Cape Peninsula University of Technology

Water footprint analysis of table grape production in the Berg River region of South Africa

by

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DECLARATION

I, ANELE SIGADLA, declare that the content of this dissertation/thesis represents my own work and that the dissertation/thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

24 May 2022

Signed	**Date**

ABSTRACT

South Africa is a water-scarce country. There are limited research results available regarding the effects of overhead netting on vegetative and reproductive performance, as well as water use efficiency (WUE) and the water footprint (WF) of table grape vineyards. The main objective of this study was to accurately quantify the water use of table grape vineyards produced without netting *vs*. those produced under overhead netting. The study, conducted over one season (2018/19), included a field trial in three commercial Crimson Seedless production blocks on the farm Môrester near Piketberg, as well as survey, conducted on the twelve commercial Crimson Seedless blocks in the Berg River region. Growing degree days (GDD) in the open blocks during the season was slightly warmer, with higher GDD compared to the netted blocks. Open blocks had a faster accumulation of GDD, because of higher average temperatures at the beginning of the season compared to the netted blocks. This resulted in the open blocks being approximately a week earlier in terms of phenology budburst, compared to the netted blocks. Overhead netting has a strong impact on shoot development by significantly increasing shoot growth compared to open blocks. The highest yield was recorded in the open blocks D8, D29 and L87. WUE based on the irrigation and ET water use ranged between (1.96 and 2.61 t/m³), and (1.41 and 1.73 t/m³). The blue WF (Irrigation) determined from total and export production, ranged from (430 to 603 m³/ton), and (618 to 877 m³/ton). There was a strong positive correlation between weekly shoot growth and FruitLook CPB for the three field trial blocks, as evident from the R^2 values of 0.824 (M5); 0.967 (M10); and 0.860 (M12). FruitLook ET (estimated water use) is considered a reliable indicator of water use for open (uncovered) blocks, but not for blocks covered with overhead netting, because overhead netting influences spectral reflection of crops, thus affecting the remote sensing data values. Further research is needed to obtain accurate remote sensing values for estimating water use of blocks covered with overhead netting. More research is needed to quantify vineyard water use of netted blocks, compared to open blocks, including sap flow measurements to determine grapevine transpiration and establish vineyard transpiration values and using the universal soil water balance method to establish vineyard ET values.

Keywords: Water footprint, table grapes, water use efficiency, overhead netting, South Africa, FruitLook.

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DEDICATION

This is dedicated to the memory of my late mother who recently passed away and could not see this thesis completed. I will always love her and may her soul rest in peace.

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CPB	Cumulative Biomass Production
CS	Crimson Seedless
GDD	Growing Degree Days
ET	Evapotranspiration
ETFL	FruitLook Evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
LAI	Leaf Area Index
PGR	Plant Growth Regulator
RDI	Regulated Deficit Irrigation
RGB	Redglobe
RH	Regulated Humidity
SA	South Africa
SATI	South African Table Grape Industry
STD	Standard program
T	Temperature
TA	Titratable Acid
TSS	Total Soluble Solids
WF	Water Footprint
WFN	Water Footprint Network
WRC	Water Research Commission
WSpd	Wind Speed
WUE	Water Use Efficiency
WUEc	Crop Water Use Efficiency

CHAPTER 1

INTRODUCTION AND BACKGROUND

1.1 Introduction

South Africa (SA) is a water-scarce country, receiving around 470 mm of rainfall per annum (Avenant *et al.,* 2017). As a result, table grapes (*Vitis vinifera* L.) are exclusively produced under irrigation in some other regions (Kangueehi, 2018). Due to the water being a scarce natural resource, there is the need to accurately quantify water use of table grape vineyards produced conventionally (without netting) or of those produced under overhead netting. Even though there is little scientific published information about the effect of overhead netting on water use of table grape vineyards, including Avenant (1994); Rana *et al.* (2004); Moratiel and Martínez-Cob (2012) and Suvočarev *et al.* (2013), there is evidence that netting has an significant effect on microclimate and vineyard water requirements (Suvočarev *et al.,* 2013).

According to Novello and de Palma (2013), netting is widely used in horticulture to protect plants from adverse conditions such as hail, wind or light excess, pest attacks and bird damage; hence the existence of several publications on this topic. Shade netting enables advanced utilisation of solar energy and facilitates the protection of plants from environmental hazards by making harsh microclimate changes more optimally suited to plants (Shahak *et al.,* 2006). Protected cultivation, including shade netting has proved to be particularly suitable for early-maturing cultivars and seedless grapes, contributing to improved grape quality, as well as decreased transpiration by vines and evaporation from the soil, resulting in a decrease in water use (Novello and de Palma, 2006).

Several parameters can be used to assess water use, including crop water use efficiency (WUEc), which is defined as the total biomass production, shoot biomass, or economic harvested yield per unit area in relation to total evapotranspiration (ET), plant transpiration or seasonal water use (irrigation and rainfall) (Chaves *et al.*, 2007). The water footprint (WF) of a product is defined as the total volume of water resources used to produce goods and services consumed by the individual, community, or business (Hoekstra *et al.,* 2009) and is categorized into three categories, namely the green, blue and grey WF (Mekonnen and Hoekstra, 2011). The blue WF refers to the volume of surface and groundwater consumed (evaporated) as a result of the production of a good; the green WF refers to the rainwater consumed; and the grey WF of a product refers to the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards (Mekonnen and Hoekstra, 2011).

WF is an indicator of both direct and indirect water use of a consumer or producer (Egan, 2011). As Mafika (2019) pointed out, SA faces several water resource challenges, including the realities of increasing water stress and competition for water due to population increase, economic growth and climate change, hence the need to improve water use efficiency (WUE) and reduce the non-beneficial use of the available water resources. Agriculture has been identified as playing a key role or as being one of the factors causing global water stresses (Herath *et al.,* 2013) due to the amount of water that this sector uses. Therefore, WFs have increasingly been used to indicate the impacts of water use by production systems (Herath *et al.,* 2013).

However, there is a lack of basic management skills on irrigation water management and practical irrigation scheduling at scheme level in SA (Fanadzo *et al.,* 2010). To date, there has been a limited number of detailed WF studies undertaken in SA (Pahlow *et al.,* 2015). WF can be calculated for any well-defined group of consumers (e.g. an individual, family, village, city, province, state, or nation) or producers (e.g. a public organization, private enterprise, or economic sector) for a single process (such as growing grapes) or any product or service (WFN, 2018).

Pahlow *et al.* (2015) pointed out that in SA, the blue WF exceeded blue water availability in several basins for several months of the year. It seems that a possible option to improve sustainable water use would be to buy the water rights of farmers growing low-value crops and allocate this water to environmental uses (Aldaya *et al.,* 2010). Crops with a high yield or large fraction of crop biomass that is harvested generally have a smaller WF per ton than crops with a low yield or small fraction of crop biomass harvested (Mekonnen and Hoekstra, 2011).

1.2 Motivation for the research

There are few publications on WUE and the WF of table grapes in SA, including Pahlow *et al.* (2015); Avenant *et al.* (2017) and Kangueehi (2018). Kangueehi (2018) pointed out that WF information can be used in sustainable water resource management and the improvement of WUE within water-scarce areas. Therefore, this study sought, drawing on the water use concerns raised, at determining and assessing the blue WF of the table grape cultivar Crimson Seedless and investigating opportunities for increasing WUE. Since there have not been many studies on WUE and WF of table grape vineyards and specifically on Crimson

Seedless, this study will contribute to the existing literature by providing novel information in this regard.

Accurate quantification of vineyard water use is important for irrigation scheduling to optimise yield, growth and quality. After two seasons of drought conditions in the Western Cape, at the start of the 2017/18 season in the Berg River region, the main concern was that water availability could become a severe problem due to low water reserves built up during the previous winters and extremely low levels of groundwater. The concern was also that the water shortage could affect the quality and post-harvest shelf life of grapes.

Increasing demands for the limited available water resources by the growing urban population of the Western Cape and the agricultural sector necessitate measures to save water and to improve WUE. The table grape cultivar Crimson Seedless was selected as the focus of the study because it is one of the main cultivars planted both in SA, Chile and other countries and it also has a long growing season (Jarmain, 2020). It is also very popular among table grape consumers.

Several South African table grape producers report observations of decreased water use under overhead netting, but they do not have scientific results to support these observations. Accurate quantification of the water use and the WF of a table grape vineyard could be used in irrigation scheduling to improve WUE, as well as in negotiations with policymakers regarding future water allocation. Against this background, quantifying table grape vineyard water use in the Berg River region, as well as the effects of overhead netting on table grape vineyard water use, has been identified as important research priorities or knowledge gaps by the Berg River Table Grape Producers Association (BTPV) Board. Through this study, a WF analysis of table grape production in the Berg River region of SA will be conducted to quantify table grape vineyard water use, as well as to determine whether overhead netting does decrease the use of water by table grape vineyards.

Currently, table grape vineyard establishment cost is R524 216 per hectare, while the production cost is R370 309 per hectare (SATI, 2020). Results of this study would contribute to verifying whether overhead netting decreases vineyard water requirements and improve grape quality. The results could be used as a basis for further field trials to, for example, investigate expected advantages of using overhead netting, namely improved production and quality, decreased water use, less sunburn, wind damage and bird damage.

1.3 Aim and Objectives

The overall aim of this study was to do a WF analysis of table grape production in the Berg River region of SA. The specific objectives were to:

- Determine and assess the effect of overhead netting on the grapevine phenology, vigour, production and quality;
- Determine and asses the seasonal water use, WUE and the WF of table grapes produced under netting versus conventional production (without netting); and
- Establish whether FruitLook remote sensing data could be used as reliable indicators of vineyard vigour and water use.

1.4 Chapter Outline

This dissertation is organised in six chapters. The first chapter gives an introduction and background and an indication of why the dissertation has been compiled. Chapter 2 presents the general literature review of the study. Chapter 3 presents general materials and methods used. This is followed by chapter 4 which presents research findings and a discussion on the effect of overhead netting on mesoclimate, vegetative and reproductive performance, as well as water use efficiency and the blue water foot print of *Vitis vinifera* L. cv. Crimson Seedless in the Berg River region of SA. Chapter 5 presents a case study on *Vitis vinifera* L. cv. Crimson Seedless in the Berg River region of SA to compare FruitLook data and field measurements for assessment of vegetative growth and water use of table grape vineyards. Chapter 6 presents the general conclusions and recommendations for further research.

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CHAPTER 2

GENERAL LITERATURE REVIEW

WATER FOOTPRINT AS AN INDICATOR OF THE WATER USE EFFICIENCY OF TABLE GRAPE PRODUCTION SYSTEMS

ABSTRACT

SA faces several water resource challenges, including the realities of increasing water stress and the competition for water due to the population increase, economic growth and climate change, hence the need to improve WUE. There is a need to accurately quantify the water use of table grape vineyards produced without netting *vs*. those produced under overhead netting. The main objective of this literature review was to document WF as an indicator of the WUE of table grape production systems. WUE evaluation and improvement have emerged as critical issues in grapevine production. Climatic and environmental factors affecting water use by vineyards include temperature, relative humidity, vapour pressure deficit, radiation, wind speed, soil water content, soil temperature, salinity, and rainfall. It was evident that cultivar development and evaluation play a vital role in selecting drought resistant cultivars. South African agricultural researchers should pursue integrated research on the WF of table grapes produced under overhead netting.

Keywords: Water footprint, table grapes, water use efficiency, overhead netting, South Africa.

2.1 INTRODUCTION

WF is an indicator that is used to assess both direct and indirect water use by a consumer or producer (Egan, 2011). SA faces a number of water resource challenges, including the realities of increasing water stress and the competition for water due to the population increase, economic growth and climate change, hence the need to improve WUE (Mafika, 2019). Increasingly, WFs are being used to indicate the impact of water use on production systems (Herath *et al.,* 2013). In SA, the blue WF exceeded blue-water availability in several basins for several months of the year (Pahlow *et al.*, 2015) and due to the low annual rainfall of 470 mm, table grapes are exclusively produced under irrigation in SA (Avenant *et al.*, 2019).

Knowledge on irrigation water management and practical irrigation scheduling at scheme level in SA is weak (Fanadzo *et al.,* 2010). To date, there have been a limited number of detailed WF studies undertaken in SA (Pahlow *et al.,* 2015) and only a few on table grapes (Avenant *et al*., 2017; Kangueehi, 2018; and Jarmain, 2020). Because SA is a water-scarce country, there is a need to accurately quantify the water use of table grape vineyards produced conventionally (without netting), as well as of those produced under overhead netting.

This chapter provides a brief overview of the South African table grape industry within the broader South African agricultural industry. A review of the available literature regarding the seasonal water requirement, WF and WUE of table grape vineyards, as well as the effect of overhead nets on table grape vineyard WUE, microclimate, phenology, vegetative and reproductive parameters, was conducted to identify the research gaps.

2.2 OVERVIEW OF THE TABLE GRAPE INDUSTRY IN SA

The SA table grape industry makes a significant economic contribution that is estimated at over R3 billion of the agricultural Gross Domestic Product (GDP) in SA (SATI, 2019). The 2016/17 crop yielded much-needed foreign currency export earnings of no less than R7 billion at the farm gate (SATI, 2019). The fact that the industry is export-driven has brought valuable foreign currency to the economy of the country and has directly created more than 13 507 permanent jobs and 65 163 seasonal or casual jobs (SATI, 2020).

During the 2019/20 South African table grape season, the largest harvest ever was recorded with 66.15 million 4.5 kg cartons exported (SATI, 2020). Table grape production is characterized by intensive use of water, which put pressure on local or regional water resources, particularly in dry regions (Permanhani *et al*., 2016). In SA, table grapes are produced in five regions (Northern Provinces, specifically in Mpumalanga and Limpopo, Orange River region, Olifants River Valley, Berg River region, and Hex River Valley) on 672 farms owned by 342 owners (SATI, 2019). Currently, the industry has invested in 20 400 hectares of table grapes, producing 66 149 984 tonnes of grapes per season, of which 95.1% get exported and 4.9% get sold on the domestic market (SATI, 2020).

2.3 WATER FOOTPRINT ASSESSMENT METHODS

Various scientists have used different methods to calculate WF after the original approach was criticized in some quarters (Hoekstra *et al*., 2011; Van de Laan, 2017; Jarmain, 2020; and Mekonnen and Hoekstra, 2010). As Jarmain (2020) points out, these methods differ in terms of how a WF is defined and how it is calculated and how the values are interpreted. Currently, there are four approaches and methods applicable to agricultural WF assessments. These include the Global Water Footprint Standard (GWFS), water footprint assessment (WFA) through life cycle assessment (LCA), Water Footprint Network (WFN), and Hydrological-based approach (Table 2.1)

Table 2.1: Approaches and methods used for WF assessment

Approaches and methods	Description	Reference
GWFS	This approach aims to assess the degree of sustainability with which freshwater is used to produce the particular product.	Mekonnen and Hoekstra (2010)
WFA through LCA	This approach focuses on the impact of certain processes on scarce freshwater resources.	Ridoutt and Pfister (2010)
WFN	This approach aims to use the WF concept to promote the transition toward sustainable, fair and efficient use of fresh water resources worldwide.	Hoekstra *et al.* (2011)
Hydrological-based approach	This approach considers all the components of the water balance, rather than water consumption only.	Van der Laan (2017)

This study formed part of a comprehensive project, WRC Project K5/2710/4, "Water footprint as an indicator of sustainable table and wine grape production" (Jarmain, 2020), solicited and funded by the Water Research Commission (WRC) and co-funded by Vinpro. The WF method agreed upon and approved by the Reference Group, for WRC Project K5/2710/4, was the GWFS (Mekonnen and Hoekstra, 2010). In WRC Project K5/2710/4, the blue, green and grey WF were assessed. This study focused on the blue WF of the production process of table grapes and GWFS was considered as the most appropriate method.

This study focused only on the blue WF, due to the following reasons: (i) the results of the WRC project indicated that in the Berg River Valley, the blue WF accounted for more than 70% of the total WF of table grape production (Jarmain, 2020); and (ii) in the WRC project, several assumptions had to be made to calculate the grey WF, due to a lack of site-specific data (Jarmain, 2020).

2.4 SEASONAL WATER REQUIREMENT, WATER FOOTPRINT AND WATER USE EFFICIENCY OF TABLE GRAPE VINEYARDS

2.4.1 Seasonal water requirement

The scarcity of water in most South African grape growing regions (Myburgh, 2011b) has consequently made irrigation water a limited resource (Myburgh, 2011a). As Myburgh (2012) highlights, irrigation water, under given conditions, must be applied to maintain the high levels of water availability required for table grape production. Annual rainfall in SA is too low for dryland (non-irrigated) commercial table grape production, hence this industry's dependence on irrigation schemes (Myburgh, 2011b).

Water use of vineyards varies according to regions, the irrigation practices used, the vineyard characteristics and the vine vigour (Avenant, 2018). The Western Cape Province has a Mediterranean climate with long and dry summers, during which almost no flow occurs in the major river systems (Myburgh, 2011a). Water statistics and improved performance metrics at the vineyard are required to optimize water use along the supply chain (Costa *et al.*, 2016). Results from previous studies indicated annual irrigation requirements of table grape vineyards in SA to be inconsistent and varying from 256 mm to 1 863 mm (Table 2.2).

Table 2.2: Annual irrigation requirements of table grape vineyards under South African conditions from previous studies

Cultivar	Irrigation method	Reference
Dan-ben Hannah	256 mm with low frequency drip irrigation to 492 mm with daily pulse drip irrigation	Myburgh and Howell (2012)
Barlinka	411 mm for drip irrigation and 569 mm for micro sprinkler irrigation	Saayman and Lambrechts (1995)
Barlinka	663 mm and 741 mm irrigated with micro sprinklers	Myburgh (1996) and Fourie (1989)
Sunred Seedless and Muscat Supreme	879 mm with micro sprinklers	Myburgh and Howell (2007)
Sultanina	655 mm and 1348 mm with micro sprinkler irrigation	Myburgh (2003)
Crimson Seedless	460 mm for drip irrigation and 1863 mm for micro sprinkler irrigation	Avenant *et al*. (2019)

2.4.2 Water footprint

Water footprint (WF) is a measure of the use of consumptive and degradative freshwater (Hoekstra, 2016). Although fruit industries mainly consider the assessment and the WF of final products, there are few specific studies for intermediates (Wróbel-Jędrzejewska *et al*., 2021). Scientists mainly consider WF as a volumetric approach, focusing on water productivity (Pfister *et al*., 2017). WF has arisen as a significant way to assess water use and the related effects from consumption of goods and services (Pfister *et al*., 2017).

Worldwide, WFs have been proposed as a sustainable indicator to assess the sustainability, efficiency and equity of water allocations (Wichelns, 2017). This approach is prominently goal-oriented, given that volumetric WFs contain information relating to just one resource, with no consideration of scarcity values, opportunity costs, or the impacts of water use on the environment, livelihoods, or on the human health (Wichelns, 2017).

2.4.3 Water use efficiency

Water use efficiency (WUE) is a measure of the amount of biomass produced per unit of water used by a plant (Hatfield and Dold, 2019). The WUE evaluation and improvement have emerged as critical issues in grapevine production (Tomás *et al*., 2012; Li and Zhang, 2017; Medrano *et al*., 2015a). WUEs of table grapes are affected by different factors such as plant function, physiological mechanisms, environmental factors, agronomic management practices, cultivar and water deficit treatment (Kangueehi, 2018; Weiler *et al*., 2019). Consequently, the optimisation of water use for vineyards, by improving WUE, is a core subject of interest to viticulture sustainability (Medrano *et al*., 2015a).

As Medrano *et al*. (2015a) emphasise, improving vineyard WUE is crucial for a sustainable viticulture industry in semi-arid regions and accurate estimation of a vineyard's water requirements is essential for irrigation scheduling (Myburgh, 2016). As Acevedo-Opazo *et al*. (2010) point out, precision irrigation in grapevines could be achieved using physiologically-based irrigation scheduling methods. Access to reliable irrigation can enable farmers to adopt new technologies, leading to increased productivity, overall higher productivity and greater returns from farming (Fanadzo, 2012).

2.5 FACTORS AFFECTING WATER USE OF TABLE GRAPE VINEYARDS

2.5.1 Climatic and environmental factors

The table grape industry is facing the risk of climate change and water scarcity in many areas of the globe and which are in turn negatively affecting the environmental and economical sustainability of the sector (Permanhani *et al*., 2016). Climatic and environmental factors affecting water use by vineyards include temperature, relative humidity, vapour pressure deficit, radiation, wind speed, soil water content, soil temperature, salinity and rainfall.

Due to the water restriction policy on agricultural sectors in the Western Cape Province of SA, drought may impose water stress on the table grape farms with irrigation systems (Araujo *et al*., 2016). When it comes to viticulture, rainfall is one of the more contradictory aspects of climate (Pienaar, 2005). A better understanding of grapevine stress physiology (e.g. water relations, temperature regulation and WUE), more robust crop monitoring or phenotyping and implementation of best water management practices will help to mitigate climate effects and will contribute to significant water savings in the vineyard (Costa *et al*., 2016). Therefore, it is necessary to encourage sufficient growth and prevent water stress in essential growth stages (Pienaar, 2005).

2.5.1.1 Temperature, relative humidity and vapour pressure deficit

Climate change predictions indicate that the global average air temperature could rise by 1.5°C between 2030 and 2050, and potentially increase heat waves, soil water deficits, and elevated vapour pressure deficit of the air in many regions of the world (Zhang *et al*., 2021). The SA's future climate trends and projections results shows that air temperature has increased by 0.02°C/year and may warm more quickly by 0.03°C/year between 1980-2016 and 2050 (Jury, 2019). As Martínez-Lüscher *et al*. (2016) highlight, the mean worldwide temperatures have increased due to a sharp rise in climatic carbon dioxide (CO_2) levels and evident implications for precipitation patterns.

The high temperatures and irradiance not only cause berries to ripen more slowly, but also contributes to a severe incidence of sunburn and shrinkage of berries (Greer and Weedon, 2013). Although climate change affects plant growth, there are opportunities to enhance WUE through plant selection and cultural practices to offset the impact of a changing climate (Hatfield and Dold, 2019). During hot periods, overhead netting reduces the photosynthetically active radiation (PAR) by approximately 20% and wind speed by approximately 40% (Kalcsits *et al*., 2017).

Covering vines with overhead netting will reduce the temperature (Greer *et al*., 2010; Avenant, 1994; Suvočarev *et al.,* 2013; Novello and de Palma, 2013; Avenant *et al*., 2017). Wind and temperature play a fundamental role in ecosystems and the water cycle, since they strongly affect evapotranspiration rates (Liuzzo *et al*., 2016). Wind speed affects the leaf boundary layer conductance for water vapour and sensible heat flux in a similar way and it is an issue that has not received much attention in the literature (Schymanski and Or, 2016).

The reduction in photosynthesis and the limited supply of sugar to plants are caused by high temperatures inactivating the CO_2 fixing enzyme Rubisco (Greer and Weedon, 2013). Even though water availability has significant interactions with both temperature and CO_2, it was however reported that water deficit delays maturity when combined with other factors (Martínez-Lüscher *et al*., 2016). Evaporative water loss from leaves during the uptake of CO_2 is unavoidable. Therefore, when water is limited, it is advantageous for grapevines to use it more 'efficiently' (Franks *et al*., 2013).

2.5.1.2 Radiation

Photosynthetically active radiation (PAR, 400-700 nm) transmittance is the most important radiometric property of covering materials from an agronomic point of view, since PAR is necessary for plant photosynthesis and growth (Castellano *et al.,* 2008). PAR under shade net is lower when compared to conditions outside shade netting (Gaurav, 2014). Temperatures exceeding 40°C outside overhead netting reduce photosynthesis by 35%, while transpiration increases nearly threefold and is accompanied by increasing stomatal conductance (Greer and Weedon, 2013).

Photosynthetic properties which are characteristic of shaded leaves include lower rates and lower light saturation levels when compared to well-exposed leaves (Greer *et al*., 2011). In Mediterranean climates, the table grape cultivar Crimson Seedless outside nets does not always achieve the commercially acceptable level of red colour, which has significant effects for the producer (Ferrara *et al*., 2015). The colour problem of berry skin is probably a consequence of high summer temperatures, climatic conditions, phenological stage and cultural practices (Ferrara *et al*., 2015). The fruit colouration depends on day and night temperature changes during the ripening of the fruit and poor colour development has been associated with high summer temperatures (30 to 35˚C during the day, and higher than 18˚C at night, for a 20 day period) (Stampar *et al*., 2002).

2.5.1.3 Wind speed

Although regular, strong synoptic winds and gentle local breezes are normal occurrences during the grapevines' growth cycle, the effect of wind on water use of table grapes under South African conditions is not extensively documented (Pienaar, 2005). North-westerly winds in the Western Cape Province of SA are indicative of approaching rainfall (Pienaar, 2005). Under certain conditions, the general expectation is that higher wind speed will result in increased transpiration (Schymanski and Or, 2016). The use of overhead nets often modifies the microenvironment around a crop (Castellano *et al.,* 2008), and it is a vineyard management technique that reduces solar irradiance, air temperature, wind speed, dust, limits leaf and fruit sunburn (Novello and de Palma, 2013; Gaurav, 2014).

2.5.1.4 Soil water content and soil temperature

Teixeira *et al*. (2007) reported that the South African average value of seasonal evapotranspiration (ET) for table grape ranges from 519 to 827 mm. Myburgh and Howell (2007) reported the mean daily ET during January decreased to 4.1 mm day^{-1} and 5.0 mm day^{-1} after the irrigation had been cut off at 12°B and 15°B, respectively. The reduction in soil water content occurs when increased soil temperatures decrease water viscosity, thus allowing more water to percolate through the soil profile (Corvalán *et al*., 2014; Kalcsits *et al*., 2018; Onwuka and Mang, 2018).

Water is predominately lost by soil evaporation when the crop is small, but once the crop is well developed and completely covers the soil, transpiration becomes the main process (Allen *et al*., 1998). There is a need for a good plant and soil water monitoring system to avoid the risk of severe water stress at periods of extreme high-temperature events (Lopes *et al*., 2011). Soil temperature is generally expressed as the thermal regime of soils, which usually includes heat flux into the soil, the thermal characteristics of the soil and the heat exchange between soil and air (Chiemeka, 2010). The advantages of using overhead netting in table grape production include lower soil temperature and lower irrigation costs due to decreased soil water loss (Mupambi *et al*., 2018; Kalcsits *et al*., 2017; and Suvočarev *et al.*, 2013).

2.5.1.5 Rainfall

Over the years 2015–2017, rainfall in the Western Cape Province of SA was below average, which resulted in the worst drought since 1904 and unprecedented water scarcity (Otto *et al*., 2018). After consecutive years of increasing water demand due to rapid population growth and expanded agricultural and tourism activities, in January 2018, Cape Town city authorities issued an alert for 'Day Zero' to occur in mid-April when dam levels were expected to drop to 10% and taps in residential areas would be turned off (Sousa *et al*., 2018).

Putting grapevines under water stress by reducing water availability could result in low yields and poor grape quality (Araujo *et al*., 2016). In many regions, viticulturists rely on irrigation water during drought periods (Souza *et al.,* 2005). Increased sustainability of water resources for vineyards can be achieved using agronomic techniques (Medrano *et al*., 2015a). Overhead netting is an agronomic technique being widely used in viticulture to prolong moisture in a low rainfall season (Novello and de Palma (2006).

2.5.2 Agronomic production practices affecting WUE

In agronomy, WUE is defined as the amount of yield produced per unit of water used (crop WUE) (Tomás *et al*., 2012). WUE is an important subject in agriculture in semi-arid regions, because of the increase of areas under irrigation and the high water requirements of crops (which consume around 70% of water available to humans) (Medrano *et al*., 2015b). Irrigated agriculture accounts for almost 30% of total crop production and is the single largest user of water in SA (Fanadzo *et al*., 2010).

South Africa is a water-scarce country, and, although water consumption through irrigation has decreased from 80 to about 50% over the past years, the need to improve WUE in irrigation farming is more imperative than ever (Fanadzo *et al*., 2010). Given the scenario of water scarcity in the country, increasing water productivity in agriculture is indispensable (Fanadzo, 2012).

2.5.2.1 Cultivar (Scion and rootstock)

Table grape production can adapt to changing environmental conditions, but this will either depend on intensive irrigation practices, or time-consuming breeding for selection of drought-tolerant cultivars that can deal with restricted water availability (Weiler *et al*., 2019). Because of the strong relationship between total transpiration and biomass produced, there is a need for drought tolerance plant breeding in grapevine species (Fort *et al*., 2017).

A clear understanding of grapevine responses to water deficit is critical, especially in increasing the efficiency of viticultural practices and guiding the development of drought-tolerant scion cultivars and rootstocks (Gambetta *et al*., 2020). A drought tolerant rootstock should allow the scion to grow and function optimally even when water is scarce (Serra *et al*., 2014). It is necessary to characterize rootstock responses to water deficit due to the increased water scarcity (Álvarez *et al*., 2020). Scion cultivars that have lower water requirements or can cope with water scarcity while maintaining yield and fruit quality need to be selected (Galindo *et al*., 2018).

Isohydric cultivars are those that close their stomata when they sense a drop in soil water potential or an increase in the atmospheric demand, while anisohydric cultivars continue to transpire even when soil water content diminishes, because of a poor stomatal adjustment capacity (Hugalde and Vila, 2014). Hugalde and Vila (2014) pointed out the qualities which allows isohydric cultivars to be more drought tolerant than anisohydric cultivars. The qualities include drought tolerance than anisohydric, which in turn is believed to minimize hydraulic risk at the expense of reduced carbon assimilation (Garcia-Forner *et al*., 2017). Five rootstock cultivars on the official list for table grapes in SA, which are considered drought tolerant include Ramsey (82%), Richter 110 (10.8%), Paulsen 1103 (4.4%), Richter 99 (1.7%), and US 8-7 (1.1%) rootstocks (Avenant, 2018).

2.5.2.2 Canopy management

Canopy management can be defined as a portfolio of vineyard management techniques, which manage a grapevine's canopy from the time of winter pruning until harvest time (Gorman-Mcadams, 2013). The highest ET on the 9 days' leaf area and shaded area is 6.99 mm recorded by Williams and Ayars (2005). Shaded leaves have the lowest rates of transpiration, but according to Medrano *et al*. (2012) a high number of shaded leaves (nearly 37% of the total) increases the plant's total water consumption (by more than 20%), resulting in a significant decrease in WUE.

Medrano *et al*. (2012) suggested the possibility to improve the whole plant WUE throughout the canopy management (i.e. selective pruning). As Kangueehi (2018) pointed out, canopy management is a very important aspect in table grape production for increased production with an improved WUE. Pascual *et al*. (2015) concurred and pointed out that grapevine canopy management strategies, such as shoot trimming to restrict growth during early phases, are effective in adapting plant response to soil water availability.

2.5.2.3 Surface and soil management

Soil management practices have a positive impact on WUE by increasing soil water holding capacity, improving root ability to extract more water from the soil profile, or decreasing leaching, which result in an increased table grape yield (Hatfield *et al*., 2001). Manipulation of the soil surface, whether through a tillage system, residue management, or living mulches, is one of the soil management practices that influence WUE (Hatfield, 2011). Similarly, WUE can be improved through better soil management practices and by engineering soil properties to maximize water availability to table grapes (Schnable, 2019). In addition, the benefits of using mulch in grapevine production include: increased WUE, weed suppression, improved soil structure, reduced soil temperature and yield increases (Chan *et al*., 2010).

Soil maintenance practices influencing soil and plant water relations as well as soil fertility and temperature have an impact on plant performance and berry quality (Costa *et al*., 2016). Mulching and cover crops are used to reduce the risk of soil erosion and water runoff and to improve soil fertility and structure, mainly when cash crops are not actively growing (Medrano *et al*., 2015a). The benefits of cover crops in vineyards also include soil erosion control, nitrogen and organic matter management, improved soil structure, increased water penetration and retention, decreased direct soil water evaporative losses, reduction of grapevine vegetative vigour, and grape and quality enhancement (Pou *et al*., 2011).

2.5.2.4 Irrigation systems and scheduling methods

In SA, most grapevines need irrigation for sustainable growth, yield and grape quality, except for some rainfed wine grape vineyards in the Coastal region of the Western Cape Province (Myburgh, 2016). Irrigation is necessary for the production of export quality table grapes during the hot and dry summer regions (Myburgh and Howell, 2007). Water is critical for viticulture sustainability since grape production, quality and economic viability are largely dependent on water availability (Medrano *et al*., 2015a).

To optimise quality, table grapes should be exposed to soil water availability levels that will contribute to an optimum balance between vegetative growth, yield and grape quality (Myburgh and Howell, 2007). For example, soil water content at field capacity (FC), wilting point (WP), and available water (i.e., the difference between FC and WP) in different types of soil (Pardossi *et al*., 2009). Consequently, there is a need to optimise the irrigation scheduling of table grapes, particularly during berry ripening, to achieve optimal vegetative growth, yield and grape quality (Myburgh and Howell, 2007). An important aspect of irrigation water management in crop production is to improve water productivity by increasing crop yield per unit of irrigation water applied (Fanadzo *et al*., 2010). To achieve ‘more crop per drop’, either production must be increased, by keeping water levels constant, or the same amount of production must be maintained while using less water (Fanadzo, 2012).

Regulated deficit irrigation (RDI) is successful in improving crop yield and quality, and in reducing water use when water availability is a problem (Blanco *et al*., 2010). RDI is generally defined as an irrigation practice whereby a crop is irrigated with an amount of water below the full requirement for optimal plant growth. As Chai *et al*. (2016) pointed out, the reduction of the amount of water used for irrigating crops improves the response of plants to a certain degree of water deficit in a positive manner, reduces irrigation amounts, and/or increase the crop’s WUE. It has emerged as a tool to mitigate the negative impact of drought on yield and quality, and to save water in modern irrigated viticulture (Permanhani *et al*., 2016).

2.5.2.5 Overhead protection (netting and plastic)

Overhead nets are widely used in various agricultural applications, including protection of fruit crops and ornamentals from excessive solar radiation, environmental hazards (hail, wind, snow), or pests (Shahak *et al.,* 2006), as well as against virus-vector insects and birds (Castellano *et al.,* 2008). Overhead netting has a relatively low cost to the total production costs of the vineyards; however, it might have an important effect on microclimate (Castellano *et al.,* 2008) and crop water requirements (Castellano *et al.,* 2008; and Moratiel and Martínez-Cob, 2012).

As temperatures increase in the future, overhead netting provides a viable option to mitigate some of the negative effects of excessive temperature and light on production in hot, dry growing regions (Kalcsits *et al*., 2017). In a vineyard covered with overhead plastic, evapotranspiration after irrigation tends to be lower (3 mm per day) compared to uncovered conditions, taking 24 days to reach its minimum value (1.9 mm per day) (Rana *et al.,* 2004). There are few publications regarding the effect of netting on crop water use of table grapes, including Avenant and Avenant (2002); Rana *et al.* (2004); Moratiel and Martínez-Cob (2012) and Suvočarev *et al.* (2013).

2.6 USE OF OVERHEAD NETS TO IMPROVE WUE AND DECREASE THE WF OF TABLE GRAPE PRODUCTION SYSTEMS

The principal aim of overhead netting is to protect shoots, inflorescences and grapes from hail (Novello and de Palma, 2013). The use of overhead netting for protection against hail damage as a requirement for the successful cultivation of table grapes is an accepted practice in the northern summer rainfall region of SA (Avenant *et al.*, 2019). Recently, there has also been a growing interest in cultivation of table grapes under netting in the Western Cape and within the Lower Orange River area (Avenant, 2018). Results from a study conducted at Roodeplaat Experimental Farm in the northern summer rainfall region of SA indicated increased leaf water potential and leaf water content, lower transpiration rate (Avenant, 1994) and a 15% decrease in water use where black hail netting with a 20% shade effect was used (Avenant and Avenant, 2002).

Nets can be used to buffer climactic extremes like intense heat, light and wind stresses so that the canopy may remain healthier, photosynthetically active for longer periods and more efficient in water usage (Mupambi *et al*., 2018). Overhead netting can improve the efficiency of agricultural production by increasing production and improving quality (both pre- and post-harvest), for lesser inputs (water, pesticides and fungicides) (Shahak, 2014), thereby contributing to increased WUE and a decreased WF.

2.7 THE EFFECT OF OVERHEAD NETS ON VINEYARD MICROCLIMATE, GRAPEVINE PHENOLOGY, VIGOUR, PRODUCTION AND QUALITY

Coloured shade netting designed specifically for manipulating plant development and growth has become available and these shade nets can be used outdoors, as well as in greenhouses (Stamps, 2009). Netting is largely used in open field applications, especially in fruit tree cultivation such as grapes, peaches, apricots and cherries, where it is installed with specific supporting structures, or directly over the plants (Castellano *et al.,* 2008).

The use of overhead nets aims at combining physical protection of the crop with specific light filtration that promotes desired physiological responses (Shahak *et al.,* 2004). Overhead nets enable modification of the microenvironment to suit specific requirements of plants at different growth stages, seasons and in different climatic regions (Gaurav, 2014). Table grape farmers have adopted the approach of protected cultivation to prevent undesired effects of hazardous climatic and environmental factors, and to enable extension of the growing season (Tanny, 2013). Overhead netting is widely used in vineyards to reduce radiative load during summer (Suvočarev *et al.,* 2013).

Avenant (1994) reported a decrease in radiation and leaf temperature under black nets with a 20% shade effect, while ambient temperature was not significantly affected. Shading from veraison to harvest may be a viable mitigation strategy against extremely high temperatures during ripening (Caravia *et al*., 2016). During full sunlight, differences in maximum fruit surface temperature between the uncovered control and the overhead protective netting are 2.6 to 4.3°C (Kalcsits *et al*., 2017). Covering vines with overhead net reduces canopy temperatures significantly protects bunches from damage and improves grape quality (Greer and Weedon, 2013; Greer *et al*., 2010). Attempts to assess overhead net covering as a means of protecting grapevines from heat damage have successfully demonstrated that canopy temperatures do markedly decrease from the reduction in radiant energy (Greer *et al*., 2010). Overhead netting reduces light transmission (Greer *et al*., 2014; Kalcsits *et al*., 2017) and modifies the light reaching the orchard canopy (Kalcsits *et al*., 2017).

Covering vineyard with overhead net reduces the canopy temperatures on average by 3.5˚C below ambient air temperature (Greer *et al*., 2010). Overhead net covering is one of the emerging techniques used by growers to protect their vineyards against various biotic and abiotic stresses, such as excessive solar radiation, insects, hail as well as wind (Mditshwa *et al*., 2019). Avenant (1994) reported that the number of days to reach bud break, flowering and veraison was not significantly affected by black nets with a 20% shade effect, although ripening was delayed. Greer *et al.* (2014) reported improved berry composition and enhanced berry ripening under nets.

Avenant (1994) reported increased leaf area, shoot growth rate and shoot length of table grape vines under black netting with a 20% shade effect. Berry mass, bunch mass and yield were not significantly affected, although there was a trend that reproductive growth as indicated by these three parameters seemed to be higher under netting. Berry chlorophyll concentration of white cultivars increased and berry anthocyanin concentration of black cultivars decreased under netting, indicating a negative impact on berry colour development.

Greer *et al.* (2011) reported that although overhead netting did not affect shoot growth, it caused a major impediment to leaf development, with expansion of individual leaves being delayed by 10–25 days when compared to leaves of exposed vines at comparable stages of development. Results from the same study also indicated that berries under shade netting expanded to a larger size than those exposed to the heat (Greer *et al*., 2010).

2.8 CONCLUSIONS

The review has demonstrated that a limited number of detailed WF studies have been undertaken in SA and only a few of them were specifically on table grapes. Major climatic and environmental factors affecting water use of table grape vineyards include temperature, relative humidity, vapour pressure deficit, radiation, wind speed, soil water content, soil temperature, salinity, and rainfall. Cultivar development and evaluation play a vital role in selecting suitable cultivars that have lower water requirements or can cope with water scarcity while maintaining yield and fruit quality. South African agricultural researchers should pursue integrated research on the WF of table grapes produced under overhead netting.

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CHAPTER 3

GENERAL MATERIAL AND METHODS

This study was carried out to conduct a WUE and blue WF analysis of table grape production in the Berg River region of SA. The study had two components, namely: (i) A field trial including three mature production blocks (consisting of a net covered block, as well as two uncovered blocks, to determine vineyard water use under nets, compared to without nets; and (ii) A survey to determine irrigation and other water uses (water used for spray applications in the vineyard and water used in the pack store), for inclusion in the WUE and WF analyses.

3.1 EXPERIMENTAL VINEYARDS

Details of the experimental vineyard blocks are presented in Table 3.1.

3.1.1 Field trial

The field trial was conducted over one season (2018/19) in three commercial *Vitis vinifera* L. cv. Crimson Seedless production blocks grafted onto Ramsey rootstock on the farm Môrester (33° 12' 39" south, 18° 58' 16" east) near Piketberg (Blocks M5, M10 and M12, indicated in Table 3.1. Due to practical reasons (evaluating the effect of nets in commercial blocks, as well as conducting this investigation within an existing research project, where the experimental blocks were already selected), the field trial consisted of three fixed blocks (two open and one netted). In the 20 central rows of each block, ten experimental units were randomly selected for plant-based measurements within each block, each containing four vines, of which one was selected as a data vine. Data vines were selected based on stem circumference.

Table 3.1: Details of the *Vitis vinifera* L. cv. Crimson Seedless blocks included in the table grape water footprint field trial and survey in the Berg River region (2018/19 season)

Sub-region	Block nr	Plant year	Rootstock	Trellis system	Block size (ha)	Spacing (m x m)	Soil type	Irrigation system
Piketberg	M5 (netted)	2014	Ramsey	Gable	6.52	3.4x2.2	Sandy clay loam	Micro-sprinkler
	M10 (open)	2002	Ramsey	Gable	4.74	3.4x1.92	Sandy clay loam	Micro-sprinkler
	M12 (open)	2013	Ramsey	Gable	6.23	3.0x2.2	Sandy clay loam	Micro-sprinkler
	M16 (open)	2012	Richter99	Pergola	4.56	3.0x2.2	Sandy clay loam	Micro-sprinkler
	B3 (netted)	2002	Ramsey	Gable	4.9	3.6x1.8	Sandy clay loam	Micro-sprinkler
	B2 (open)	2002	Ramsey	Gable	3.1	3.6x1.8	Sandy clay loam	Micro-sprinkler
	B10 (open)	2016	Ramsey	Gable	3.7	3.6x1.8	Sandy clay loam	Micro-sprinkler
	K1 (open)	2011	Paulsen1103	Gable	1.77	3x1.75	Sandy clay loam	Micro-sprinkler
Morreesburg	D8 (open)	2009	Ramsey	Gable	1.98	3x2.0	Sandy loam	Micro-sprinkler
	D29 (open)	2014	Ramsey	Gable	2.32	3x1.8	Clay loam	Micro-sprinkler
	D6 (open)	2004	Richter110	Gable	3.72	3x1.8	Sandy loam	Micro-sprinkler
Paarl	L87 (open)	2005	Ramsey	Gable	6.00	3x1.88	Clay loam	Micro-sprinkler

3.1.2 Survey

The survey was conducted on 12 commercial *Vitis vinifera* L. cv. Crimson Seedless production blocks in the Berg River region, selected from the 236 blocks (representing 35 cultivars), included in the comprehensive WRC Project K5/2710/4, conducted in three regions (Jarmain, 2020). Selection of the twelve blocks was done in consultation with Berg River Table Grape Producers Association (BTPV) and South African Table Grape Industry (SATGI), based on region (Berg River), cultivar (Crimson Seedless) and the completeness of survey data obtained from the participating farms.

In the accepted WRC project proposal, it was envisaged that the experimental blocks would include the following four categories; with at least three blocks in each category: (i) Mature block in full production (4th leaf or older) conventionally produced (without nets); (ii) Mature block in full production (4th leaf or older) established under nets; (iii) Young production block 2nd or 3rd leave and in production; and (iv) Young block in its season of establishment (1st leaf). The 12 blocks that were selected for the survey, represented only categories (i), (ii) and (iii), with nine, two and one block in each, respectively. These 12 blocks were the only blocks for which sufficient survey data were obtained to meet the objectives of this study.

3.2 DATA COLLECTION

3.2.1 Field trial

Mesoclimate data of the field trial blocks were collected (Section 4.2.2) to establish the effect of overhead nets on climate variables and link it to phenology (section

4.2.3), vegetative parameters (section 4.2.4), and reproductive parameters (section 4.2.5), as well as WU, WUE and the WF (section 4.2.6) of the respective blocks.

Plant-based measurements were conducted (sections 4.2.4 to 4.2.5) to evaluate the effect of overhead nets on vegetative and reproductive parameters, as well as to establish the correlation between field measurements and remote sensing (FruitLook) data for assessing vegetative growth (section 5.2.3). Commercial total production and export production of each block were obtained from the farm's harvest and packing records, to use in WUE and WF calculations.

Total seasonal Estimated ET (FruitLook ET) and irrigation volumes (obtained from the irrigation records of the experimental blocks) were divided by the blocks' average yield to determine yield water use efficiency (WUEy) and water productivity (WP) (section 4.2.6). Water use and production data were used to determine and compare the blue WF of the experimental blocks, according to the method of Hoekstra *et al*. (2011). Estimated ET (FruitLook ET) and seasonal irrigation volumes (m^3) were divided by the average yield (tonnes) to determine the blue WF of table grapes, based on ET and irrigation water use respectively. WUE and WF were calculated separately for total production and export production of the experimental blocks.

3.2.2 Survey

Interviews and questionnaires were used to obtain the relevant water use and production information to determine the WUE and blue WF of the blocks included in the survey. A "WU/WF questionnaire" was compiled and used for obtaining information from producers regarding water use, namely irrigation volumes, water used during spraying operations in vineyards (for application of fertilisers, fungicides, insecticides and herbicides), as well as water used in pack stores. Commercial total production and export production data, as well as total seasonal estimated ET (FruitLook ET) and total seasonal irrigation volumes, were obtained as described in section 3.2.1. Calculations of WUE and WF were done as described in section 3.2.1. The total seasonal measured irrigation and recorded rainfall (water applied) were compared to the total seasonal Estimated ET (water used) (section 5.2.5).

3.3 STATISTICAL ANALYSIS

The experimental design of the field trial consisted randomised design of three fixed blocks (one open and two netted), with 10 randomly selected experimental units in each block, each containing four vines, of which one was selected as data vine for the plant-based measurements. Analysis of variance (ANOVA) using the GLM (General Linear Models) Procedure of SAS software (Version 9.4; SAS Institute Inc, Cary, USA) was performed on all variables assessed, for each observation time separately.

Observations over time (shoot growth, berry mass and berry juice quality parameters) were also combined in a split-plot ANOVA with time as a sub-plot factor (Little, 1972). Shapiro-Wilk test was performed on the standardized residuals from the model to test for normality (Shapiro, 1965). In cases where there was a significant deviation from normality, outliers were removed when the standardized residual for an observation deviated with more than three standard deviations from the model value. Fisher's least significant difference was calculated at the 5% level to compare treatment means (Ott, 1998). A probability level of 5% was considered significant for all significance tests.

Additionally, regression analysis was performed on the above-mentioned growth parameters measured over time, using the NLIN Procedure of SAS software (Version 9.4; SAS Institute Inc, Cary, USA). The appropriate regression function with observation day as independent variable was fitted for each experimental unit. Regression parameters obtained for each experimental unit were also subjected to ANOVA to compare trends under different conditions (open and netted).

Shoot growth and cumulative FruitLook biomass production data were analysed using Statistica 10® software (Statsoft, Tulsa, UK). Pearson's regression was used to determine the relationship between these two variables. The assumptions that underpin a Pearson's correlation are: (1) the two variables should be measured at the continuous level; (2) there needs to be a linear relationship between the two variables; (3) there should be no significant outliers; and (4) the variables should be approximately normally distributed.

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CHAPTER 4

THE EFFECT OF OVERHEAD NETTING ON MESOCLIMATE, VEGETATIVE AND REPRODUCTIVE PERFORMANCE, AS WELL AS WUE AND THE BLUE WF OF *Vitis vinifera* L. cv. CRIMSON SEEDLESS IN THE BERG RIVER REGION OF SOUTH AFRICA

ABSTRACT

There are limited research results available regarding the effects of overhead netting on vegetative and reproductive performance, as well as WUE and the WF of table grape vineyards. There is a need to accurately quantify the water use of table grape vineyards produced without netting compared to those produced under overhead netting. The objective of this study was to determine the effect of overhead netting on mesoclimate, vegetative and reproductive performance, as well as WUE and the blue WF of *Vitis vinifera* L. cv. Crimson Seedless in the Berg River region of SA. The study, conducted over one season (2018/19), included a field trial in three commercial Crimson Seedless production blocks on the farm Môrester near Piketberg, as well as a survey, conducted on 12 commercial Crimson Seedless blocks in the Berg River region. In the field trial, a faster accumulation of heat units and a higher total seasonal growing degree days were recorded for the open blocks, compared to the netted block, due to higher temperatures of the open blocks at the beginning of the season compared to the netted block. This contributed to the open blocks reaching bud break approximately a week earlier, compared to netted block. The netted block had larger leaves, as well as more vigorous shoot growth. Total irrigation water use ranged between 7469 and 10 017 m^3/ha. WUE, based on the irrigation and ET water use ranged 1.96 to 2.61 t/m^3, and 1.41 to 1.73 t/m^3, respectively. The blue WF (Irrigation) determined from total and export production, ranged from 430 to 603 m^3/ton, and 618 to 877 m^3/ton, respectively. There was no clear trend observed regarding WUE and WF of netted block compared to the open blocks. More research is needed to quantify vineyard water use of netted blocks compared to open blocks, including sap flow measurements to determine grapevine

transpiration and establish vineyard transpiration values and using the universal soil water balance method to establish vineyard ET values.

Keywords: Water footprint, table grapes, water use efficiency, overhead netting, South Africa.

4.1 INTRODUCTION

WUE is a measure of the amount of biomass produced per unit of water used by a plant (Li and Zhang, 2017; Kangueehi, 2018; Hatfield and Dold, 2019; and Weiler *et al*., 2019). There is limited research-based consensus on the effects of overhead netting on vegetative and reproductive performance, as well as WUE of table grape vineyards. Furthermore, limited published scientific research results about the effect of overhead netting on water use in table grapes are available, including Avenant (1994); Rana *et al.* (2004); Moratiel and Martínez-Cob (2012); and Suvočarev *et al.* (2013).

Overhead netting has been reported to increase the exportable yield and quality of grapes (Serat and Kulkarni, 2015). Research results (Avenant, 1994; Avenant and Avenant, 2002) from a study conducted in the northern summer rainfall region of SA, indicated a 15% decrease in water use where hail netting with a 20% shade effect was used. Preliminary results of a trial at Kanoneiland in the Lower Orange River with white nets with a 20% shade effect, indicated that the seasonal transpiration volume of a table grape vineyard under nets was 14% lower compared to the open subplot and the total irrigation volume applied was 17.7% lower under the nets compared to open subplots (Avenant and Avenant, 2002). No other published results regarding the effect of netting on water use of table grapes in SA is available. Overhead netting treatments resulted in a 50% reduction in water use of wine grapes in Chile, with no detrimental effects on grapevine physiology, yield or grape quality (Gil *et al*., 2018).

Overhead netting is one of the tools to minimize the direct exposure of vines to sunlight (Serat and Kulkarni, 2015). Exposure to radiation and heat can be reduced by shading the grapevines, but could create an imbalance in the carbon budget, reducing vine biomass and consequently its reproductive allocation (Greer *et al*., 2011). Serat and Kulkarni (2015) pointed out that overhead netting contributes to maintaining microclimatic conditions during high as well low temperatures and thus, helps to maintain normal physiological activities, and thereby quality. The objective of this study was to determine the effect of overhead netting on mesoclimate, vegetative and reproductive performance, as well as WUE and the blue WF of *Vitis vinifera* L. cv. Crimson Seedless in the Berg River region of SA.

4.2 MATERIALS AND METHODS

4.2.1 Experimental vineyards

Refer to section 3.1 for details of the experimental vineyard blocks and the experimental layout.

4.2.2 Mesoclimate

Mesoclimate data for the 2018/19 season was obtained from two iLEAF automatic weather stations (ileaf.co.za) on Môrester Farm, near Piketberg. Continuous measurement of mesoclimate variables was conducted for the one-year monitoring period (September 2018 to August 2019). Variables were measured at 10 minutes and stored in the logger at hourly intervals. Hourly values were processed into daily and monthly averages or totals.

4.2.3 Phenology

Grapevine phenological stages of the field trial blocks were determined by visual observations throughout the growing season, as well as by obtaining records of the experimental vineyards from the farm Môrester near Piketberg.

4.2.4 Vegetative parameter measurements

4.2.4.1 Shoot growth

Shoot length was measured weekly from 05 October 2018 until 13 February 2019 for the 2018/19 season. Two shoots per vine, on the third cane, between node positions 4 and 9 were tagged and non-destructive shoot measurements were taken throughout the growing season, using a measuring tape. Wind damage, shoot removal and topping early in the season necessitated the selection of new data shoots that were comparable to the original ones (only for eight of the originally 60 selected shoots). Shoot growth measurements were done weekly starting from the time when the shoots were 15 cm long, up to the termination of shoot growth. Measurements were taken on all the selected data vines in the 10 experimental units of the three blocks.

4.2.4.2 Leaf area

Leaf samples for determining leaf area (LA) were collected on 19 February 2019. In each experimental unit, 30 undamaged, mature, healthy leaves opposite bunches were sampled. Leaf area was measured using a Licor LI-3100 leaf area meter (LI-3100, LI-COR, inc. Lincoln, Nebraska USA).

4.2.4.3 Cane Mass

Cane mass was determined as an indicator of vigour. During dormancy, all data vines in the experimental units were cane-pruned and the mass of all one year old canes removed from each data vine was determined using a digital hanging scale.

4.2.5 Reproductive parameter measurements

4.2.5.1 Berry sampling

For monitoring berry development and ripening from 20 December 2018 to 19 February 2019 (harvest), a random sample of 100 berries was collected weekly from each experimental unit for determining berry mass, length and diameter, as well as total soluble solids (TSS), pH and titratable acid (TA). The sample mass was determined with a three-decimal digital scale (Precisa, Type. 280-9826, PAG Oerlikon AG, Zurich, Switzerland). Berry length and diameter were measured with a digital caliper. After the sample was homogenised with a household blender and separated from materials other than clear juice, the TSS (°Brix) was measured with a digital pocket refractometer (Atago PAL-1, Tokyo, Japan). A volume of 50 ml clear juice was measured out with a 50 ml glass pipette and poured into a 100 ml measuring glass beaker, which was placed in the rotor of an automatic titration device (Metrohm 785 DMP Titrino, Herisau, Switzerland) connected to a bench pH meter (Crison Basic 20 with Crison 5531 PT1000 electrode, Barcelona, Spain) for the measurement of TA (g/L) and pH. The TA was determined using sodium hydroxide at a concentration of 0.33%. The Metrohm was calibrated before each batch of analysis.

4.2.5.2 Yield and bunch mass

At the commercial harvest date of the three field trial blocks (when berry total soluble solids reached the minimum export requirements), yield (kg/vine), the number of bunches per vine, as well as bunch mass were determined for the data vines in all experimental units of blocks M5 and M12. No yield data measurements were done for M10 because the farm had harvested the whole block already before the agreed date for harvesting of the field trial blocks.

4.2.6 Water use, water use efficiency and the blue water footprint

Water use, WUE and the blue WF were calculated as described in section 3.2.1

4.2.7 Statistical analysis

Refer to section 3.3 for the descriptions of the experimental design and statistical analysis.

4.3 RESULTS AND DISCUSSION

4.3.1 Mesoclimate

Monthly average values of temperature (T), wind speed (WSpd), relative humidity (RH) and accumulated growing degree days (GDD) are presented in Tables 4.1 and 4.2. As expected, temperature and wind speed were higher in the open blocks, compared to the netted block. In the open blocks, the RH tended to be lower compared to the netted block (Tables 4.1 and 4.2).

Table 4.1: Monthly values of mesoclimate variables recorded by iLEAF Weather Services at Môrester in the open block near Piketberg between September 2018 and August 2019

Month	Avg T (°C)	Max T (°C)	Min T (°C)	RH % Avg	RH % Max	RH % Min	WSpd (km/h)	Ave Max WSpd (km/h)
2018-09	13.3	34.9	2.9	76.3	95.8	15.7	7.3	10.9
2018-10	21.3	41.7	7.2	51.7	94.3	6.6	9.9	14.8
2018-11	21.0	37.6	8.3	49.8	94.2	8.0	11.1	16.4
2018-12	22.0	36.4	12.5	59.4	92.7	11.7	9.3	13.9
2019-01	23.5	40.4	12.3	52.2	91.9	9.4	11.0	16.1
2019-02	24.8	42.0	13.5	55.5	93.0	12.2	10.1	14.9
2019-03	21.5	37.8	12.5	65.9	95.2	11.8	8.5	12.7
2019-04	19.0	34.2	9.2	63.3	95.1	15.0	8.9	13.0
2019-05	17.1	33.9	8.5	66.7	95.6	12.7	8.3	12.0
2019-06	13.8	30.1	3.7	72.4	97.0	13.5	8.4	12.3
2019-07	13.0	23.1	3.6	81.1	97.0	27.6	8.2	12.5
2019-08	12.8	28.9	3.0	77.1	97.2	15.9	6.8	11.2
Mean	18.6	35.1	8.1	64.3	94.9	13.3	9.0	13.4

Table 4.2: Monthly values of mesoclimate variables recorded by iLEAF Weather Services at Môrester in the netted block near Piketberg between September 2018 and August 2019

Month	Avg T (°C)	Max T (°C)	Min T (°C)	RH % Avg	RH % Max	RH % Min	WSpd (km/h)	Ave Max WSpd (km/h)
2018-09	13.7	37.3	3.2	82.2	100.0	18.5	1.6	3.3
2018-10	21.4	43.3	5.8	58.0	99.7	9.1	2.0	4.2
2018-11	21.3	39.8	6.4	54.8	96.5	10.7	2.1	4.4
2018-12	22.1	37.2	11.6	66.6	98.8	19.2	1.4	3.2
2019-01	9.5	37.2	2.0	58.9	97.7	0.0	1.8	52.2
2019-02	21.3	42.4	2.0	62.9	99.6	18.2	1.4	3.4
2019-03	21.4	38.7	11.1	72.8	100.0	20.1	0.9	2.5
2019-04	18.6	35.1	7.6	71.4	100.0	21.9	1.1	2.8
2019-05	16.6	34.5	7.4	74.1	100.0	16.7	1.2	2.7
2019-06	13.6	30.8	2.2	79.6	100.0	17.7	1.5	3.2
2019-07	13.0	24.0	2.8	87.2	100.0	36.3	2.0	3.8
2019-08	13.1	30.0	2.8	82.5	100.0	20.0	1.2	2.6
Mean	17.1	35.9	5.4	70.9	99.4	17.4	1.5	7.4

Growing degree days are presented in Figures 4.1 and 4.2. Higher monthly and accumulative GDD values were recorded for the open compared to the netted block. Open blocks had a faster accumulation of heat units because of higher average temperatures at the beginning of the season compared to the netted blocks. This resulted in the open blocks reaching budburst approximately a week earlier, compared to the netted blocks (Kangueehi, 2018; see section 4.3.2).

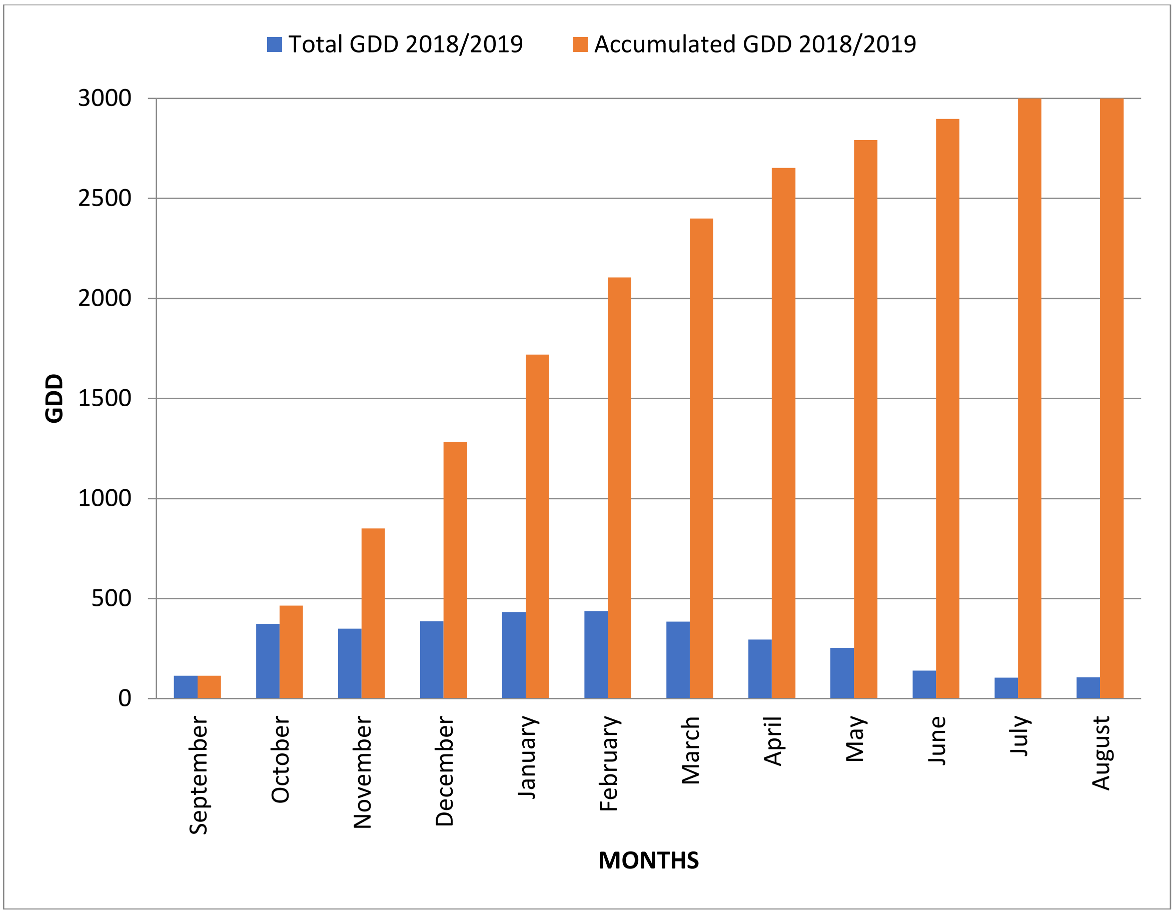


Figure 4.1: Growing degree days (GDD) relative to days after 1st September calculated for the 2018/19 season for the open blocks at Môrester near Piketberg

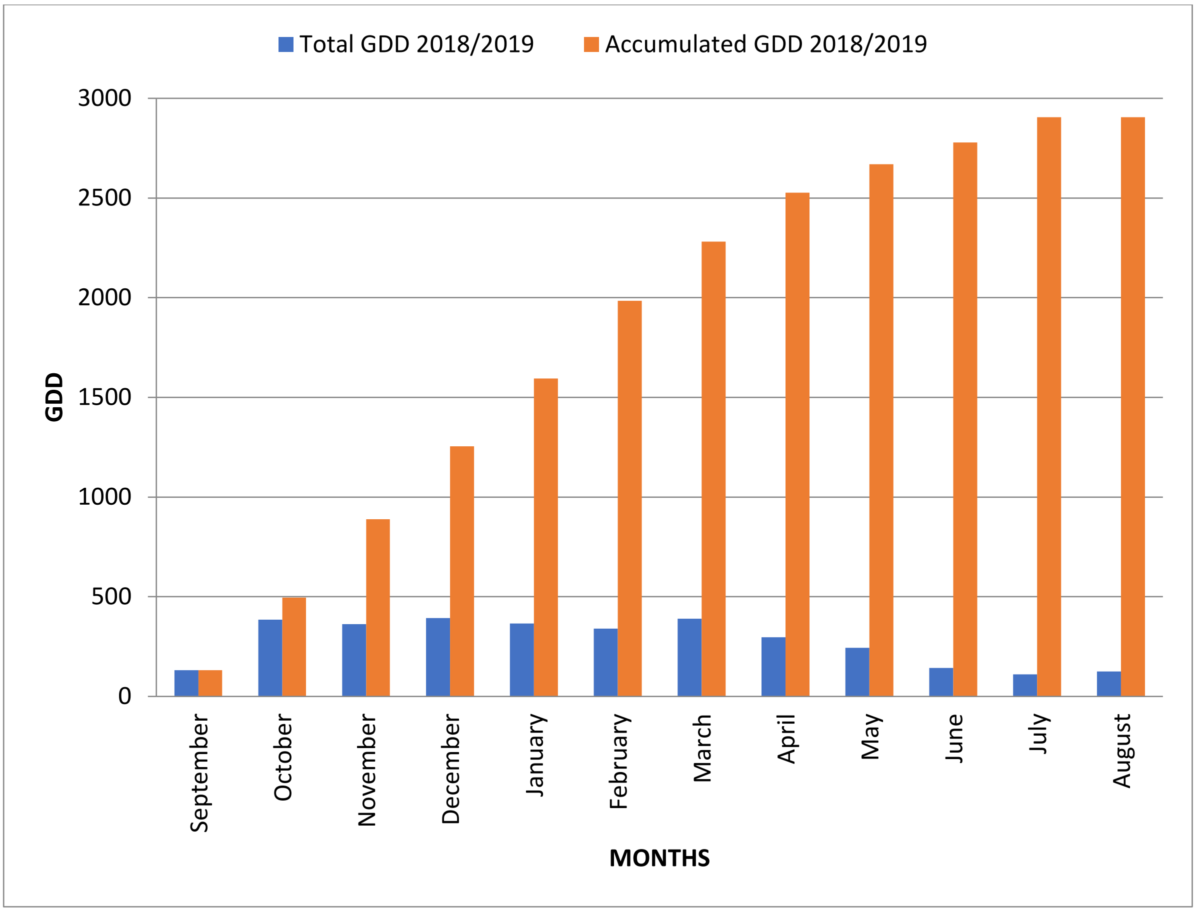


Figure 4.2: Growing degree days (GDD) relative to days after 1st September calculated for the 2018/19 season for the netted block at Môrester near Piketberg

Hourly radiation values of the open and netted and blocks from 7th January 2019 (veraison date of M5) to 9th January 2019 (veraison date of M10), indicated that radiation measured in the open block was higher compared to the netted subplot from sunrise (06h00) to sunset (20h00) (Figure 4.3). The maximum radiation values, recorded between 12h00 and 14h00, were 23.4 to 26.4% lower under the nets. Radiation under shade net is lower when compared to conditions outside shade netting (Gaurav, 2014).

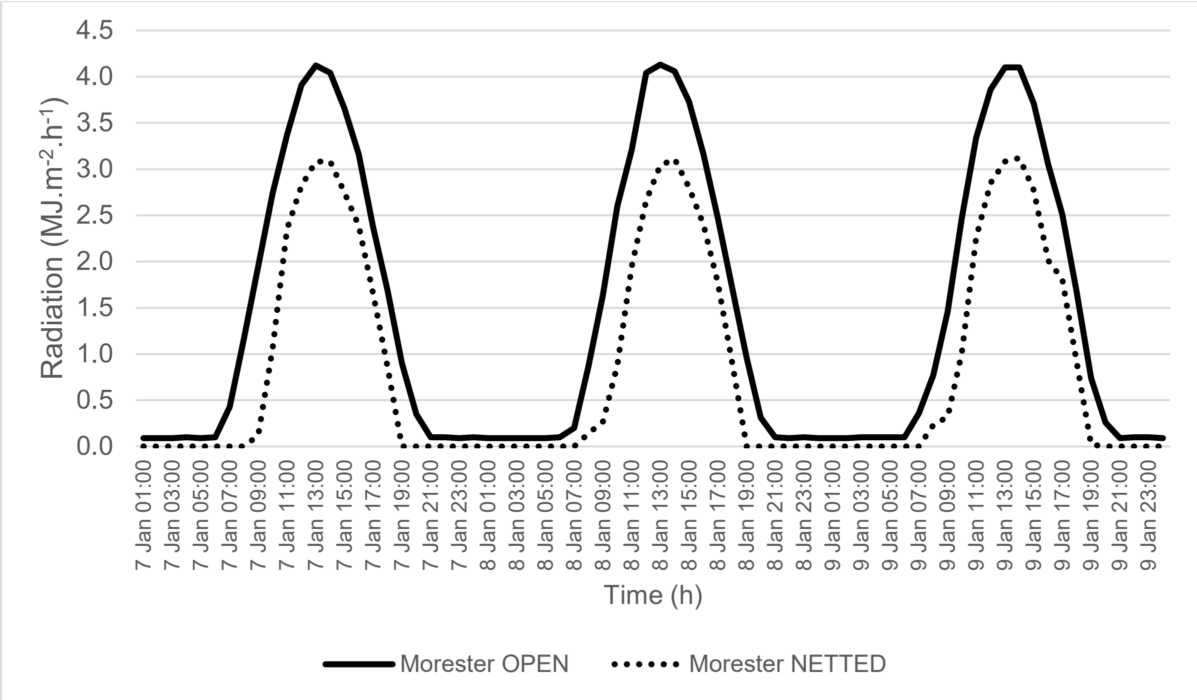


Figure 4. 3: Hourly radiation values recorded by iLEAF Weather Services at Môrester for the netted and blocks near Piketberg between 7th and 9th January 2019

4.3.2 Phenology

Important phenological stages of the three commercial blocks are presented in Table 4.3. Bud break was 5 and 3 days earlier in the open blocks M10 and M12, respectively, compared to the netted block M5. This could be due to higher temperature (and consequently heat unit accumulation) outside netting. Avenant (1994) also reported delayed bud break under nets. Regarding the flowering, veraison and harvest dates, a clear trend regarding the difference between the open and the netted blocks was not observed (Table 4.3). This might be due to the fact that the dates of the phenological stages were determined by general observations of the blocks and not by assessing, for example, each data vine every second day during a specific stage.

Table 4.3: Phenological stages of *Vitis vinifera* L. cv. Crimson Seedless in the Water Use field trial experimental blocks of the Berg River Region (2018/19 season)

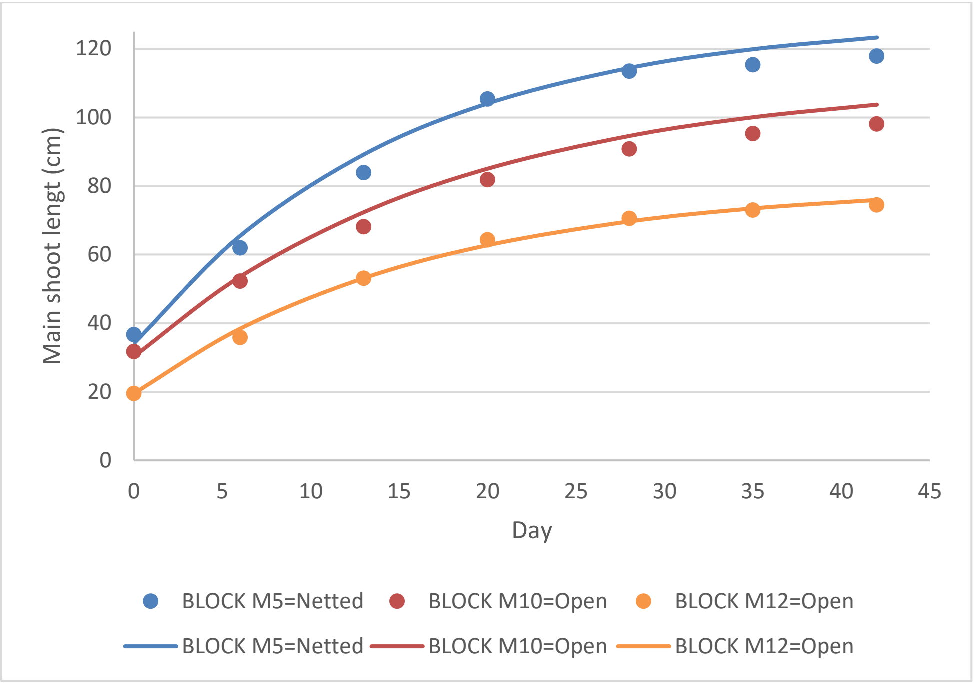
Date	9-1	9-8	9-15	9-22	9-29	10-6	10-13	10-20	10-27	11-3	11-10	11-17	11-24	12-1	12-8	12-15	12-22	12-29	1-5	1-12	1-19	1-26	2-2	2-9	2-16	2-23	3-2	3-9
Phenological stage	Final prune	Bud Break								Full Bloom		Pea Size							Veraison						1st Harvest			Last harvest
OPEN Block M12	9-3	9-10								11-6		11-19							1-14						2-14			3-7
days	7		64								13		56							31						21		
OPEN Block M10	9-5	9-10								11-6		11-19							1-9						2-5			2-14
days	5		57								13		51							27						9		
NET Block M5	9-7	9-17								11-2		11-20							1-7						2-14			
days	10		46								18		48							38						21		

The difference in the duration of the harvest period could also have been caused by other factors such as differences in crop load and/ or colour development. Avenant (1994) reported no significant difference between flowering, fruit set and veraison dates of open and netted blocks, while GWA (2020) reported a minimal difference in flowering progression. Avenant (1994) and Sen *et al*. (2016) reported that overhead netting delayed ripening and harvest date.

4.3.3 Vegetative parameters

4.3.3.1 Shoot growth

Main shoot length and number of main shoot nodes of the three field trial blocks and are presented in Figures 4.4 and 4.5. The change in the length of the shoots followed a similar pattern for all treatments. Similar results were also obtained by Zhou *et al*. (2018). Block M5 had the longest shoots (Figure 4.4), although it had fewer internodes per main shoot (Figure 4.5). These results indicate that the netted block M5 had more vigorous shoot growth, similar to results found with overhead netting by Avenant (1994); Corvalán *et al*. (2014); Novello *et al*. (2015); and Zhou *et al*. (2018).



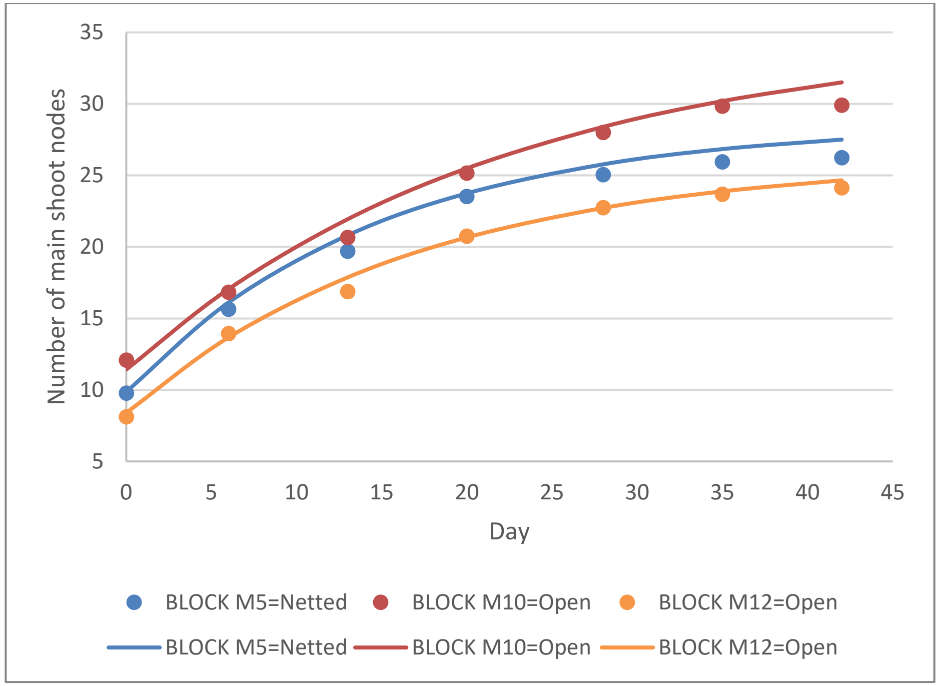


Figure 4.4: Main shoot length (cm) measured from 05/10/2018 until 13/02/2019 of the three field trial blocks for the 2018/19 season (day 0 = 05/10/2018, and day 45 = 13/02/2019)

Figure 4.5: Number of main shoot nodes measured from 05/10/2018 until 13/02/2019 of the three field trial blocks for the 2018/19 season (day 0 = 05/10/2018, and day 45 = 13/02/2019)

4.3.3.2 Leaf area and cane mass

Leaf area, shoot length and average internode length at harvest, as well as cane mass of the three field trial blocks, are presented in Table 4.4. Block M5 had a larger leaf area per leaf compared to blocks M10 and M12 (Table 4.4). Avenant (1994), Diaz-Perez (2013), Corvalán *et al*. (2014) and Novello *et al*. (2015) also reported increases in grapevine leaf area with overhead netting.

Block M5 had the longest shoot length at harvest (significantly longer compared to block M12), while its internode length was significantly longer compared to both open blocks (Table 4.4). The average cane mass at winter pruning of the three blocks was 1.07 kg/vine. This was lower than the 1.36 kg/vine reported by Avenant (1994) as an average of four cultivars, 3.61 kg/vine reported by Avenant (1998) for Festival Seedless, 1.26 kg/vine reported for ungrafted Sultanina (Clone H4) by Myburgh (2003), and 1.20 kg/vine for own-rooted Sultanina (Clone14/2) reported by Myburgh and Van der Walt (2005). This could be because the farmer pruned some canes before the agreed date for winter pruning and cane mass measurements of the field trial blocks, which compromised the results. Therefore, the obtained cane mass values cannot be deemed reliable indicators of the vigour of the three blocks. The shoot length and number of nodes per main shoot, measured over time (Figures 4.3 and 4.4), leaf area, as well as the shoot length and internode length at harvest, are considered reliable indicators of the vigour of the three blocks.

Table 4.4: Leaf area, shoot length and internode length at harvest, as well as cane mass of the three field trial blocks in the Berg River Region (2018/19 season)

Block No.	Treatment	Leaf area (cm^2/leaf)	Shoot Length at harvest (cm)	Internode length at harvest (cm)	Cane mass (kg/vine)
M5	Netted	162.11a	129.04a	6.24a	1.60a
M10	Open	144.89a	111.32a	4.85b	0.93b
M12	Open	120.53b	80.52b	4.46b	0.69b
Mean		142.51	106.96	5.18	1.07
$LSD_{p=0.05}$		18.691	23.943	1.77	0.54

4.3.4 Reproductive parameter measurements

4.3.4.1 Berry and berry juice quality parameters

Berry and berry juice quality parameters of the three field trial blocks are presented in Figures 4.6 to 4.9. Results indicate that there was a gradual increase in berry mass as the season progressed from 20 December 2018 to 13 February 2019 in all three blocks (Figure 4.6). Block M5's berry mass was lower compared to blocks M10 and M12 (Figure 4.6). Similar results were also found by Oliveira *et al*. (2014), and Rojas-Lara and Morrison (2015). Avenant (1994) recorded no significant difference in berry mass between netted and open treatments. However, Zoratti *et al*. (2015) reported that overhead nets significantly increased berry size and mass compared to berries grown in an open field.

For all three blocks, a downward trend in TA (Figure 4.7) and increase in TSS values Figure 4.8) was observed throughout the sampling period, as berry development and ripening progressed. The trends observed regarding the rates of TSS increase (Figure 4.7), TA decrease (Figure 4.6) and TSS/TA increase (Figure 4.7), indicate that ripening progressed the fastest in Block 10 (open), followed by Block 5 (net) and Block 12 (open). Therefore, the differences observed in the rate of ripening cannot only be ascribed to the effect of the netting, but are most probably linked to crop load; with the lowest crop load recorded for Block 10, followed by Block 5 and Block 12 (Tables 4.5 and 4.6).

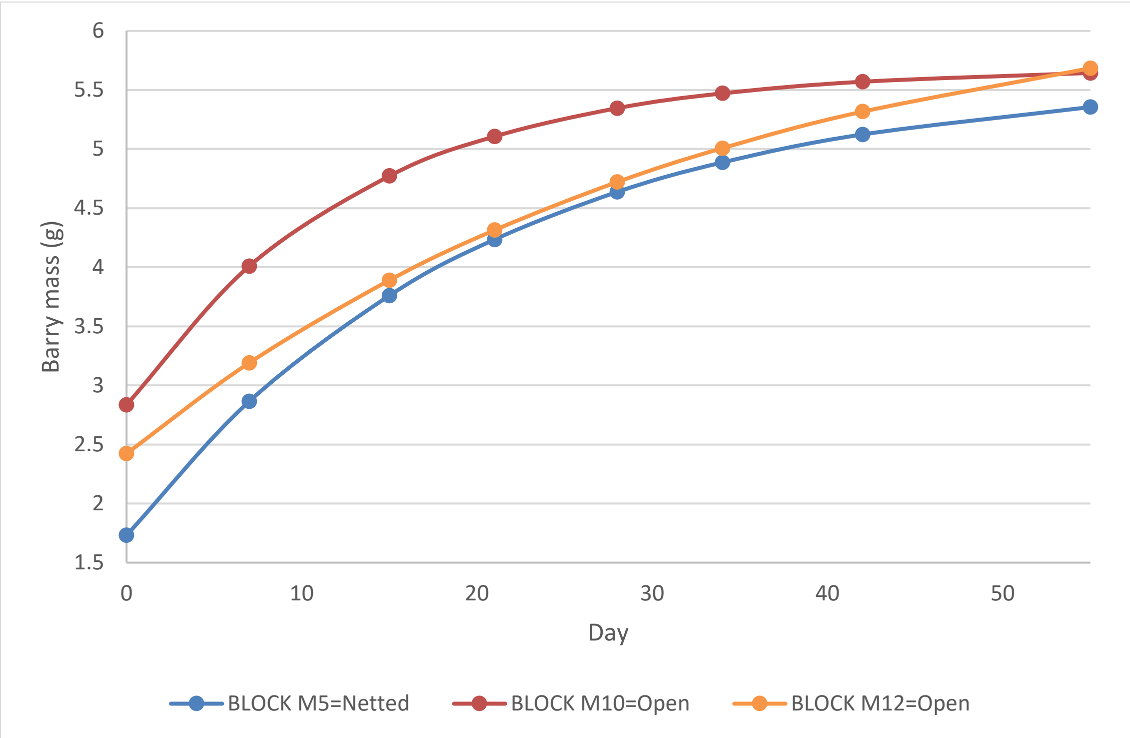


Figure 4.6: Berry mass (kg) measured from 20/12/2018 until 13/02/2019 of the field trial blocks for the 2018/19 season (day 0 = 20/12/2018, and day 55 = 13/02/2019)

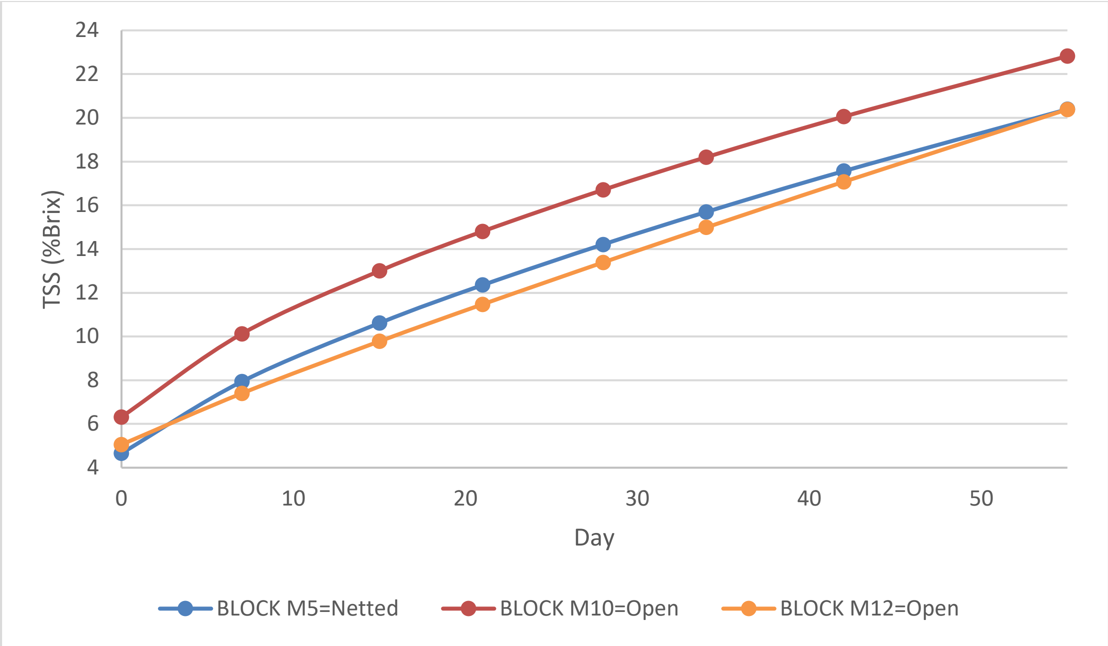


Figure 4.7: Total soluble solids (%Brix) measured from 20/12/2018 until 13/02/2019 of the three field trial blocks for the 2018/19 season (day 0 = 20/12/2018, and day 55 = 13/02/2019)

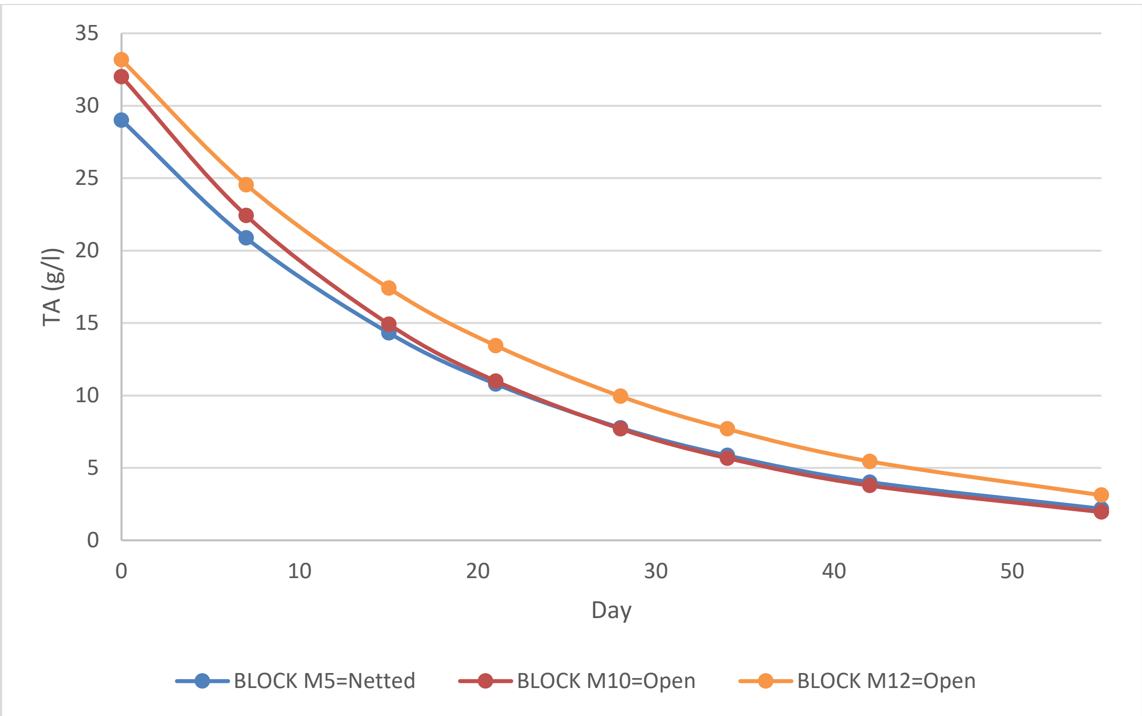


Figure 4.8: Titratable acidity (g/l) measured from 20/12/2018 until 13/02/2019 of the three field trial blocks for the 2018/19 season (day 0 = 20/12/2018, and day 55 = 13/02/2019)

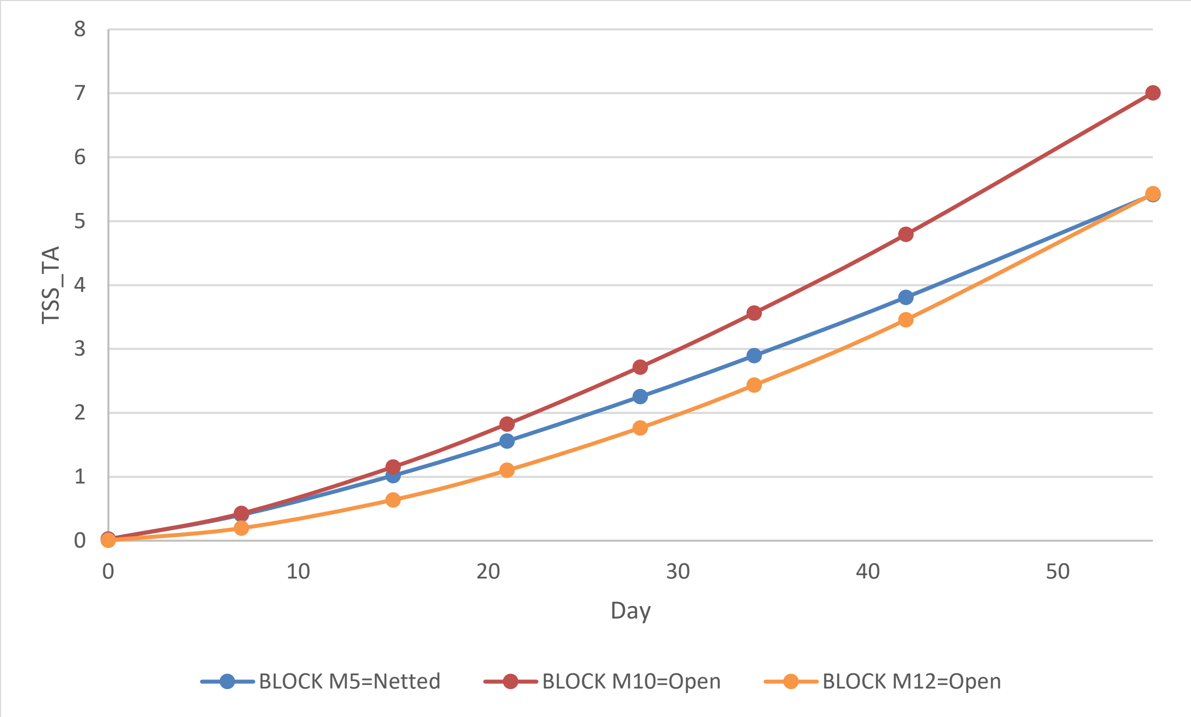


Figure 4.9: Total soluble solids and titratable acidity ratio measured from 20/12/2018 until 13/02/2019 of the three field trial blocks for the 2018/19 season (day 0 = 20/12/2018, and day 55 = 13/02/2019)

4.3.4.2 Yield and its components

Yield parameters of two of the field trial blocks are presented in Table 4.5. Yield was not significantly impacted by netting. Avenant (1994) also reported no significant effect of netting on yield. The number of bunches/vine, berry mass, berry length and berry diameter did not differ significantly between the netted block M5 compared to the open blocks M10 and M12. Similar results were recorded by Avenant (1994), Greer (2013) and Serat and Kulkarni (2015). Bunch mass in the netted block M5 was significantly higher than in the open blocks M10 and M12 (Table 4.5).

Commercial yield data of the three field trial blocks in the Berg River Region are presented in Table 4.6. The open block M12 had the significance highest total yield, but the lowest export production and export percentage. The discrepancies in measured yield data of the data vines and the commercial yield of the field trial blocks (yield and bunch mass) are ascribed to the fact that the farm has harvested some grapes from the data vines already before the agreed date of harvesting of the field trial blocks, which affected the results. The commercial yield data was obtained from the farm's harvest and packing records and are considered a true reflection of the total and export production of the three blocks. Therefore, the commercial yield data were used for the calculations of WUE and WF presented in section 4.3.5.

Table 4.5: Yield and its components of the two *Vitis vinifera* L. cv. Crimson Seedless field trial experimental blocks in the Berg River Region (2018/19 season)

Block	Treatment	Yield (kg/vine)	Cartons (per ha)	Yield: cane mass ratio	Bunch number (per vine)	Bunch mass (g)	Berry mass (g/berry)	Berry length (mm)	Berry diameter (mm)
M5	Netted	7.55a	2467a	11.02a	29.3a	274.23a	5.2a	21.36a	10.68a
M12	Open	6.75a	2206a	5.64a	31.6a	221.98b	5.6a	21.26a	12.14a
Mean		7.15	2336	8.51	30.4	248.10	5.2	20.96	10.92
$LSD_{p=0.05}$		2.30	751.3	5.65	13.21	61.42	0.25	0.64	0.35

Table 4.6: Commercial yield data of the three *Vitis vinifera* L. cv. Crimson Seedless field trial experimental blocks in the Berg River Region (2018/19 season)

Block	Treatment	Total Cartons (per ha)	Export Cartons (per ha)	Total Yield (t/ha)	Export production (t/ha)	Export %	Yield (kg/vine)	Calculated bunch mass (g)
M5	Netted	3911	3178	17.6	14.3	81	11.6	397
M10	Open	1905	1519	15.4	6.8	80	10.1	337
M12	Open	4074	2747	18.2	12.3	67	12.4	391
Mean		3297	2481	17.1	11.1	76	11.49	375

4.3.5 Water use, WUE and the blue WF

Blue water consumption contributed to a large share of water use, through ET, irrigation, spray applications and pack store water use. Yield, WU (through irrigation and ET), as well as WUE and WF values of the 12 experimental blocks are presented in Tables 4.7 and 4.8. Calculated WUE and WF values presented in Tables 4.7 and 4.8 were based on total production and export production respectively.

The total irrigation water use based on total production and export ranged between 7469 and 10 017 m³/ha, which is higher than the range of 4000 to 7000 m³/ha reported by Temnani *et al*. (2021) in irrigation protocols of different water availability scenarios for Crimson Seedless under Mediterranean Semi-Arid conditions. Avenant *et al.* (2019) reported total seasonal irrigation water use of 7 400 m³/ha in the Berg River region, 4 600 to 10 500 m³/ha in the Hex River Valley, 12 300 to 18 600 m³/ha in the Lower Orange River region and 4 700 to 8 400 m³/ha in the Northern Provinces.

It is not clear whether the lower ET estimates of netted blocks B3 and M5 were the result of improved WUE (which is to be expected) or whether it is caused by differences in the spectral responses obtained for crops under nets as well as uncertainty about the reliability of spectral results for netted sites (Jarmain, 2020). ET Fruitlook showed the highest volumes in the open blocks, ranging between 11 173 and 11 144 m³/ha. Block B10 was a young block, in its first season of production – therefore the low irrigation volume, low yield, high FruitLook ET (probably due to evaporation losses from the soil) and thus low WUE. Fruitlook ET values for block L87 are not included, because Block L87 was not included in the comprehensive project, WRC Project K5/2710/4, (Jarmain, 2020).

Table 4.7: Water use efficiency (WUE) and the blue water footprint (WF) of the twelve experimental *Vitis vinifera* L. cv. Crimson Seedless blocks in the Berg River region determined based on total production, irrigation volumes and evapotranspiration (ET) values, from September 2018 to August 2019

			WATER USE		WUE (t/m³)			
Block	**Treatment**	**Yield(t/ha)**	**Irrigation applied (m³/ha)**	**ETfl (m³/ha)**	**WUE irrigation**	**WUE (ET)**	**Blue WF irrigation m³/ton**	**Blue WF ET m³/ton**
B3	Netted	20.3	6300	7923	3.22	2.56	310	390
B2	Open	20.3	6300	7770	3.22	2.56	310	383
B10	Open	4.5	3500	9635	1.29	0.47	778	2141
M5	Netted	17.6	9454	9485	1.86	1.86	537	539
M10	Open	15.4	6873	11173	2.24	1.38	446	726
M12	Open	18.2	8961	11144	2.03	1.63	492	612
M16	Open	19.8	7700	10984	2.57	1.80	389	555
K1	Open	15.4	9978	10650	1.54	1.45	648	683
D8	Open	27.9	8254	10110	3.38	2.76	296	362
D29	Open	26.8	8395	10378	3.19	2.58	313	392
D6	Open	18.7	7625	10933	2.45	1.71	405	585
L87	Open	27.3	6290	Unknown	4.34	Unknown	230	Unknown
Mean		14.63	7469	10017	2.61	1.73	430	618

Table 4.8: Water use efficiency (WUE) and the blue water footprint (WF) of the twelve experimental *Vitis vinifera* L. cv. Crimson Seedless blocks in the Berg River region determined based on export production, irrigation volumes and evapotranspiration (ET) values, from September 2018 to August 2019

			WATER USE		WUE (t/m³)		Blue WF irrigation	Blue WF ET
Block	Treatment	Export production (t/ha)	Irrigation applied (m³/ha)	ETfl (m³/ha)	WUE irrigation	WUE (ET)	m³/ton	m³/ton
B3	Netted	16.1	6300	7923	2.55	2.03	392	493
B2	Open	13.6	6300	7770	2.16	1.75	464	572
B10	Open	3.3	3500	9635	0.94	0.34	1063	2925
M5	Netted	14.3	9454	9485	1.51	1.51	661	664
M10	Open	6.8	6873	11173	0.99	0.61	1005	1635
M12	Open	12.3	8961	11144	1.37	1.10	731	909
M16	Open	12.5	7700	10984	1.62	1.14	616	879
K1	Open	12.3	9978	10513	1.23	1.17	808	851
D8	Open	23.4	8254	10110	2.83	2.31	352	431
D29	Open	22.8	8395	10378	2.72	2.11	368	461
D6	Open	15.5	7625	10933	2.03	1.42	492	705
L87	Open	22.3	6290	Unknown	3.55	Unknown	282	Unknown
Mean		14.6	7469	10017	1.96	1.41	603	877

WUE based on the irrigation water use of the 12 experimental blocks ranged between 1.96 and 2.61 t/m³. WUE based on ET ranged between 1.41 and 1.73 t/m³. WUE based on irrigation volume of table or raisin grapes on horizontal trellis systems reported from other studies, ranged 5.5 kg/m³ for Sultanina in California (Araujo *et al*., 1995), 4.05 kg/m³ for Sultanina in Australia (Yunusa *et al*., 1997), 1.9-3.3 kg/m³ for Sultanina in the Orange River region, SA (Myburgh, 2003), and 0.44 to 4.96 kg/m³ for Crimson Seedless in four SA regions (Avenant *et al.*, 2019). The WUE values determined based on total production, was higher compared to the WUE determined based on export production.

The blue WF (irrigation) determined from total production, ranged from 430 to 603 m³/ton, which was lower than the blue WF (irrigation) determined from export production, which ranged from 618 to 877 m³/ton. Avenant *et al*. (2019) reported a blue WF based on irrigation water use of 202 (mature block in the Hex River Valley) to 1 705 m³/ton (young/ low yielding block in the Orange River region), as well as 274 m³/ton (mature block in the Berg River region). Jarmain (2020) recorded a blue WF total for table grapes ranging between 500 and 714 m³/ton, with a median value of 619 m³/ton. The WF values determined based on total production, was lower compared to the WF determined based on export production. There was no clear trend observed regarding WUE and WF of netted blocks compared to open blocks. Therefore, a comparison of calculated water applied and estimated water used was made and is presented in chapter 5, section 5.3.3.

Blue water use (based on spray applications for table grape vineyards) are presented in Table 4.9. Of the 12 blocks included in the survey, spray records were supplied for Blocks M5, M10, M12 and M16 only and the same program was followed for these four blocks, because all four were mature Crimson Seedless blocks on the same farm. To compare the values obtained in the survey, data from other regions, included in the comprehensive project, WRC Project K5/2710/4 (Jarmain, 2020), are also presented in this section.

Total seasonal blue water use volumes for spray applications of Crimson Seedless, as an example of a cultivar classified as MED-HIGH regarding plant growth regulator (PGR) spray applications needed (PGR treatment needed for bunch thinning and/or berry sizing and/or colour improvement). As well as for Redglobe as an example of a cultivar classified as LOW regarding PGR spray applications needed (No or only ONE PGR treatment required for either bunch thinning, berry sizing or colour improvement). For Crimson Seedless, the lowest total water use for spray applications per season (16.2 m^3/ha) was recorded for the program followed for Blocks M5, M10, M12 and M16.

The lower water use for spray applications in these blocks, compared to volumes recorded for the standard programs (STD) of the Berg, Hex and Olifants River regions, is ascribed to: (i) lower spray application volumes that were used for the plant protection and nutrition sprays (300 to 500 L/ha) instead of the 500 L/ha to 1000 L/ha of the STD programmes; and (ii) intensive monitoring of conditions favourable for the occurrence of diseases or pests and strictly planning and implementing spray applications only as needed. The lower water use for spray applications in the Olifants River region, compared to volumes recorded for the Berg River region and Hex River Valley is ascribed to the lower total rainfall and less frequent occurrence of rainfall events in the region, compared to these other two regions, resulting in a lower risk of the occurrence of fungal diseases.

Table 4.9: Blue water use based on spray applications for table grape vineyards (2018/19): Plant protection spray applications (pest and disease control), Nutrition, Plant growth regulators, Herbicides

Region	Block number/ Programme	Cultivar	Cultivar Category regarding PGR use#	Plant protection	Nutrition	Plant bio regulators	Herbicides	Total per season
				m³/ha	m³/ha	m³/ha	m³/ha	m³/ha
Berg River	M5, M10, M12, M16	Crimson Seedless	Med-High	9.3	1.8	4.1	1.0	16.2
Berg River	STD*	Crimson Seedless	Med-High	16.3	2.8	6.5	1.0	26.6
Berg River	STD*	Redglobe	Low	16.3	2.8	2.5	1.0	22.6
Hex River Valley	STD* + actual	Crimson Seedless	Med-High	12.35	4.5	6.5	1.0	24.4
Hex River Valley	STD* + actual	Redglobe	Low	12.35	4.5	0.5	1.0	18.4
Olifants River	STD* + actual	Crimson Seedless	Med-High	10.35	1.0	6.0	1.0	18.4
Olifants River	STD* + actual	Redglobe	Low	1235	0.0	1.0	1.0	14.4

Key: ***BASF, 2019. (P. de Kock); **#**Blue water category based on PGR spray application treatments; **High**: PGR treatment needed for bunch thinning, berry sizing and colour improvement - one or more of each; **Med-High**: PGR treatment needed for bunch thinning and/or berry sizing and/or colour improvement; **Low**: No or only ONE PGR treatment required for either bunch thinning, berry sizing or colour improvement. Sets well filled bunch naturally. Natural berry berry size is medium to large

Blue water use based on table grape pack store water use is presented in Table 4.10. Of the 12 blocks included in the survey, pack store water use data were supplied for one farm (M) only and it is estimated values (no water meter installed in the pack store). To compare the values obtained in the survey, data from other regions, obtained from a previous study (Avenant, 2019), as well as from the comprehensive project, WRC Project K5/2710/4 (Jarmain, 2020), are also presented in this section. Pack store water use refers to water used for cleaning of crates and work surfaces, as well as in pre-cooling systems.

In the study of Avenant (2019), only one farm (Farm 20) supplied measured values obtained via a water meter in the pack store. All other values were obtained as calculations or estimates by the producers. A vast variation in the pack store water use values was recorded, due to amongst others: no pre-cooling done in some pack stores in the Western Cape, while pre-cooling was applied in the Olifants River region, Orange River region and Northern Provinces. In the Northern Provinces, closed systems were used for pre-cooling and less water was used.

The Farms 20 and 21 (Limpopo) and Farm M (Berg River region) had the lowest total pack store blue water used per season (34 m^3) and (144 m^3), as well as the lowest blue WF based on pack store blue water used per season (0.04 m^3/ton) and (0.05 m^3/ton). Additional to differences in pre-cooling technologies used and its impact on blue water use, differences in values recorded could also be ascribed to differences in pack store processes applied and the process flow in each pack store, as described by Le Roux (2017). For future WU and WF assessments and to enable detailed comparisons between different pack stores, it is recommended that a more detailed breakdown of pack store water uses should be obtained and that where possible, measured values should be obtained.

Table 4.10: Blue water use based on table grape pack store water use (2018/19 season)

Region	Farm Number	Season	Total production	Pack store water use per season	Pack store water use/ha		Pack store water use per 4.5kg carton				Blue WF
					Pack store size of unit	Pack store processes	Pack store capacity	Pack store capacity	Pack store capacity	Packstore water use	Packstore water use
			tonnes	m³/season	ha	m³/ha	cartons/day	days/season	cartons/season	L/carton	m³/ton
Berg River region	M	2018/19	2624	144	60	2.4	11662	50	583111	0.25	0.05
Hex River Valley	B	2018/19	506	321	32	10.0	1874	60	112444	2.85	0.63
Hex River Valley	G	2018/19	934	242	40	6.1	5189	40	207556	1.17	0.26
Olifants River	D	2018/19	1012	771	46	16.8	7496	30	224889	3.43	0.76
Orange River*	18	2014/15	1800	900	80	11.3	6667	60	400000	2.25	0.50
Orange River*	19	2014/15	1800	900	80	11.3	6667	60	400000	2.25	0.50
Orange River*	20	2014/15	1800	900	80	11.3	6667	60	400000	2.25	0.50
Orange River*	20	2015/16	1800	944	80	11.8	6667	60	400000	2.36	0.52
Limpopo*	21	2014/15	1035	195	46	4.2	3833	60	230000	0.85	0.19
Limpopo*	23	2014/15	788	34	35	1.0	2917	60	175000	0.19	0.04

*Avenant (2019)

4.5 CONCLUSIONS

Through the field trial and the survey, a range of WU, WUE and blue WF values were established for table grape production in the Berg River region of SA, which could be used by the industry in water management and irrigation scheduling. The total seasonal vineyard water use (estimated ET and irrigation volumes applied) that was quantified, could be considered as bench mark values for table grape vineyard water use in the Berg River region. There was no clear trend observed regarding WUE and WF of netted blocks compared to open blocks. Further research is needed to obtain accurate remote sensing values for estimation of water use of blocks covered with overhead netting. More research is also needed to quantify vineyard water use of netted blocks, compared to open blocks, including sap flow measurements to determine grapevine transpiration and establish vineyard transpiration values and using the universal soil water balance method to establish vineyard ET values. The WUE and WF calculations based on estimated ET and irrigation volumes in this research is the first step towards gaining insight into the impact of table grape production on the water resource in the selected study area.

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CHAPTER 5

COMPARISON OFTHE FRUITLOOK DATA AND FIELD MEASUREMENTS FOR ASSESSMENT OF VEGETATIVE GROWTH AND WUE OF TABLE GRAPE VINEYARDS

ABSTRACT

South African agricultural production faces a major constraint of water scarcity, hence the need to optimise blue water use for sustainable viticulture production. Satellite remote sensing for assessing vineyard vigour, water management and hydrological hazard monitoring has potential for supporting sustainable water use in viticulture. The main objective of this study was to compare FruitLook data and field measurements for assessment of vegetative growth and water use of table grape vineyards. The study, conducted over one season (2018/19), included a field trial in three commercial Crimson Seedless production blocks on the farm Môrester near Piketberg, as well as a survey, conducted on 12 commercial Crimson Seedless blocks in the Berg River region. Weekly shoot growth measurements recorded in the field trial blocks were correlated with FruitLook cumulative biomass production (CPB) and a strong positive correlation was found between main shoot length measured and FruitLook CPB, as evident from the R^2 values of 0.824 (M5); 0.967 (M10); and 0.860 (M12), indicating that FruitLook CPB could be used as a reliable indicator of vigour and cumulative shoot growth. Total estimated FruitLook ET ranged between 739 and 1098 mm. FruitLook ET (estimated water use) is considered a reliable indicator of water use for open (uncovered) blocks, but not for blocks covered with overhead netting, because overhead netting influences spectral reflection of crops, thus affecting the remote sensing data values.

Keywords: FruitLook, cumulative biomass production, evapotranspiration, leaf area index, water use efficiency, netting, South Africa.

5.1 INTRODUCTION

South African agricultural production faces a major constraint of water scarcity, hence the need to optimise blue water use for sustainable viticulture. It is considered to be a water-stressed country with around 1 000 m^3 of water available per capita per annum (Baleta and Pegram, 2014). Satellite remote sensing for water management and hydrological hazard monitoring has progressed dramatically in monitoring of nearly all components of the water balance and vegetation health (Sheffield *et al*., 2018). Improving agricultural productivity requires direct action to conserve and enhance water use (FAO, 2017).

The South African Government introduced the National Water Act (NWA; Act No. 36 of 1998), as a response to this severe problem, to promote an integrated and decentralised water resource management approach (Walter *et al*., 2011). To prepare for future water shortages, some measures aimed at streamlining and optimizing the efficiency of water consumption in the agricultural sector are critical, given the large volumes of water required for crop production (Mancosu *et al*., 2015). Agricultural water use sustainability is a line of research that has gained importance worldwide (Velasco-Muñoz *et al*., 2018). It is at the core of any discussion of water and food security (Swatuk *et al*., 2015).

This study was conducted as a case study to compare FruitLook data and field measurements for assessment of vegetative growth and water use of table grape vineyards on *Vitis vinifera* L. cv. Crimson Seedless in the Berg River region of SA. The objective was to establish whether FruitLook remote sensing data could be used as reliable indicators of vineyard vigour and water use.

5.2 MATERIALS AND METHODS

5.2.1 Study area

To evaluate the accuracy of FruitLook spatial data products available to table grape producers, 12 Crimson Seedless table grape blocks under different cultivation conditions, i.e. soil types and produced either with or without overhead netting in the Berg River region, were selected and studied during the 2018/19 growing season (Refer to section 4.1 in chapter 4 for details of the experimental blocks).

5.2.2 FruitLook

The FruitLook service is an open web portal funded by the Western Cape Department of Agriculture. The project is managed by eLEAF (eleaf.com) from the Netherlands, in cooperation with a South African partner, Blue North (bluenorth.co.za). The generated spatial data are provided on www.fruitlook.co.za. This web-based program uses satellite-based data to assist farmers with their crop management. Metrics such as biomass production, evapotranspiration and WUE are provided on a weekly basis for the largest part of the Western Cape, throughout the year.

FruitLook data was extracted directly from their website, using the block coordinates to define the borders of the blocks, to create the polygon necessary for data extraction. Data was extracted for only the 2018/19 season. FruitLook data is provided at a 20 m x 20 m spatial resolution and made available weekly for the main growing season. The FruitLook data is categorised in three groups: growth, moisture and mineral parameters. Growth parameters include biomass production (kg) (total above and below ground dry matter), leaf area index (LAI) and the vegetation index. Moisture parameters in FruitLook consist of evapotranspiration deficit (mm), actual evapotranspiration (mm) and biomass WUE (kg/m^3). The mineral parameters comprise of nitrogen (N) (kg) present in the upper leaf layer, as well as N in the total plant. In line with the objectives of this case study, only FruitLook data collected for biomass production, LAI and FruitLook actual evapotranspiration (ETFL), are presented.

5.2.3 Shoot growth and biomass production

Shoot growth was measured as a growth indicator (Refer to Chapter 4.3.3). Shoot growth was compared to the accumulated FruitLook biomass production and the correlation between these two variables was determined for the three field trial blocks. Biomass production is the total dry matter increase of total above and below ground dry matter in kg/ha/week. Accumulated biomass production is the total biomass produced in the FruitLook monitoring period up to a specific point in time.

5.2.4 Leaf area index

LAI is the total one sided area of leaf tissue per unit ground surface area (Watson, 1947). LAI can be used as an indicator of grapevine canopy cover. The FruitLook LAI shows the leaf surface at the time of satellite overpass and reflects all above ground vegetation.

5.2.5 Actual evapotranspiration

FruitLook actual evapotranspiration (ETFL) is the sum of the amount of water that is evaporated from the soil and the amount of water that is lost through transpiration by the grapevine. ETFL were used to estimate the actual amount of water consumed during the table grape production process and is expressed in mm/week.

5.2.6 Statistical analysis

Refer to Section 3.3 for the descriptions of the experimental design and statistical analysis.

5.3 RESULTS AND DISCUSSION

5.3.1 Shoot growth and biomass production

FruitLook cumulatived biomass production (CPB) of seven experimental blocks is depicted in Figure 5.1. FruitLook CPB for the season indicated that the open blocks (M12, M16 and M10) had the highest CPB, with lower values recorded for the netted blocks B3 and M5 (Figure 5.1). However, the shoot growth results indicated that the netted block M5 had more vigorous shoot growth compared to the open blocks M10 and M12. The treatments started to differ noticeably from the period of January upwards. Overhead netting has an effect on the spectral reflection of crops, thus affecting remotely sensing data values obtained (Jarmain, 2020).

There was a strong positive correlation between shoot growth measurements and the FruitLook CPB for the three field trial blocks (Figure 5.2), as evident from the R^2 values of 0.824 (M5); 0.967 (M10); and 0.860 (M12). Ge *et al*. (2016) also reported a strong positive correlation between shoot growth and pixel count of remote sensing images (R^2 = 0.952). Similarly, Kangueehi (2018) also found a strong positive correlation (R^2 = 0.84) between shoot growth measurements and the FruitLook CPB, where four Crimson Seedless blocks with different soil type and irrigation system combinations were compared over two seasons.

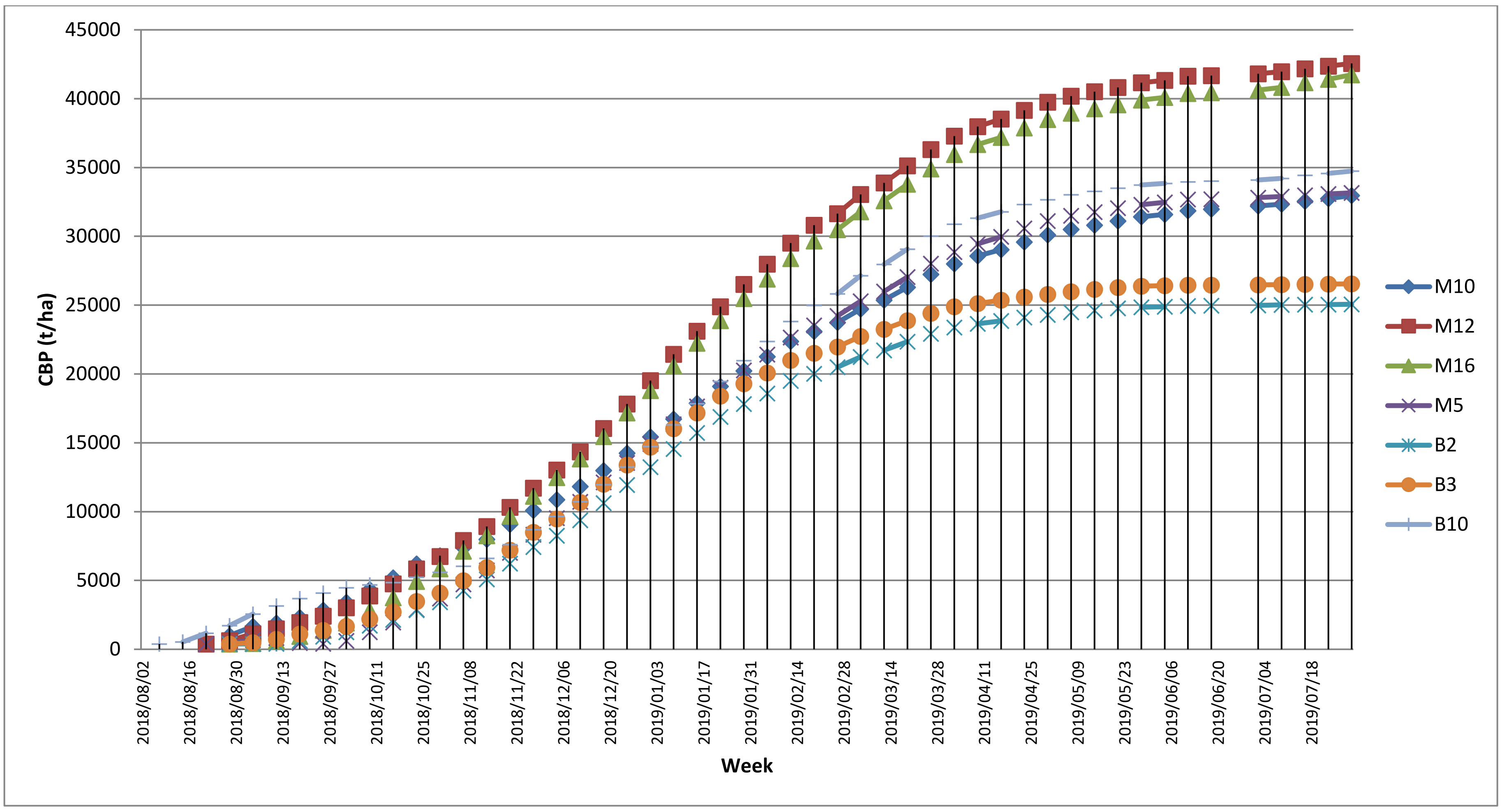

Figure 5.1: FruitLook cumulative biomass production from 02/08/2018 until 18/07/2019 of the seven field trial experimental and survey blocks for the 2018/19 season

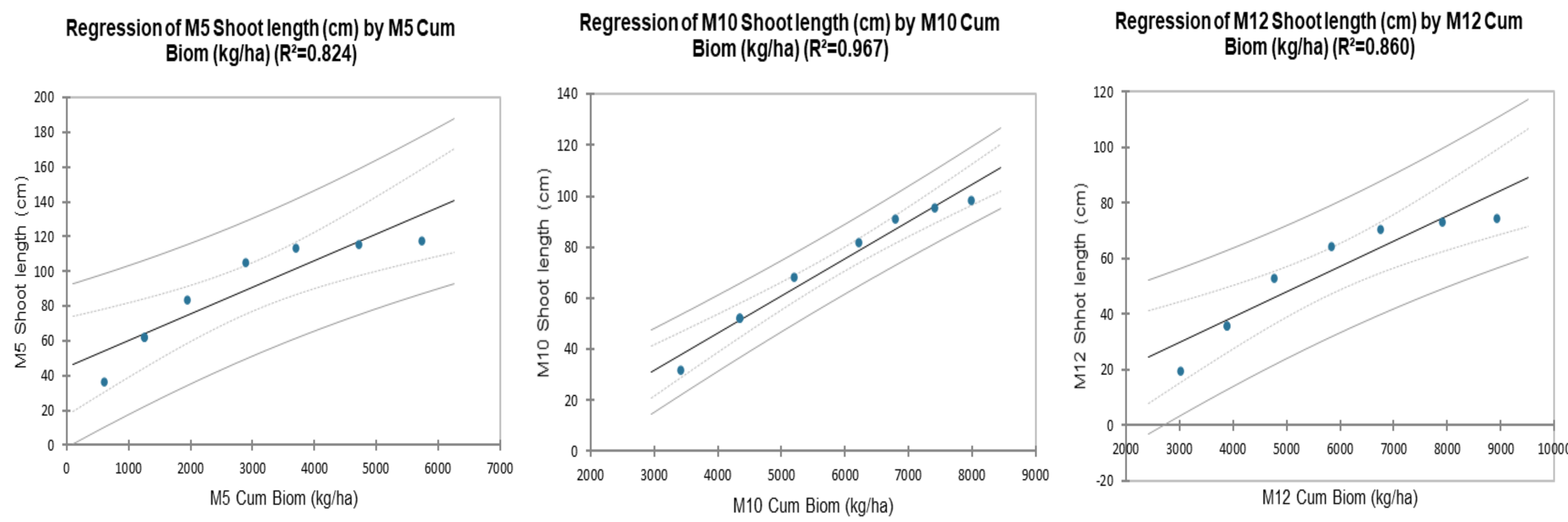

Figure 5. 2: Relationship between main shoot length measured and cumulative FruitLook biomass production for the three *Vitis vinifera* L. cv. Crimson Seedless field trial blocks (2018/19 season). Regression results: R^2 (M5) = 0.824; R^2 (M10) = 0.967; R^2 (M12) = 0.860

5.3.2 Leaf area index

FruitLook LAI of the seven experimental blocks for the season is depicted in Figure 5.3. As expected, there was a gradual increase in LAI during the season. The LAI declined at the onset of leaf fall. The LAI of the netted M5 and B3 blocks showed a stable profile throughout the season. This can be ascribed to the fact that overhead netting influences the spectral reflection of crops, thus affecting remotely sensing data values obtained (Jarmain, 2020), including the FruitLook LAI.

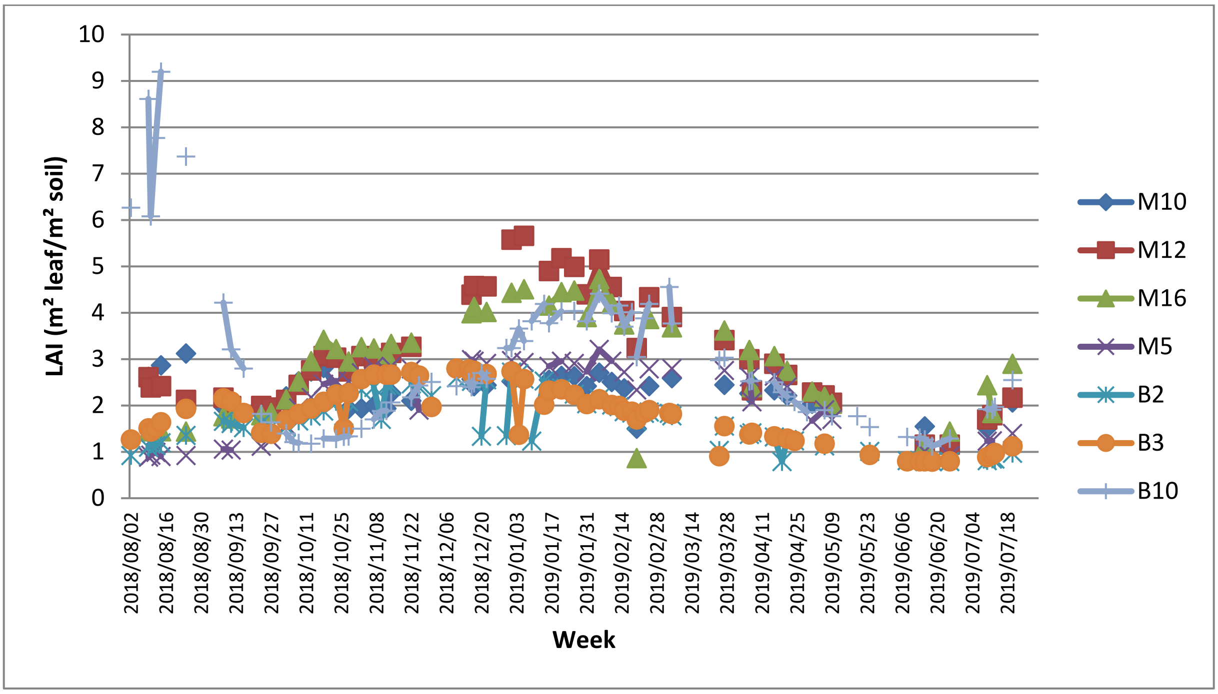

Figure 5.3: FruitLook leaf area index (LAI) from 02/08/2018 until 18/07/2019 of the seven experimental blocks in the 2018/19 season

5.3.3 Estimated evapotranspiration

Estimated evapotranspiration (ET), irrigation applied and rainfall of the 12 *Vitis vinifera* L. cv. Crimson Seedless experimental blocks are presented in Table 5.1. Based on the values obtained, the netted M5 and B3 blocks had the smallest difference between water used and water applied, but as overhead netting influences spectral reflection of crops, thus affecting the remote sensing data values obtained (Jarmain, 2020), including the FruitLook ET, these values are assumed to be lower that the actual ET of the respective blocks.

Total estimated FruitLook ET ranged between 739 and 1098 mm. Cumulative FruitLook ET, irrigation applied and rainfall for the experimental blocks are depicted in Figure 5.4. The total seasonal estimated ET of the open blocks (M10, D29, D6, M16, K1, and M12) ranged from 1000 to 1300 mm. The same cumulative rainfall data, obtained from the Môrester Ileaf Automated Weather Stations (AWS) were used and are presented for all blocks in Table 5.1 and Figure 5.4. This is because: (i) no other rainfall data was obtained during the survey; (ii) farms M and B were located next to each other and farm K was located close by; and (iii) it was assumed that the rainfall data of this AWS was representative of the rainfall of this subregion of the Berg River region.

Very low rainfall occurred in the subregion (101 mm annual total) which emphasizes why the table grape industry in this region is dependant on irrigation throughout the grapevine growing season. The total estimated irrigation water applied on the Crimson Seedless blocks ranged between 350 and 1559 mm. This might have been due to high air temperatures and vapor pressure deficit, resulting in larger evaporative response (Kustas *et al*., 2018).

Table 5.1: Monthly and total estimated ET, irrigation applied and rainfall for *Vitis vinifera* L. cv. Crimson Seedless blocks in the Berg River region (2018/19 season)

Descriptor	FruitLook ET, irrigation and rainfall												
	Sep	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Total**
	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm
M5 FruitLook ET	4	12	83	131	142	163	133	105	81	56	26	11	949
M5 Irrigation	12	38	96	92	135	147	169	102	48	0	0	0	839
M5 Rain	21	31	0	0	9	0	1	0	0	7	17	15	101
M5 Water used - Water applied	-29	-57	-13	39	-2	16	-37	3	33	49	9	-4	8
M10 FruitLook ET	16	32	98	131	153	197	162	121	93	63	33	18	1117
M10 Irrigation	12	62	91	114	143	122	162	70	15	0	0	0	791
M10 Rain	21	31	0	0	9	0	1	0	0	7	17	15	101
M10 Water used - Water applied	-17	-61	7	17	1	75	-1	51	78	56	16	3	225
M12 FruitLook ET	15	33	100	138	155	195	162	119	90	60	29	17	1114
M12 Irrigation	12	62	93	114	155	156	161	70	15	0	0	0	838
M12 Rain	21	31	0	0	9	0	1	0	0	7	17	15	101
M12 Water used - Water applied	-18	-60	7	24	-9	39	0	49	75	53	12	2	175
M16 FruitLook ET	7	25	103	144	155	188	158	116	91	60	30	21	1098
M16 Irrigation	12	62	90	114	143	148	110	118	18	0	0	0	815
M16 Rain	21	31	0	0	9	0	1	0	0	7	17	15	101
M16 Water used - Water applied	-26	-68	13	30	3	40	47	-2	73	53	12	6	182
B3 FruitLook ET	23	91	115	116	168	97	77	54	34	7	5	5	739
B3 Irrigation													630
B3 Rain													101
B3 Water used - Water applied													7
B2 FruitLook ET	18	88	110	111	168	98	77	55	7	8	5	4	694
B2 Irrigation													630
B2 Rain													101
B2 Water used - Water applied													-37
B10 FruitLook ET	40	63	92	118	208	148	106	83	47	12	16	29	881
B10 Irrigation													350
B10 Rain													101
B10 Water used - Water applied													429
D8 FruitLook ET	15	18	77	136	157	185	142	108	81	51	28	12	1011
D8 Irrigation	25	22	145	188	160	147	100	50	27	0	0	0	864
D8 Rain	21	31	0	0	9	0	1	0	0	7	17	15	101
D8 Water used - Water applied	-31	-35	-68	-53	-12	38	41	58	54	44	10	-3	46
D29 FruitLook ET	9	22	86	138	168	186	140	109	80	53	30	17	1038
D29 Irrigation	25	23	113	107	125	126	59	36	21	0	0	0	635
D29 Rain	21	31	0	0	9	0	1	0	0	7	17	15	101
D29 Water used - Water applied	-38	-31	-27	31	33	60	80	72	59	46	12	2	302
D6 FruitLook ET	16	25	82	148	174	197	151	117	87	55	28	13	1093
D6 Irrigation	33	50	212	341	305	301	189	70	59	0	0	0	1559
D6 Rain	21	31	0	0	9	0	1	0	0	7	17	15	101
D6 Water used - Water applied	-38	-56	-130	-193	-139	-104	-39	47	28	48	11	-2	-567
K1 FruitLook ET	13	15	87	151	158	181	146	108	80	57	35	20	1051
K1 Irrigation	26	33	169	214	208	170	128	6	40	0	4	1	998
K1 Rain	21	31	0	0	9	0	1	0	0	7	17	15	101
K1 Water used - Water applied	-34	-49	-82	-63	-59	11	17	102	40	50	14	4	-48

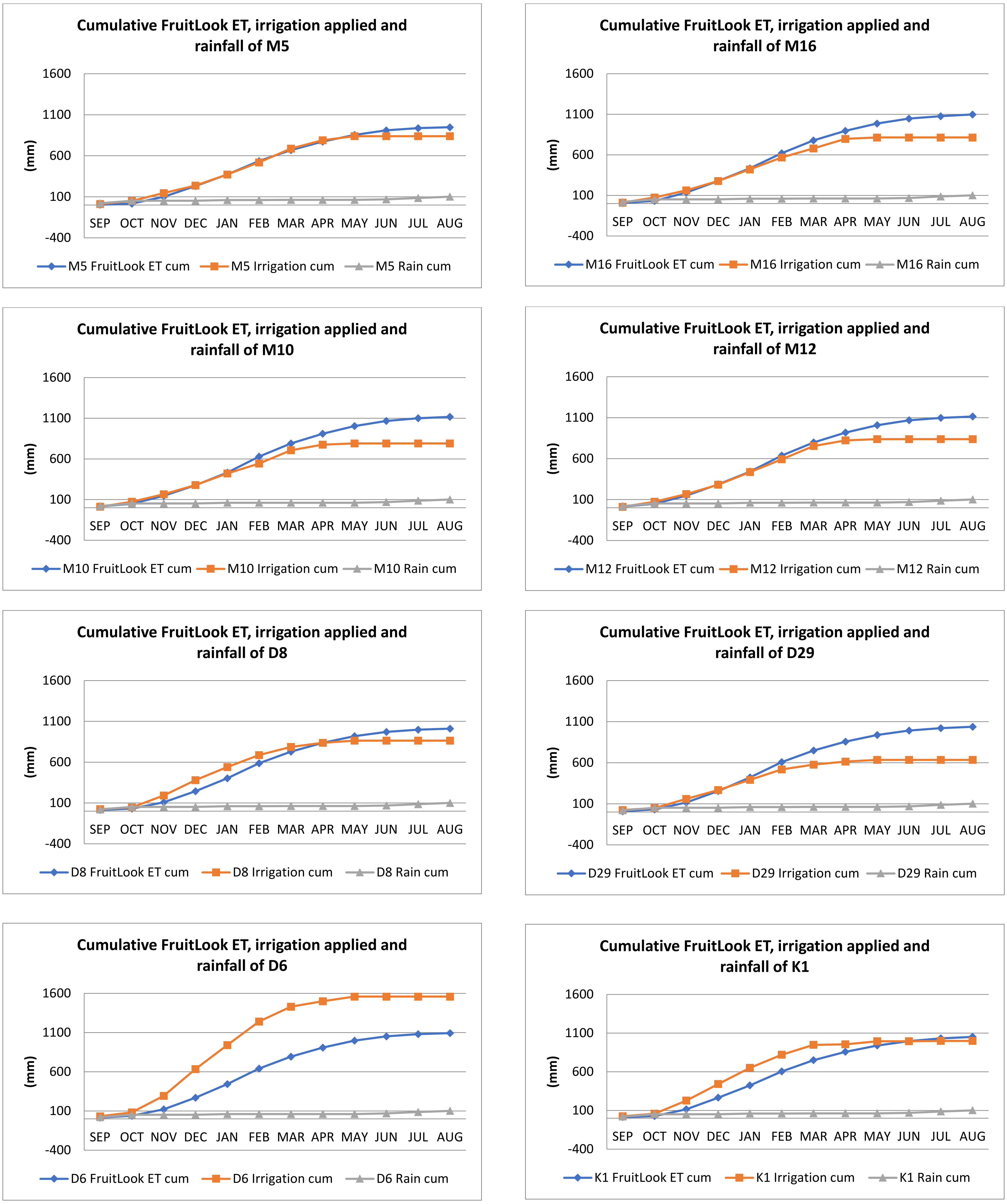

Figure 5.4: Cumulative FruitLook ET, irrigation applied and rainfall for *Vitis vinifera* L. cv. Crimson Seedless blocks in the Berg River region (2018/19 sseason)

5.4 CONCLUSIONS

The resuts indicated that there was a strong positive correlation between weekly shoot growth and FruitLook CPB for the three field trial blocks, as evident from the R^2 values of 0.824 (M5); 0.967 (M10); and 0.860 (M12), indicating that FruitLook CPB could be used as a reliable indicator of vigour and cumulative shoot growth. Total estimated FruitLook ET ranged between 739 and 1098 mm, while the total seasonal estimated ET of the open blocks ranged from 1000 to 1300 mm. FruitLook ET (estimated water use) is considered a reliable indicator of water use for open (uncovered) blocks, but not for blocks covered with overhead netting, because overhead netting influences spectral reflection of crops, thus affecting the remote sensing data values.

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CHAPTER 6

GENERAL CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The study demonstrated the total irrigation water use based on total production and export volume ranged between 7469 and 10 017 m³/ha. WUE based on the irrigation water use of the 12 experimental blocks ranged between 1.96 and 2.61 t/m³, which was higher than the WUE based on ET ranges between 1.41 and 1.73 t/m³. Because ET is normally lower at the beginning and at the end of the season as the grapevine development is respectively just initiated or over its peak. Peak values are typically reached in mid-summer, but greatly depend on the plant physiology and management. The blue WF (Irrigation) determined from total production, ranged from 430 to 603 m³/ton, which was lower than the blue WF (Irrigation) determined from export production, which ranged from 618 to 877 m³/ton. As this study only considered one season therefore, there was no clear trend observed regarding WUE and WF of netted blocks compared to open blocks.

There was a strong positive correlation between weekly shoot growth and FruitLook CPB for the three field trial blocks, as evident from the R^2 values of 0.824 (M5); 0.967 (M10); and 0.860 (M12), indicating that FruitLook CPB could be used as a reliable indicator of vigour and cumulative shoot growth. Total estimated FruitLook ET ranged between 739 and 1098 mm, while the total seasonal estimated ET of the open blocks ranged from 1000 to 1300 mm. ET (estimated water use) is considered a reliable indicator of water use for open (uncovered) blocks, but not for blocks covered with overhead netting, because overhead netting influences spectral reflection of crops, thus affecting the remote sensing data values.

6.2 RECOMMENDATIONS

More research is needed to quantify vineyard water use of netted blocks, compared to open blocks, including sap flow measurements to determine grapevine transpiration and establish vineyard transpiration values and using the universal soil water balance method to establish vineyard ET values. The WUE and WF calculations based on estimated ET and irrigation volumes in this research is the first step towards gaining insight into the impact of table grape production on the water resource in the selected study area. The total seasonal vineyard water use (estimated ET and irrigation volumes applied) that were quantified, could be considered as bench mark values for table grape vineyard water use in the Berg River region.

Few studies have been conducted on table grape WUE and blue WF and this study contribute to the limited information available. Through the field trial and the survey, a range of WU, WUE and blue WF values were established for table grape production in the Berg River region of SA, which could be used by the industry in water management and irrigation scheduling. FruitLook ET (estimated water use) could be considered as reliable indicator of water use for open (uncovered) blocks, but not for blocks covered with overhead netting, because overhead netting influences spectral reflection of crops, thus affecting the remote sensing data values.

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