollution include the use of chemicals as a result of crop cultivation. The increased use of agrochemicals in intensive agriculture highly influences water quality and the availability of clean water for future production (Molden et al., 2010).

Nitrate ($NO_3^{-}N$) leaching is one of the common issues in irrigated agricultural regions where crops with high water and nitrogen (N) requirements tends to increase potential risk of $NO_3^{-}N$ pollution to fresh and marine water bodies (Shen et al., 2011). Even so, many farmers continue to apply excess amounts of water and fertilisers to ensure maximum growth and avoid any risks of deficiencies. Nutrient management, particularly of N, is tightly linked to water management, for example over-irrigation can cause leaching of NO_3^-N from the soil. Fertilisers and water are expensive inputs that decrease farmers profit margins, thus farmers need to realise the importance of optimal irrigation and nutrient scheduling to obtain higher yields with decreased input resources (Levidow et al., 2014). Excessive N fertiliser use potentially causes eutrophication, loss of diversity, water and air pollution. Therefore, it is essential to apply optimal rates of agrochemicals to avoid health challenges and the amount of nutrients lost through leaching. Even though increased crop yields over the past decade were partly due to higher fertiliser use in agriculture, N applied to croplands in excess of crop demand can end up entering the freshwater system causing degradation of water quality and eutrophication of rivers and lakes which has already resulted in loss of biodiversity, human health hazards and killing of marine life (Rosegrant and Cline, 2003). Other agrochemicals such as pesticides, herbicides, etc. also have an effect on water pollution of ground water bodies (Franke et al., 2013). Therefore, this agrochemical should be monitored to ensure water quality and availability.

Although water is considered a renewable resource its availability is finite in terms of the amount available per unit of time in any one region (Pimentel et al., 2004). Even so, water runoff carries sediments, nutrients and pesticides from agricultural fields into surface and below ground water bodies leading to nonpoint-source pollution. Increases in pollution in surface and sub-surface water bodies, do not only pose a threat to public and environmental health but also contributes to the high cost of water treatment, further limiting the availability of freshwater. As a measure of water pollution, the pressure that N pollution puts on freshwater resources is recognised as the grey water footprint (WF_{grey}). The objective of this study was to estimate the volumetric grey water footprint (WF_{grey}) of carrot (a root crop) and Swiss chard (a leafy vegetable) grown in Gauteng Province, South Africa, according to the Water Footprint Network approach developed by Franke et al. (2013).

4.2. Materials and methods

4.2.1. Study site and trial management

The study sites were the same for Hatfield and Tarlton as described in Chapters 2 and 3.

4.2.2. Calculation of the grey water footprint

In the calculation of the WF_{grey} of carrot and Swiss chard, the nutrient N was considered as the only nutrient that leaches from the production field into surface or sub-surface water bodies. These calculations are shown for different planting dates for the two crops in Appendix III. The leaching fraction (portion of N that reaches the surface and/or sub-surface water bodies) was assumed to be 10% as used throughout the literature for all countries and crops (Mekonnen and Hoekstra, 2010; Chapagain et al., 2006). However, the value is a rough estimate since the leaching fraction depends on several factors including crop type, crop-specific N fixation, soil composition and condition, meteorological conditions such as rainfall, local climate and topography among other factors. For the purpose of this study, the recommended ambient N water quality standards of 10 mg l^{-1} and ambient N concentration of 0 mg l^{-1} were used to calculate WF_{grey} (Aldaya et al., 2012).

4.3. Results

4.3.1. The volumetric grey water footprint of carrots

The WF_{grey} of carrots in Tarlton was relatively higher compared to Hatfield in both seasons. The WF_{grey} for autumn grown carrots at Tarlton was 80 L kg^{-1}, followed by that of Hatfield during the autumn growing season at 65 L kg^{-1}, and then the summer grown carrots at Hatfield at 54 L kg^{-1}. The variation of carrot WF_{grey} for the two locations was mainly influenced by crop yields that were obtained at different planting dates but also the amount of N fertiliser applied, which was influenced by agronomic management practices and environmental factors. The WF_{grey} showed a large variation for the two regions with different soil composition, weather conditions and crop yields. In Tarlton, the average fertiliser application rates were double those of Hatfield, as their crop was grown for longer growing periods double those of Hatfield.

Table 4.1: The volumetric grey water footprint of carrots grown at both Hatfield and Tarlton

Location	Average fertiliser application rate (kg N ha^{-1})	Nitrogen leaching fraction	Ambient nitrogen concentration (mg N L^{-1})	Effluent discharge standard (mg N L^{-1})	Yield (tonnes ha^{-1})	Total WF_{grey} (Lkg^{-1})
Hatfield (summer)	200	10%	0	10	37	54
Hatfield (autumn)	200	10%	0	10	31	65
Tarlton (autumn)	418	10%	0	10	52	80

4.3.2. The volumetric grey water footprint of Swiss chard

Table 4.2 shows the volumetric WF_{grey} of Swiss chard grown in two different growing seasons. WF_{grey} for the crop grown during summer was 63 L kg^{-1}, which was slightly lower than WF_{grey} in autumn of 69 L kg^{-1}. As the leaching load was very similar for both seasons, yield plays an important role in determining WF_{grey}. Average yields also play an important role in influencing the volumetric WF of a crop. The average yields were 32 t ha^{-1} in summer and 29 t ha^{-1} in autumn.

Table 4.2: The volumetric grey water footprint (WF_{grey}) of Swiss chard grown in two different growing seasons in Hatfield

Crop	Average fertiliser application rate (kg ha^{-1})	N leaching fraction (%)	Ambient nitrogen concentration (mg N L^{-1})	Effluent discharge standard (mg N L^{-1})	Yield (tonnes ha^{-1})	Total WF_{grey} (L kg^{-1})
Swiss chard (summer)	200	10	0	10	32	63
Swiss chard (autumn)	200	10	0	10	29	69

4.4. Discussion

The amount of nutrients leaching below the root zone are influenced the amount of water applied, fertiliser application rates, fertiliser application methods as well as other external factors, including soil composition and weather conditions. One of the most common factors that influence nutrients leached into surface and sub-surface water bodies include over-irrigation in production fields. As reported in this study, large fractions of water were lost as drainage in both Hatfield and Tarlton, which can easily leach N. The inefficient use of freshwater resources could potentially leach high levels of salts, nutrients and trace elements. However, the level of leaching in vegetable fields varies across different vegetable crops in similar or different crop categories. Variations are shown in this study, were carrots and Swiss chard had different values of WF_{grey}. This is supported by Laspidou (2014) whom indicated that the leaching fraction is mainly dependent on crop yield even though other factors such as fertiliser application rates as well as the accumulation of N in plants can slightly influence crop yield. Furthermore, the variation in WF_{grey} is predominantly driven by water drainage and surface runoff, which is greatly influenced by soil composition, weather conditions, and crop management and yields (Brueck and Lammel, 2016).

Even though leaching contributes to the contamination of surface and sub-surface water bodies, other challenges occur if salts are not leached from the soil profile. These include problems of soil salinity, which is common mainly in arid and semi-arid areas (Multsch et al., 2013). South Africa is a semi-arid region with scarce water resources, therefore, the accumulation of salts in the soil profile may have different implications than in water abundant countries and hence soil salinity is inevitable because of low erratic rainfall patterns and water resources. The amount of salt that has accumulated in the root zone may also influence the amount of water absorbed by the roots as high levels of salts reduce water absorption. The accumulation of salt also affects the crop yields as it influences transpiration that is directly linked to the production of biomass. Reducing the amount of drainage water that may carry nutrients, reduces the amount of pollutants that are discharged into water bodies. However, the quality of available water resources determines the level of utilisation (for example, if the water can be used for agriculture, domestic or industrial) (Dabrowski et al., 2009). Therefore, it is essential to know both quantity and quality of water used and their effects on the farm productivity.

Fertiliser application rate also plays an important role in N leaching and accumulation in crops. As reported by Yang and Zhang (2010), the application rate of N fertiliser influence crops water productivity as influenced by the rate of photosynthesis, canopy size and the harvest index. The increased rate of N application generally increases plant growth and crop yields, however, higher crop yields can also be achieved at optimal fertilisation (Tilman et al., 2002). Sufficient supply of N in crop production is essential to ensure improved crop productivity. However, different crops take up nutrients to their optimal level depending on N fertiliser applied (Hochmuth and Hanlon, 2013). Therefore, there are greater possibilities that higher volumes of water can result in contamination of ground and surface water bodies as a result of high N application rates.

Optimal management practices can help reduce NO_3^-N leaching to a certain extent, but losses of NO_3^-N are inevitable and artificially remain high even with good management practices. This indicates that it is important to do more research to define the leaching fraction better for site-specific conditions. These should be done for different areas, crops and soil types in order to obtain more accurate WF_{grey}

values. Other important values in calculating the WF_{grey} is C_{nat} and C_{max} in the receiving water bodies. Until recently, most publications reported on the value of C_{nat} to be zero while C_{max} is 50 mg NO_3^-N L^{-1} according to the World Health Organisation and the European Union. Even so, the recommended C_{max} value for United States has shown to be lower than the 10 mg NO_3^-N L^{-1} which is mostly used in literature (Chapagain et al., 2006, Mekonnen and Hoekstra, 2011a). Liu et al. (2012) showed different results where C_{nat} is not stated to be zero, even though all rivers are considered to naturally transport nutrients. This indicates that the results are based on assumptions thus these results can be used to create awareness rather than to indicate the level of pollution as the volume of available water in receiving water bodies is unknown.

4.5. Conclusions

The WF_{grey} of selected vegetable crops showed relative variation between different growing seasons in different locations as influenced by a number of factors including crop type and the variation in climatic conditions within the two seasons. The effect of different crop cultivars was not addressed in this study. Even so, it is important that all factors influencing NO_3^-N should be evaluated to get more conclusive results. In addition, even though the same crop is grown in the same area under different weather condition, WF_{grey} differ. However, since the WF_{grey} gives a rough estimate leaving out factors such as runoff rates, rainfall intensity, soil properties, slopes, management practices and the amount of already mineralized N in the upper soil layer, this indicates that the values of the WF_{grey} do not necessarily show a true reflection of water pollution caused by NO_3^-N leaching.

The use of water in the production of crops should be considered carefully to avoid incidences of reduced water quality as a result of N pollution. In addition, rainfall is not the only factor that influences the level of leaching from the root zone, however, factors such as N application rate, type of irrigation system, irrigation amounts and environmental factors also greatly influence leaching, thus WF_{grey}. Hence, more research should be done to better understand N losses. Furthermore, more focus should be placed on improved irrigation and N management because both factors influence the amount NO_3^-N leaching into surface and/or ground water bodies. In addition, intense rainfall patterns can also influence the leaching factors of nitrates, therefore, it should also be taken into consideration.

GENERAL CONCLUSIONS AND RECOMMENDATIONS

The study investigated the volumetric WF of two selected vegetable crops planted at different dates and locations. The size of the volumetric WF of the crops grown in summer was dominated by the green volumetric WF, while a large fraction of WF_{blue} was measured during the dry autumn growing season. The ratio of blue:green water consumption indicates the importance of green water resources in food production, even though South Africa has low, erratic rainfall patterns that are unevenly distributed throughout the summer season. This is why production is often supplemented by irrigation water, even in the rainy season. Effective use of rainwater can help reduce the use of blue water resources, and thus decrease pressure on scarce freshwater resources, especially in arid and semi-arid regions. However, optimal management to ensure improved crop water use efficiency may contribute significantly to reducing blue water use. Most importantly, the results illustrated the importance of separating the blue and green water use in order to obtain reliable results on how production influences water availability, thus ensuring sustainability.

Most studies show the importance of producing agricultural products using green water resources, particularly in water abundant countries where green water is sufficient to satisfy local production. However, this may not be possible in many arid and semi-arid regions where food production is satisfied by the use of both blue and green water to meet crop water requirements. Even so, as a result of increased temperatures in the summer growing season, the amount of water used throughout the growing season is often higher as compared to the autumn growing season. When possible, it is important that farmers consider growing their crops in the rainy season in order to reduce the use of blue water resources in vegetable production.

The planting and harvesting dates, and therefore the length of the growing period used in the study varied as influenced by weather conditions. In the summer growing season, the length of the growing season was shorter as a result of higher temperatures that directly influences the amount of biomass produced per unit of time. The cooler temperatures in autumn lead to slow crop growth and development, hence, increasing the length of the growing season and related water use. Therefore, it can be advised that farmers especially in water scarce regions grow their vegetable crops in the summer growing season, rather than, during the dry autumn season. The choice of the planting and harvesting dates clearly influences the estimated crop WF. The variation in crop WF at different planting dates was also influenced by the other environmental and agronomic management practices that varied between the two locations. Therefore, more field trials should be conducted under different site-specific conditions or model to determine the best methods to reduce the crop WF.

Commercially produced crops have shown lower WFs as compared to research field trials as a result of higher yields obtained on the Greenway Farms (Forster et al., 2013), therefore, more studies should consider working on a larger scale to measure the water-related impact of one crop on different catchment areas. For example, the Greenway farm is the largest carrot producer in Africa thus measuring the WF of carrots in this region provides a lot of insight on the real issues that influences water availability and scarcity challenges in Tarlton. South Africa’s annual carrot production sufficiently supply the domestic market, leaving a surplus to be exported to other countries. With more frequent droughts experienced in this country, the current and future food production is unknown, therefore, more research should be done at different catchment areas to measure the impact on water use, and thus ensure sustainability.

Carrot and Swiss chard have different water requirements as one is a root crop and the other is a leafy vegetable crop. Therefore, this shows that the total volumetric WF of these crops cannot easily be compared. In addition, there was a large variation in WFs for the same crop in different growing seasons in a single location and this indicates that the WF can differ notably both between similar and different crops. With different harvestable parts, swiss chard have lower WF than carrots even though carrots grown in Tarlton had a lower than Swiss chard grown in autumn. Swiss chard is a leafy vegetable crop that can be harvested over several months from a single planting, while carrots are only harvested once the crop is fully mature. This indicates that Swiss chard has a greater potential to reduce the WF because of the length of the growing season that resulted in higher yields generated from several harvesting events.

Vegetable crops have different cultivars that are adaptable to the diverse environmental factors around South Africa. Therefore, various cultivars should be evaluated regarding their suitability for different environmental conditions, thereby potentially replacing less optimal crops in a specific area. For a certain region, an alternative crop variety may pose an opportunity to raise both sustainability and efficiency. In general, the WF can be reduced by increasing crop yields and avoiding unproductive evaporation (E). This can be done, for example, by careful objective irrigation scheduling in order to improve water use efficiency and thus WF_{blue}.

Although weather conditions play an important role in ET and yields, the amount of water used by a crop is also largely influenced by agronomic management practices. For example, on the commercial farm, the carrot crop was grown on a ridge that potentially allows better root development and water infiltration, compared to carrots grown on a flat surface. Other strategies that can help reduce the pressure on freshwater resources in SA include improving crop water and nutrient uptake, improving water availability, improving infiltration and soil water-holding capacity and improving nutrient availability. Management practices that can help achieve this include mulching, application of organic amendments, measuring soil water content to inform irrigation scheduling and others. The improvement of these management strategies may not work for all areas, therefore all the different factors that can improve crop WF needs to be assessed on a site-specific basis.

Soil properties play an essential role in water storage capacity thus the amount of water stored in the soil for vegetation. The soil water holding capacity is based on the dominant soil type, especially texture. Soil properties also play an important role for the estimated WF_{grey} as water pollution is also affected by the ability of a soil to hold nutrients. WF_{grey} was relatively lower in all the measured trials at Hatfield while higher values were recorded for Tarlton as a result of different management practices, including soil composition, water use, fertiliser application rates, crop cultivars and the application methods. All research trials of the same crop at Hatfield were considered to receive the same fertiliser application rate, however, many commercial farmers, including Greenway Farms tend to apply excessive fertiliser, while subsistence and small holder farmer depend on crop residues and manure to ensure N application.

N was the only pollutant considered for WF_{grey} in this study, acknowledging that other pollutants such as other nutrients, pesticides and herbicides may also be important. Phosphorus (P) is another common nutrient that contributes to eutrophication as a result of surface runoff that also contributes to water pollution, therefore, its potential to influence water pollution should also be assessed in future studies. The WF_{grey} is measured based mostly on assumptions which give a rough estimate, leaving out the local factors that influence the precise leaching loads and runoff rates. These factors include the amount of N that has already mineralised in the soil layer, rainfall intensity, soil properties and slope.

The availability of water resources are declining with the change in climate and increased weather variability, thus based on currently available water resources, farmers could consider shifting production of each crop to a specific growing season and location where it is most efficient. An improvement in production practices as well as crop yields are necessary to reduce the WF and since vegetable crops are adaptable to warm summer weather, these high value crops can be grown in an area where the available water resources can meet the crop water requirements without significantly affecting the availability of water resources. More importantly, the impact of the WF of a specific commodity should be measured in a confined area as water availability and water stress are measured for specific geographic regions. Different activities exist in one confinement, these activities may include water supply for domestic purposes or industry that differently influence water availability. Hence, measuring the temporal and spatial dimensions of the WF for each of the goods or services may provide distinct information in evaluating sustainability.

Each of the selected crops in a specific region has a specific WF, thus there is no precise value of a crop WF in a certain area. Therefore, careful consideration should be taken in drawing conclusions from this study, as average WFs of one product may vary from one location to the other, making comparison difficult even in very similar crops grown for specific regions. When two similar goods have the same WF, this means that those commodities have the same prerogative on regional freshwater resources (Carmo et al., 2008). However, if the WF of one commodity is in a water-rich area while the other is in a water scarce region, then their local impact on fresh water resources differ significantly.

In semi-arid regions like South Africa where the production of fruits and vegetables use about 90% of the irrigation water (Annandale et al., 2011), it is important to understand environmental sustainability of activities in terms of water use with the aim to reduce the overall amount of water used per unit of production. Water scarcity is a key challenge that is identified in confined areas, where blue water scarcity can be addressed for temporal dimensions to assess the influence of crop production on available water resources on local scale. Therefore, it is important to assess the impact of the WF of vegetable crops grown on large commercial farms as controlled research trials may be biased as data collected may allow accurate results in measuring the WF for the specific area and time. The level of water scarcity occurring in different countries has proven to encourage WF reduction in irrigated agriculture by improving water use efficiency of green water resources that will help save blue water resources and therefore ensuring sustainability.

Based on the findings from this study, the following future research is recommended:

- Determine the variation of different crop cultivars on WF metrics,
- Clearly evaluate the influence of harvest number in leafy vegetable crops that can re-grow on the WF,
- Base WF research on commercial farms to better quantify actual water impacts for a specific area or catchment,
- Improve WF_{grey} methodology to incorporate other aspects influencing water pollution where possible,
- Integrate the use of crop residues and manure in the WF,
- Measure the WF of vegetable crops in all growing seasons (spring, summer, autumn, winter),
- Include pack house and wastage WFs to enable further comparisons between crops and further along the supply chain.
- Standardise on WF_{grey} pollution criteria

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Appendices

Appendix I

Table 1: Soil profile modelling parameters for the Hatfield Experimental Farm and Tarlton Greenway Farm

Parameters	Hatfield	Tarlton
Runoff no. (dimensionless)	400	1000
Field capacity (kPa)	-10	-10
Permanent wilting point (kPa)	-1500	-1500
Drainage factor (0-1)	0.60	0.80
Drainage rate (mm day^{-1})	50	70
Root depth limit (m)	1.0	1.0
Bulk density (kg m^{-3})	1400	1464

Appendix II

Table 2: Local parameters of the two selected vegetable crops for the Soil Water Balance (SWB-sci) model used to simulate the data required for calculating the volumetric water footprints

Parameters	Carrot	Swiss chard
Extinction coefficient	1.31	0.44
Dry-Matter-Water Ratio (kPa)	8	6.5
Conversion efficiency (kg MJ^{-1})	0.00087	0.0030
Base temperature (°C)	7.2	4.4
Temperature optimal light(°C)	15.0	25.0
Cut off temperature (°C)	23.9	23.9
Emergence day degree(°C)	103	50
Maturity day degree(°C)	1450	2800
Transition day degree(°C)	1238	2800
Maximum leaf age	1450	1509
Maximum height (m)	0.4	0.4
Maximum root depth (m)	0.6	0.8
Stem to grain translation	0.5	0.5
Canopy storage (mm)	1	1
Minimum leaf water potential (kPa)	-1500	-1500
Maximum transpiration (mm day^{-1})	9	10
Specific leaf area (m^2 kg^{-1})	17.9	12.64
Leaf stem partitioning (m^2 kg^{-1})	0.45	1.46
Total dry mass at emergence or transplanting (kg m^{-2})	0.0005	0.0003
Root fraction	0.1	0.28
Root growth rate	2.0	3.5
Stress index	0.95	0.85

Appendix III

Calculation of the grey water footprint for carrot in two seasons (summer and autumn) for the Hatfield Experimental Farm and Tarlton Greenway Farms

Hatfield Experimental Farm

Summer production

$$\text{Grey WF}\left(\frac{\text{L}}{\text{kg}}\right) = \left(\frac{\alpha * \text{AR}}{\text{C}_{\text{max}} - \text{C}_{\text{nat}}}\right) \times \left(\frac{1}{\text{Y}}\right)$$

$$= \left(\frac{0.1 * 200\ \frac{kg}{ha}}{10\frac{mg}{L} - 0\frac{mg}{L}}\right) \times \left(\frac{1}{37\frac{ton}{ha}}\right)$$

$$= \left(\frac{20\ \frac{kg}{ha}}{10\ \frac{mg}{L}}\right) \times \left(\frac{1}{37\frac{ton}{ha}}\right)$$

$$= \left(2\frac{kg\ L}{mg\ ha}\right) \times \left(\frac{1}{37\frac{ton}{ha}}\right)$$

$$= 0.054\frac{\text{kg L}}{\text{mg ton}} \times \frac{1\ \text{ton}}{1000\ \text{kg}} \times \frac{1\ 000\ 000\ \text{mg}}{1\ \text{kg}}$$

$$= 54\ \frac{L}{kg}$$

Autumn production

$$\text{Grey WF}\left(\frac{\text{L}}{\text{kg}}\right) = \left(\frac{\alpha * \text{AR}}{\text{C}_{\text{max}} - \text{C}_{\text{nat}}}\right) \times \left(\frac{1}{\text{Y}}\right)$$

$$= \left(\frac{0.1 * 200\ \frac{kg}{ha}}{10\frac{mg}{L} - 0\frac{mg}{L}}\right) \times \left(\frac{1}{31\frac{ton}{ha}}\right)$$

$$= \left(\frac{20\ \frac{kg}{ha}}{10\ \frac{mg}{L}}\right) \times \left(\frac{1}{31\frac{ton}{ha}}\right)$$

$$= \left(2\frac{kg\ L}{mg\ ha}\right) \times \left(\frac{1}{31\frac{ton}{ha}}\right)$$

$$= 0.0645 \frac{\mathbf{kg\ L}}{\mathbf{mg\ ton}} \times \frac{\mathbf{1ton}}{\mathbf{1000\ kg}} \times \frac{\mathbf{1\ 000\ 000\ mg}}{\mathbf{1\ kg}}$$

$$= 65\ \frac{L}{kg}$$

Tarlton Greenway Farms

$$\mathbf{Grey\ WF}\left(\frac{\mathbf{L}}{\mathbf{kg}}\right) = \left(\frac{\alpha * \mathbf{AR}}{\mathbf{C_{max}} - \mathbf{C_{nat}}}\right) \times \left(\frac{\mathbf{1}}{\mathbf{Y}}\right)$$

$$= \left(\frac{0.1 * 418\ \frac{kg}{ha}}{10\frac{mg}{L} - 0\frac{mg}{L}}\right) \times \left(\frac{1}{52\frac{ton}{ha}}\right)$$

$$= \left(\frac{41.8\ \frac{kg}{ha}}{10\ \frac{mg}{L}}\right) \times \left(\frac{1}{52\frac{ton}{ha}}\right)$$

$$= \left(4.18\frac{kg\ L}{mg\ ha}\right) \times \left(\frac{1}{52\frac{ton}{ha}}\right)$$

$$= 0.080 \frac{\mathbf{kg\ L}}{\mathbf{mg\ ton}} \times \frac{\mathbf{1\ ton}}{\mathbf{1000\ kg}} \times \frac{\mathbf{1\ 000\ 000\ mg}}{\mathbf{1\ kg}}$$

$$= 80\ \frac{L}{kg}$$

2. Calculation of the grey water footprint of Swiss chard in two seasons (summer and autumn)

Hatfield Experimental Farm

<u>**Summer production**</u>

$$\mathbf{Grey\ WF}\left(\frac{\mathbf{L}}{\mathbf{kg}}\right) = \left(\frac{\alpha * \mathbf{AR}}{\mathbf{C_{max}} - \mathbf{C_{nat}}}\right) \times \left(\frac{\mathbf{1}}{\mathbf{Y}}\right)$$

$$= \left(\frac{0.1 * 200\ \frac{kg}{ha}}{10\frac{mg}{L} - 0\frac{mg}{L}}\right) \times \left(\frac{1}{32\frac{ton}{ha}}\right)$$

$$= \left(\frac{20\ \frac{kg}{ha}}{10\ \frac{mg}{L}} \right) \times \left(\frac{1}{32\,\frac{ton}{ha}} \right)$$

$$= \left(2\,\frac{kg\ L}{mg\ ha} \right) \times \left(\frac{1}{32\,\frac{ton}{ha}} \right)$$

$$= 0.0625\,\frac{\text{kg L}}{\text{mg ton}} \times \frac{\text{1ton}}{\text{1000 kg}} \times \frac{\text{1 000 000 mg}}{\text{1 kg}}$$

$$= 63\ \frac{L}{kg}$$

<u>Autumn production</u>

$$\text{Grey WF}\ \left(\frac{\text{L}}{\text{kg}}\right) = \left(\frac{\alpha * \text{AR}}{\text{C}_{\text{max}} - \text{C}_{\text{nat}}}\right) \times \left(\frac{1}{\text{Y}}\right)$$

$$= \left(\frac{0.1 * 200\ \frac{kg}{ha}}{10\,\frac{mg}{L} - 0\,\frac{mg}{L}} \right) \times \left(\frac{1}{29\,\frac{ton}{ha}} \right)$$

$$= \left(\frac{20\ \frac{kg}{ha}}{10\ \frac{mg}{L}} \right) \times \left(\frac{1}{32\,\frac{ton}{ha}} \right)$$

$$= \left(2\,\frac{kg\ L}{mg\ ha} \right) \times \left(\frac{1}{29\,\frac{ton}{ha}} \right)$$

$$= 0.0690\,\frac{\text{kg L}}{\text{mg ton}} \times \frac{\text{1 ton}}{\text{1000 kg}} \times \frac{\text{1 000 000 mg}}{\text{1 kg}}$$

$$= 69\ \frac{L}{kg}$$