Water footprint analysis to improve water use efficiency in table grape (*Vitis vinifera* L. *cv*. Crimson Seedless) production. A South African case study

by

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Pectora roborant cultus recti

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DECLARATION

By submitting this dissertation electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third-party rights and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

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SUMMARY

Water scarcity is a major impediment to agricultural production, warranting economically viable water use strategies globally. The aim of this study was to evaluate the effects of differing cultivation conditions as well as environmental effects on table grapes (*Vitis vinifera* L. *cv.* Crimson Seedless) in terms of plant growth, plant physiology, yield water use efficiency (WUE_y) and irrigation water use efficiency (WUE_{irr}) in the Hex River Valley of the Western Cape, South Africa. The experiment consisted of four commercial vineyard blocks with the following irrigation system/soil scenarios: (1) drip on sandy clay loam; (2) micro-sprinkler on sandy clay loam; (3) micro-sprinkler on loamy fine sand and (4) drip on sandy clay loam. No treatment was applied in this study, and standard viticulture management practices as recommended for the production of export quality Crimson Seedless table grapes were applied in each block by the specific farm. The blue water footprint along the production chain only was determined for three regions in South Africa (one winter & two summer rainfall areas). Data used for the water footprint analysis were obtained through interviews and questionnaires. FruitLook data were also validated against field measurements.

The four selected blocks showed great variability in terms of their soil characteristics and vegetative growth responses. Block D had vigorous growth in both seasons and the highest yield during the 2013/14 season, with the best fruit quality in both seasons. In contrast, Block A had poor vegetative growth, lower yield, as well as poor fruit quality in both seasons. Blocks B and D had higher specific leaf area (SLA). Blocks A and B had a tendency towards thinner leaves, which could have been linked to the lower stem water potential (Ψ_S) measured in those blocks at the different phenological stages. Higher values of net carbon assimilation rate and stomatal conductance corresponded with larger berry size and higher yield.

The two blocks that were irrigated with micro-sprinklers had higher irrigation volumes and evapotranspiration (ET). Furthermore, the two micro-sprinkler irrigated blocks had a tendency towards a higher WUE_y in the 2014/15 season, due to the higher ET and yield measured in these blocks. The drip irrigated Block D had a higher WUE_{irr} in both seasons, and also produced grapes of the best quality, which means a certain stress level can be applied even when grapevines are cultivated for table grape production, without forfeiting fruit quality. Thus, using a drip irrigation system and irrigation applications as applied for Block D and under similar conditions to that in this study, could reduce the volume of irrigation water used and contribute to saving water.

The regional average blue water footprint (WF) over two seasons was 210.35 m^3/ton, 392.19 m^3/ton and 272.42 m^3/ton for the Western Cape, Lower Orange River region and the Northern Province respectively. The regional average WUE_y values for both seasons was 5.04 kg/m^3, 3.00 kg/m^3 and 3.68 kg/m^3 for Western Cape, Lower Orange River and Northern Province regions, respectively.

Water footprints provide useful information on the water use of a specific area and strategies to improve WUE can be developed based on this information. This information can aid in decision making as to which crop can be produced sustainably with better economic benefits to the production area. Thus, WF determination can be used as a tool to raise awareness, as well as determine crop efficiency, which can be used in debates and decision making regarding water allocations. FruitLook data validation also showed a potential to be used in irrigation management decisions that could contribute to improved WUE.

Few studies have been conducted on table grapes WUE and blue WF and this study can contribute to that limited information availability. Most of the studies conducted on WUE and WF of

grapevines in general and table grapes specifically, were desktop studies and did not include actual plant growth and physiological measurements. Additionally, most of the global data available do not make a distinction between the different grape types (table grapes, raisin & wine grapes). The plant based measurements in this study also contributes to the scientific knowledge and understanding of how the grapevine's water use and performance is affected by different soil types and irrigation systems, through direct plant based measurements during critical phenological stages.

OPSOMMING

Waterskaarste is ‘n uiters belangrike beperking in landbouproduksie. Gevolglik is ekononies volhoubare watergebruikstrategië noodsaaklik. Die doel van hierdie studie was ‘n ondersoek na die effek van verskillende verbouingstoestande, asook omgewingseffekte op tafeldruiwe (*Vitis vinifera* L. *cv.* Crimson Seedless) in terme van plantgroei, fisiologie, produksie-watergebruik-effektiwiteit (WUE_y) en besproeiingswatergebruik-effektiwiteit (WUE_{irr}) in die Hexriviervallei van die Wes-Kaap, Suid-Afrika. Die eksperiment het bestaan uit vier kommersiële wingerdblokke met die volgende besproeiingstelsel-grond scenario’s: (1) drupbesproeiing op sand-klei-leem; (2) mikrospuit op sand-klei-leem; (3) mikrospuite op leem-fynsand; en (4) drupbesproeiing op sand-klei-leem. Geen behandeling is toegepas in hierdie studie nie en standaard wingerdkundige bestuurspraktyke soos aanbeveel vir die produksie van uitvoergehalte Crimson Seedless tafeldruiwe is toegepas in elke blok op die spesifieke plaas. Die blou watervoetspoor van die produksiesproses alleen is bepaal vir drie streke in Suid-Afrika (een winter- en twee somerreënvalgebiede). Data gebruik vir die watervoetspoorontledinig is verkry deur middel van onderhoude en vraelyste. FruitLook data is ook geverifieer teen veldmetings.

Die vier geselekteerde blokke het groot variasie getoon in terme van grondeienskapppe en vegetatiewe groeireaksies. Blok D het die sterkste groeikrag in beide seisoen gehad, die hoogste produksie in die 2013/14 seisoen, asook die beste druifgehalte in beide seisoene. In teenstelling hiermee, het Blok A swak vegetatiewe groei, swak produksie, asook swak druifgehalte in beide seisoene gehad. By blokke B en D is ‘n hoër spesifieke blaaroppervlak (SBO) gevind. Vir Blokke A en B is ‘n tendens van die voorkoms van dunner blare gevind, wat geassosieer kan word met die laer blaarsteelwaterpotensiaalwaardes (Ψ_S) gemeet in daardie blokke gedurende die verskillende fenologiese stadia. Hoër netto-waardes vir koolhidraat-assimmilasietempo’s en huidmondjiegeleiding was geassosieer met groter korrels en hoër produksie.

Die twee blokke wat met mikrospuite besproei was, se besproeiingsvolumes en evapotranspirasie (ET) was hoër. By die twee mikrospuit besproeide blokke is ‘n tendens van hoër WUE_y in die 2014/15 seisoen gevind, weens die hoër ET en opbrengs gemeet in hierdie bloke. Die drupbesproeide Blok D het ‘n hoër WUE_{irr} in beide seisoene gehad en het ook die beste gehalte druiwe gelewer in beide seisoene, wat aandui dan selfs in tafeldruifverbouing ‘n sekere mate van vogspanning toegepas kan word sonder dat vruggehalte benadeel word. Dus, gebruik van ‘n drupbesproeiingstelsel en besproeiingstoedienings soos toegepas vir Blok D, onder soortgelyke toestande as in hierdie studie, kan die volume besproeiingswater gebruik verminder en bydra tot waterbesparing.

Die streeksgemiddelde blou watervoetspoor (WV) oor die twee seisoene was onderskeidelik 210.35 m^3/ton, 392.19 m^3/ton en 272.42 m^3/ton vir die Wes-Kaap, Benede-Oranjeriviergebied en die Noordelike Provinsie. Die streeksgemiddelde WUE_y-waardes oor beide seisoene was onderskeidelik 5.04 kg/m^3, 3.00 kg/m^3 en 3.68 kg/m^3 vir die Wes-Kaap, Benede-Oranjeriviergebied en die Noordelike Provinsie

Watervoetspoorwaardes verskaf waardevolle inligting oor watergebruik in ‘n spesifieke gebied en strategieë om WUE te verbeter kan ontwikkel word op grond daarvan. Hierdie inligting kan bydra tot besluitneming ten opsigte van watter gewas volhoubaar geproduseer kan word met ekonomiese voordele vir die produksiegebied. Dus, WV-bepaling kan gebruik word as hulpmiddel vir bewusmaking, asook vir evaluering van gewas-effektiwiteit tydens besluitneming oor watertoekennings. Verifikasie van FruitLook data met veldmetings, het aangetoon dat die FruitLook

platform potensiaal het om gebruik te kan word in besproeiingsbestuursbesluite, wat kan bydra tot verbeterde WUE.

Enkele studies is reeds uitgevoer op WUE en blou WV van tafeldruiwe en hierdie studie kan bydra tot die beperkte inligting tans beskikbaar, Meeste studies wat tot op hede gedoen is oor WUE en blou WV van die wingerd in die algemeen en tafeldruiwe spesifiek, was “desktop” studies en het nie werklike plantgroei en fisiologiese metings ingesluit nie. Meeste globale data beskikbaar, tref geen onderskeid tussen die verskillende druiftipes nie (tafeldruiwe, droogdruiwe & wyndruiwe). Deur middel van die direkte plantgebaseerde metings geneem tydens kritiese fenologiese stadia, dra hierdie studie ook by tot die wetenskaplike kennis en begrip van hoe die wingerstok se watergebruik en prestasie beïnvloed word deur verskillende grondtipes en besproeiingstelsels.

This dissertation is dedicated to my family and friends for their love, support and encouragement

"I can do all things through Christ, who strengthens me" Phil 4:13

BIOGRAPHICAL SKETCH

Grace Nandesora Kangueehi was born in Windhoek, Namibia on 27 May 1977. She matriculated from Windhoek High School in 1996. In 1997 she did an Agriculture upgrading course at The University Centre for Studies in Namibia (TUCSIN). She then joined the University of Namibia and graduated with a BScAgric (Crop Science) in 2002. She started working as an assistant production manager at the Namibia grape company in 2002, and later become a production manager at the same company. She then completed her MScAgric (Horticulture) degree at the University of Stellenbosch in 2008 on the topic "Nutrient requirement and distribution of intensively grown 'Brookfield Gala' Apple Trees". In 2009 she joined the Namibia University of Science and Technology in a lecturing capacity, with the department of Agriculture and Natural Resources Sciences, a position she currently holds. In 2013 she enrolled for PhD (Agric) in Viticulture at the University of Stellenbosch.

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PREFACE

This dissertation is presented as a compilation of seven chapters. Each chapter is introduced separately and is written according to the style of the South African Journal of Enology and Viticulture.

Chapter 1	**General introduction and project aims**
Chapter 2	**Literature review** A review of water use efficiency and water footprints of table grapes
Chapter 3	**Research results** Investigating Crimson Seedless grapevine phenology and vegetative growth performance under differing cultivation conditions
Chapter 4	**Research results** Selected physiological parameters, reproductive indicators and yield water use efficiency of Crimson Seedless grapevines
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Chapter 1

General introduction and project aims

CHAPTER I: GENERAL INTRODUCTION AND PROJECT AIMS

1.1 Introduction

South Africa is considered a semi-arid country, receiving approximately 50% of the average annual global rainfall of 840 mm (Department of Water Affairs and Forestry, 2004*)*. The National Water Act (NWA) of 1998 indicated that water resources are scarce and unevenly distributed across the country due to past laws and practices (National Water Act, 1998). Therefore, water availability in water scarce areas caused a restraint on social and economic development (Department of Water Affairs and Forestry, 2000). In an attempt to rectify the uneven distribution of water, improve living conditions as well as economic benefits of everyone, the National Water Act of 1998 proposed a sustainable water resource management strategy, in which three principles are emphasised, namely equity, sustainability and efficiency (Department of Water Affairs and Forestry, 2004). Furthermore, adversely dry climatic conditions and water scarcity alongside projected climate change can potentially hinder prospects of future development (Ashton, 2003), subsequently giving rise to strong competition among different water use sectors. It is therefore important that those affected sectors must use this scarce resource sustainably. According to the Department of Water Affairs and Forestry (2004), the water use by different water use sectors such as agriculture, domestic and urban, mining and commercial forestry are 62%, 27%, 8% and 3%, respectively. Since the agriculture sector uses a substantially higher proportion of the available freshwater than other sectors, there was a call for more efficient water use in agriculture. The high proportion of water use by this sector relative to other sectors also resulted in pressures to divert some of this water to urban and industrial water needs (Department of Water Affairs and Forestry, 2004).

In many countries, including South Africa, the agriculture sector depends on irrigation (Department of Water Affairs and Forestry, 2004). With predicted climate change patterns, of which lower rainfall is already perceived with higher evaporation, this can have a negative impact on future agricultural developments (Ashton, 2003; Department of Water Affairs and Forestry, 2004; Bredell, 2012) leading to increasing competition among the water use sectors. Consequently, agriculture faces a huge challenge of increasing production with minimum water use to satisfy the ‘more crop per drop’ concept. Several approaches at both local and international level, aimed at improving water use efficiency, have been developed or adopted by the Water Research Commission and Agriculture Research Council (Seckler, 1996; Reinders *et al.*, 2013). However, there is a call for more to be done in order to become more water use efficient, due to differences in water use by producers and inappropriate irrigation scheduling (Stevens, 2006; Roux *et al.*, 2008). Water use efficiency (WUE) is affected by different factors such as the cultivar, soil, crop load, cultivation practices as well as climatic conditions. Therefore, tools that can combine plant physiological indicators and soil water monitoring are needed in irrigation scheduling to improve WUE.

All commercial table grape vineyards in South Africa are under irrigation. Recent studies on grapevine WUE focused on deficit irrigation scheduling (De Souza *et al.*, 2005; Chaves *et al.*, 2007; Acevedo-Opazo *et al.*, 2010) and using physiological indicators to detect grapevine water status (Choné, 2001; Williams & Araujo, 2002; Cifre *et al.*, 2005; Girona *et al.*, 2006; Flexas *et al.*, 2010). The focus of the above-mentioned studies are in agreement with Jones (1990), who reported that plant physiology is more sensitive to plant water status than soil water content. This observation emphasises the need to combine soil water monitoring with plant water status monitoring in order to supply the vines with sufficient water, but also to allow efficient plant water use. Different plant-based water status monitoring techniques such as leaf or stem water potential measurements (Jones, 2004; Girona *et al.*, 2006), sap flow measurements (Eastham & Gray, 1998) and stomatal conductance measurements (Cifre *et al.*, 2005) are effective for early determination of water deficits in plants, before stress occurs. Therefore, they can be used as stress indicators and aid in irrigation scheduling to avoid unnecessary irrigation and to improve WUE. FruitLook, a remote sensing satellite-based information website that provides spatial datasets for the deciduous fruit producing areas of the Western Cape, can be used as a water management tool (www. fruitlook.co.za). The FruitLook parameter maps are derived from a combination of satellite and field data, and the ETLook algorithm is used (Bastiaanssen *et al.*, 2012).

Water scarcity is a major impediment to agricultural production (Tomás *et al.*, 2012), warranting economically viable water use strategies globally. There are very few published results available on seasonal total water use and water footprinting of table grape vineyards in South Africa. Results from studies regarding annual irrigation requirements/applications of table and raisin grape vineyards under South African conditions are inconsistent, since water use depends on different factors such as production regions, irrigation practices, canopy characteristics and vine vigour. For Dan-ben Hannah table grapes growing in the Berg River Valley, Myburgh and Howell (2012) reported that low frequency drip irrigated vines required 260 mm of water per season compared to 490 mm for grapevines irrigated with daily pulse drip irrigation. An average seasonal water use of 411 mm for drip irrigation and 569 mm for micro irrigation of Barlinka in the Hex River Valley was reported by Saayman and Lambrechts (1995). Myburgh (1996) and Fourie (1989) reported 663 mm and 741 mm, respectively, for Barlinka irrigated with micro sprinklers in the Hex River Valley. Water use for Sunred Seedless and Muscat Supreme irrigated with micro sprinklers in the Hex River Valley was estimated to be 879 mm (Myburgh & Howell, 2007). It should be noted that the rooting depth of the grapevines was 1.2 m. Myburgh (2003b) reported 655 mm to 1348 mm and 8541 to 13430 m^3 for micro sprinkler and flood irrigated Sultanina in the Lower Orange River region. Few studies on table grape water footprint have been done in South Africa, apart from a study in the Breede River Catchment, which was an economic impact assessment of crop water use (Pegasys, 2010). Water footprint is the total quantity of water utilised for activities of a single social entity (Hoekstra *et al.*, 2011). In terms of table grape production, it would be the quantity of water used per kg or tonnage grapes produced. Water footprint is categorised in different components, namely the blue, green and grey water (Clothier *et al.*, 2010; Hoekstra *et al.*, 2011; Mekonnen & Hoekstra, 2010). The blue water footprint indicates the quantity of surface or groundwater evaporated, embedded into a product or settled in other areas than before (Hoekstra *et al.*, 2011). The green water footprint indicates the quantity of rainwater evaporated or embedded in a product. The grey water footprint indicates the quantity of freshwater needed to integrate the load of pollutants to acceptable levels that won't be harmful to the environment (Hoekstra *et al.*, 2011; Mekonnen & Hoekstra, 2010). Pegasys (2010) determined a total water footprint (blue & green) of 500 m^3/ton for table grapes in the Breede River catchment. A national survey by Stevens (2006) indicated that only 18% of farmers adopted optimal water management practices in model-assisted irrigation schedules. Based upon block information of 136 commercial blocks from the Berg River Table Grape block competition over an 11 year period (2004/05 to 2016/17), it was evident that most producers use some form of irrigation scheduling equipment. However, in the majority of cases (60%) producers still adhere to a fixed irrigation programme (total hours at a specific phenological stage) (E. Avenant, personal communication, 2017). Consequently, a considerable number of producers are using water less efficiently. Therefore, addressing such inefficiencies can improve WUE in the viticulture sector. Most of the deficit irrigation studies in grapevines indicated a reduction in vegetative growth with a similar or, in some cases, an increase in yield, as well as improvement in fruit quality (Chaves *et al.*, 2007; Costa *et al.*, 2007; Blanco *et al.*, 2010; Romero *et al.*, 2013). Furthermore, in studies where grapevines were irrigated according to plant available water depletion levels it was also shown that irrigating with less water (mild stress) improved colour and fruit quality of table grapes (Myburgh, 1996; Myburgh, 2003a). Based on the above-mentioned studies, it is possible to reduce irrigation water applied in order to save water without compromising yield and quality. Consequently, there is a need to determine the water footprint of table grapes, as well as the quantity of water needed for table grape production.

Water footprint information can be used in sustainable water resource management as well as improving WUE in water scarce areas. This study therefore seeks to determine the blue water footprint of Crimson Seedless table grapes and to investigate opportunities for increasing 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 South Africa and globally and it also has a long growing season. It is also very popular with table grape consumers. Since there have not been many studies pertaining to WUE and water footprinting of Crimson Seedless, this study will contribute novel information in this regard.

1.2 Project Aims

The aims of this study were:

1.2.1 To determine the effects of differing cultivation conditions on table grape *(Vitis vinifera* L. *cv*. Crimson Seedless) phenology, vegetative growth, WUE, yield, fruit quality and physiology.

This objective aimed to contribute to the scientific knowledge and understanding of how the grapevine's performance is affected by differing cultivation conditions, *i.e.* soil types, irrigation systems and cultivation practices, through direct plant-based measurements during critical phenological stages. Vineyard blocks with differing soil texture classes and differing irrigation systems were compared in terms of plant growth (vegetative & reproductive), plant physiology, WUE as well as environmental influence (climatic, soil conditions & soil water content).

1.2.2 To conduct a blue water footprint analysis for the production of table grapes in the Hex River Valley and other regions in South Africa.

This objective aimed to contribute to the scarce information on the potential water footprint of table grapes in South Africa. Questionnaire surveys were conducted to obtain the relevant production information from three main table grape production regions (Hex River Valley, Lower Orange River and Northern Province) to determine the blue water footprints. FruitLook data were incorporated in this study and could be a vital practical tool for the water footprint assessment.

1.2.3 Setting guidelines for improved water resource management in table grape production.

Accurate information on the water footprint and WUE of table grapes could empower table grape producers, individual farms and catchment areas to farm sustainably and efficiently under limited water resources. Accurate quantification of table grape water use could be used to formulate strategies for negotiations with policy makers regarding water allocation. FruitLook data were validated against field measured data in order to determine whether FruitLook satellite data reflects what is happening in the vineyard and whether it could add value in irrigation management and water footprint determination.

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Chapter 2

Literature review

A review of water use efficiency and water footprints of table grapes

CHAPTER II: A REVIEW OF WATER USE EFFICIENCY AND WATER FOOTPRINTS OF TABLE GRAPES

2.1 Introduction

In view of the escalating demands on the scarce water resources, sustainable table grape production requires a very high water use efficiency (WUE) (Tomás *et al.*, 2012). Water use efficiency is defined as the ratio of biomass production over a given period, to total water loss (Steduto, 1996; Bacon, 2004; Chaves *et al.*, 2004; Chaves *et al.*, 2007; Costa *et al.*, 2007; Tyerman *et al.*, 2010). Stanhill (1986) and Steduto (1996) defined the concept of efficiency into two forms, the first being the hydrological approach “efficient water use” which refers to water as the component of both “output and input”. The second definition is based on the physiological approach “water use efficiency” referring to the carbon gain against water lost. Consequently, WUE is a complex term having different meanings to different fields of study and its definition depends on the context in which it is used and, whether it is in relation to leaf, plant or crop as well as the measurement time scale (Steduto, 1996; Bacon, 2004; Chaves *et al.*, 2004; Jones, 2004a; Morison *et al.*, 2008). Some researchers have argued that WUE in the context mentioned above is not a proper term since true efficiency is not measured. This argument is based on the fact that only a small portion of water taken up by plants is used in plant growth and biomass production and the rest is lost to the environment (Stanhill, 1986; Steduto, 1996; Chaves *et al.*, 2004; Jones, 2004a; Perry, 2007; Heydari, 2014). There is also the assumption that efficiency should be based on a “dimensionless ratio between the output of a quantity and its input” (Jones, 2004a; Perry, 2007; Heydari, 2014). For this reason, some researchers argued that carbon gained against water lost must not be referred to as WUE, but it should rather be referred to as water productivity (Perry, 2007; Heydari, 2014). In some studies WUE is interchangeably used as water productivity (Perry, 2007; Morison *et al.*, 2008; Boutraa, 2010), while some researchers argue that a distinction must be made since these two terms mean two different things (Stanhill, 1986; Steduto, 1996; Heydari, 2014). Even though the WUE term has its critics in some literature, it is a widely accepted term in the agriculture and plant physiology fields and will be the term used in this review and the entire dissertation.

Water scarcity is becoming a major constraint to agricultural production, hence the need to optimise green and blue water use for sustainable viticulture production. For the viticulture sector to realise that, there is a need to determine the water footprint (WF) of table grapes and schedule irrigation optimally to improve WUE. The aim of this chapter is to review the types and concepts of WUE and water footprints of table grapes.

2.2 Water use efficiency

Grapevine WUE can be measured at different levels and time during the growing season, ranging from instantaneous measurement at the leaf level to seasonal measurements at the plant or crop level (Steduto, 1996; Bacon, 2004; Chaves *et al.*, 2004; Jones, 2004a; Morison *et al.*, 2008; Medrano *et al.*, 2015a). The different types of WUE and its concepts will be discussed in the following sections.

2.2.1 Leaf water use efficiency

Leaf water use efficiency (WUE_l), also known as photosynthetic or physiological WUE, is measured at the leaf level and is defined as the ratio of leaf net carbon assimilation rate (CO_2) to leaf transpiration or stomatal conductance (Steduto, 1996; Bacon, 2004; Chaves *et al.*, 2004; Jones, 2004a; Flexas *et al.*, 2010; Medrano, *et al.*, 2015a). Intrinsic and instantaneous WUE is determined from single leaf gas exchange measurements and can be conducted any time. Intrinsic water use efficiency (WUE_i) is defined as the ratio of leaf net carbon assimilation rate (A) to stomatal conductance of water vapour (gs), *i.e.* A/gs (Jones, 2004a; Flexas *et al.*, 2010; Schultz & Stoll, 2010; Medrano *et al.*, 2015a). Instantaneous WUE (WUE_{inst}) is defined as the ratio of leaf net carbon assimilation rate (A) to leaf transpiration rate (E), *i.e.* A/E (Flexas *et al.*, 2010; Schultz & Stoll, 2010; Medrano *et al.*, 2015a). Transpiration is affected by stomatal opening as well as the vapour pressure deficit (VPD) surrounding the leaf, therefore environmental conditions have an influence on WUE_{inst}. The WUE_i, however, excludes fluctuations of evaporative demand for leaf water outflow pertaining only to stomatal opening (Bierhuizen & Slatyer, 1965). It is therefore important to evaluate the integral changes in WUE regardless of the prevailing atmospheric conditions (Bota *et al.*, 2001; Chaves *et al.*, 2004; Souza *et al.*, 2005). Jones (2004a) reported that the ratio of WUE_i is constant over a range of stomatal conductance showing linear relationships except in cases where the stomata are wide open. The rate of carbon assimilation in C3 plants corresponds to the internal CO_2 levels controlled by stomatal conductance. Therefore, if stomatal conductance increases above the effective point, leaf photosynthetic rate would slightly increase thus reducing WUE (Chaves *et al.*, 2007). An increase in midday stomatal conductance under conditions of water stress reduces net carbon fixation, thereby depleting CO_2. This in turn reduces photosynthetic efficiency with subsequent low intrinsic WUE (Chaves *et al.*, 2007). Carbon isotope discrimination is also used in field studies to determine intrinsic WUE (Farquhar & Richards, 1984; Schultz & Stoll, 2010). This measurement differs to leaf gas exchange in the sense that it integrates intercellular to atmospheric CO_2 concentration for longer periods of time (Schultz & Stoll, 2010). In field studies ^{13}C is mostly used compared to ^{12}C due to the intrinsically lower reaction of the primary carboxylating enzyme, ribulose-1,5-bisphosphate carboxylase-oxygenase (Rubisco) (Farquhar & Richards, 1984).

2.2.2 Plant and crop water use efficiency

Plant water use efficiency (WUE_p) is defined as the rate of biomass or dry matter production divided by transpiration and is also referred to as transpiration efficiency (TE) in some literature (Steduto, 1996; Chaves *et al.*, 2004; Jones, 2004a; Morison *et al.*, 2008; Flexas *et al.*, 2010; Iland *et al.*, 2011). These measurements are normally done over a season and only consider water loss through transpiration (Flexas *et al.*, 2010). Crop water use efficiency (WUE_c) is defined as the total biomass production, shoot biomass or economic harvested yield per unit area against total evapotranspiration (ET), plant transpiration (E) or seasonal water use (irrigation & rainfall) (I) (Chaves *et al.*, 2004; Gregory, 2004; Jones, 2004a; Tyerman *et al.*, 2010; Iland *et al.*, 2011). It is usually expressed in terms of dry mass, fresh mass or glucose equivalent of those masses per unit of water used (Jones, 2004a). Crop WUE is also referred to as agronomic WUE, production WUE and yield WUE by different researchers (Iland *et al.*, 2011). Different equations are used for determining WUE_c, for example Gibberd *et al.*, 2001 and Tyerman *et al.* (2010) proposed the following equation for crop WUE:

$$WUE_c = TE \times SWE \times HI \qquad \text{(Eq. 2.1)}$$

where TE is transpiration efficiency, SWE is soil water extraction and HI is harvest index.

It was also reported that an increase in any of these components will improve WUE_c (Gibberd *et al.*, 2001; Tyerman *et al.,* 2010). Grapes are considered a strong sink for carbohydrates since it imports about 90% of carbohydrates produced and is therefore regarded as a good indicator of WUE (Flexas *et al.*, 2010). Yield water use efficiency (WUE_y) is described as total harvested yield (Y) per unit of water applied (irrigation & rainfall) (Jones, 2004a; Iland *et al.*, 2011) or evapotranspiration (Bacon, 2004; Jones, 2004a), therefore the units of WUE_y are kg/m^3 or mm. The following equation is used for determining WUE_y:

$$WUE_y = Y \div I, ET \text{ or } E \qquad \text{(Eq. 2.2)}$$

where Y is harvested yield (tons/kg) and I is total water used (irrigation plus effective rainfall), ET is evapotranspiration and E is transpiration expressed per specified area.

Furthermore, Chaves *et al.* (2004) referred to the relationship of harvested yield to irrigation water use as irrigation water use efficiency. Steduto (1996) defined yield WUE as the “product of above-ground consumptive biomass WUE times the Harvest Index”.

2.2.3 Economic water use efficiency

Economic water use efficiency (WUE_e) refers to the monetary value of the harvested yield ($) divided by the water use (I) expressed per specified area (Iland *et al.*, 2011), where:

$$WUE_e = \$ \div I \qquad \text{(Eq. 2.3)}$$

where $ is the price per kg grapes and I is the water use.

Economic water use efficiency is affected by all factors affecting WUE_y, thus good management strategies need to be adhered to in order to have higher WUE_y as well as WUE_e.

2.3 Factors affecting water use efficiency

For a vineyard to be water use efficient, its’ water use must be reduced or productivity increased using the same or less water than before. There are a number of different factors that interact and affect each other which contribute to grapevine WUE (Flexas *et al.*, 2010; Schultz & Stoll, 2010). Flexas *et al.* (2010) presented a diagram demonstrating the different interacting factors that have an impact on WUE_c and WUE_l (Figure 2.1). The two main functions of WUE_p and WUE_c is carbon or dry matter production and water use. Grapevine carbon or dry matter production is determined by photosynthesis and respiration. Water use is determined by transpiration, evaporation and runoff. Grapevine photosynthesis and transpiration share the same transport pathway, therefore they are both affected by the same factors such as canopy growth and structure, leaf area index, leaf angle, light interception and prevailing climatic conditions (Flexas *et al.*, 2010). Steduto (1996) reported a linear relationship between biomass production and transpiration, mainly influenced by intercepted radiation used in both these processes as well as the sharing of the transport pathway by CO_2 and water vapour. However, he indicated that light intercepted has a higher impact on the relationship since only 400-700 nm of intercepted radiation (PAR) is used in photosynthesis whereas the rest is used in transpiration. Transpiration is affected mainly by canopy leaf area and light interception; thus, a bigger leaf area will have a higher transpiration. Moreover, WUE is also affected by night transpiration as well as respiration in different plant tissues during the day, which is not taken into account during the leaf gas exchange measurements for WUE_l determination (Medrano *et al.*, 2015a). Therefore, these physiological processes could decrease WUE_c without affecting WUE_l. The WUE_p depends on water loss during transpiration (day & night) as well as respiration that is not accounted for in leaf gas exchange measurements (Tomás, 2012; Medrano *et al.*, 2015b). In a study conducted by Medrano *et al.* (2015b) on grapevines, night transpiration accounted for approximately 10% of daily transpiration losses and respiration accounted for 33% to

45% of losses, depending on the water stress experienced by the grapevines. Clearly this difference is not accounted for when scaling up from leaf WUE to whole canopy/plant and that can contribute to the inconsistency found in scaling from leaf to whole plant WUE measurements. Furthermore, it was eluded that most studies pertaining to grapevine focused more on WUE_l with fewer studies focusing on whole plant/crop WUE (Gibberd *et al.*, 2001; Tomás *et al.*, 2012). Several authors have also indicated the complexities of comparing WUE_l methods to whole plant/crop canopies since the different methods might not correspond, and yield and quality might not even be linear (Iland *et al.,* 2011; Tomás *et al.*, 2012).

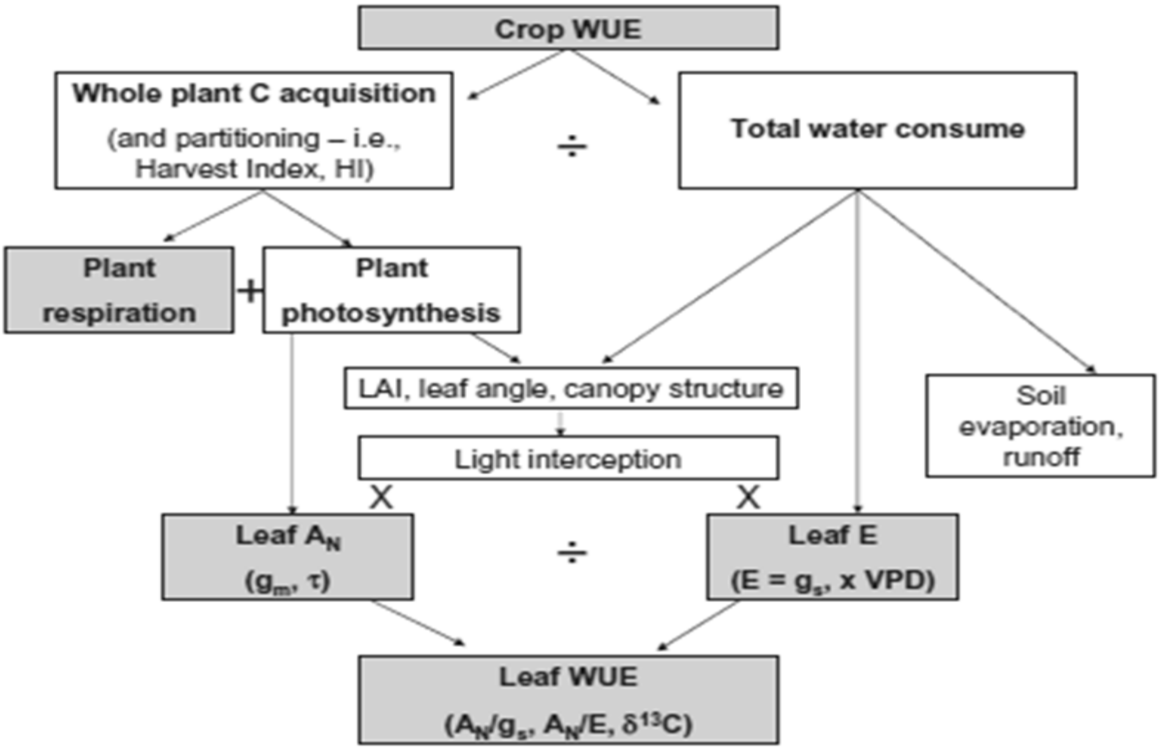

Figure 2.1: Diagram showing interaction of different processes affecting crop water use efficiency (Flexas et al., 2010).

Water use efficiency is affected by different factors such as plant function, physiological mechanisms, environmental factors and agronomic management practices that will be discussed in the following section.

2.3.1 Plant function

2.3.1.1 Grapevine phenology

Grapevine phenology is the study of the natural process that takes place in the life cycle of a vine and how it is influenced by climate and its growing environment. The yearly life cycle of the grapevine begins with bud break in late winter to early spring ending with leaf fall in autumn followed by winter dormancy (Coombe, 1995). The vegetative stage is the stage shortly before bud break up to just before flowering. The initial growth is depended on reserve nutrients from the mother plant (Kangueehi, 2008). After leaf formation, shoot growth depends more on photosynthesis produced by the leaves and water become critical in the process of transporting the nutrients (Van der Westhuizen, 1974). Young leaves only start exporting their own organic nutrients when they become about 40-50% of their normal size, with maximum assimilation rate at about 30-40 days after leaf unfolding (Iland *et al.*, 2011). Moisture deficiency at this stage is unfavourable and can negatively affect growth vigour and crop productivity. After bud break, shoots elongate, leaf area increases and water use also increases. Sufficient soil moisture before and during this stage is very important for root development. Grapevines are sensitive to water deficiency at the flower development and berry/fruit set stage since it causes poor fruit set. Berry growth takes place in three phases which is sometimes referred to as a double sigmoidal growth curve (Coombe, 1992). The three phases are: berry development, véraison and ripening. Lack of moisture at the berry development stage affects berry size and bunch mass, therefore necessary precaution should be taken to avoid any water shortages (Van der Westhuizen, 1974). In order to improve WUE, a certain degree of water stress can be applied to vines in the form of water deficits just after fruit set in order to control shoot vigour thereby reducing vegetative growth (Van der Westhuizen, 1974). However, the stress should be such that efficient leaf function during berry formation and berry ripening is still maintained (Iland *et al.*, 2011). Water supply can be reduced few weeks before harvesting in black grapes without negatively affecting fruit quality (Iland *et al.*, 2011). Irrigation is essential in the post-harvest to the dormant period because water helps with root development and reserve build up for the succeeding season. Additionally, water deficiency at this stage stimulates early leaf abscission (ethylene) affecting reserve build up that can support new growth of the succeeding growing season negatively (Scholefield *et al.*, 1978).

2.3.1.2 Rootstocks

Viticulture worldwide have adapted the use of the American *Vitis* species rootstocks that are more resistant to phylloxera that destroyed European grapevines in the 19th century (Granett *et al.*, 2001; Iland *et al.*, 2011). There are two important considerations when selecting a suitable rootstock. The first one is the influence it will have on the production and grape quality depending on the successful integration with the scion. Secondly, is the performance on the specific site which is greatly determined by the tolerance of the rootstock to a variety of biological, physical and chemical soil factors (Avenant, 2013). About 43 rootstock cultivars are on the official list of rootstocks for table grapes in South Africa, of which Ramsey and Richter 110 makes up about 88% of all existing planting (Avenant, 2013). Ramsey rootstock performs well on poor sandy soils such as the soils in the Hex River Valley, because it is a strong vigorous rootstock with good root distribution (Teubes, 2014). The good root branching gives it an advantage in more water extraction from the soil. Furthermore, it has a high resistance to nematodes and a moderately fair resistance to phylloxera (Saayman, 2009). However, it is not advisable to use this vigorous rootstock with strong growing scion cultivars such as Crimson Seedless in fertile soils since it will result in bud fertility and setting problems (Teubes, 2014). Botrytis can also be a serious problem on fertile soils. Ramsey is also known for good bunch quality, but on fertile soils cultivars such as Crimson and Barlinka often have a problem with berry colouring. Richter 110 can control vigorous growth thereby improving fertility. Furthermore, it has a long growth cycle making it suitable for the late ripening cultivars. The rootstock is drought resistant but light sandy soils must be avoided.

2.3.1.3 Table grape cultivars

Table grape cultivars are divided into six categories as follows: i) white seedless, ii) white seeded, iii) red seedless, iv) red seeded, v) black seedless and vi) black seeded. The different categories and the main table grape cultivars grown in South Africa in each category are indicated in Table 2.1. Seedless grape cultivars constitute the largest portion of the total table grape vineyard areas and contributed about 83% towards export from South Africa during the 2015/16 season (SATI, 2016). Table 2.2 indicates a 5-year (2011/12 – 2015/16) average of the national production per variety category (4.5 kg equivalent cartons) of which white seedless, red seedless and black seedless grapes contributed about 35%, 31% and 10%, respectively, towards table grape exports (SATI, 2016). This is also an indication that customers prefer seedless table grapes compared to seeded table grapes.

Table 2.1: Main table grape cultivars grown in South Africa.

Category	**White seedless**	**White seeded**	**Red seedless**	**Red seeded**	**Black seedless**	**Black seeded**
Cultivar names	Thompson Seedless/ Sultana	Dauphine	Sunred Seedless	Red Globe	Midnight Beauty	Barlinka Clone 47
	Sugraone	Waltham Cross	Flame Seedless	Alpha Red	Autumn Royal	Barlinka Clone 27
	Regal Seedless	Waltham Cross Clone 13	Crimson Seedless	Tropical Delight	Sable Seedless	La Rochelle
	Prime Seedless	Waltham Cross Clone 22, 44 and 8	Ralli Seedless	African Delight	Desert	Alphonse Lavallée
	Early Sweet	Victoria	Starlight			Dan-Ben Hannah
	Coachella	Moonballs	Tawny			Ronelle (Black Gem
	Arra 15		Evans Delight			Bonheur
	Sundance		Scarlotta Seedless			Ebony Star

Table 2.2: National production per cultivar category as expressed in 4.5 kg equivalent cartoons. Data is an average of 5 seasons (2011/2012 – 2015/16) (SATI, 2016)

Cultivar Category	**4.5 kg equivalent cartons**	**Production % per cultivar**
Black Seeded	4 097 219	8
Black Seedless	5 520 269	10
Red Seeded	5 274 879	10
Red Seedless	16 912 021	31
White Seeded	3 622 291	7
White Seedless	18 847 671	35
Total	54 274 349	100

2.3.1.4 Cultivar differences

Genetic differences are reported to play a huge role in WUE of grapevines (Bota *et al.*, 2001; Gibberd *et al.*, 2001; Schultz, 2003; Souza *et al.*, 2005; Flexas *et al.*, 2010; Roux *et al.*, 2014). Bota *et al.* (2001) reported high variably in assimilation, conductance and WUE$_i$ in a study conducted on different grapevines under different irrigation regimes. Furthermore, other studies indicated that some grapevines are more tolerant to low soil moisture than others (Schultz, 2003; Soar *et al.*, 2006). Where Syrah and Grenache grapevines were under deficit irrigation, Syrah exhibited anisohydric stomatal response whereas Grenache exhibited isohydric stomatal response (Schultz, 2003; Soar *et al.*, 2006). In this regard, the isohydric response means that the plant can maintain a stable leaf water status irrespective of soil water status while anisohydric behaviour is less effective in leaf water status control (Bota *et al.*, 2001; Schultz, 2003; Cifre *et al.*, 2005; Iland *et al.*, 2011).

This is an indication that different grapevines can behave differently under the same cultivation conditions. Some cultivars might increase their productivity with a constant stomatal regulation while others reduce productivity because of partial or complete stomatal closure. However, some researchers argued that stomatal response in grapevines can be changed by environmental conditions, thus, the isohydric or anisohydric status can vary according to prevailing weather conditions and the effects it has on the grapevines (Souza *et al.*, 2005; Chaves *et al.*, 2010). Few studies have considered whole plant grapevine WUE, while most studies focused on physiological WUE. From a glasshouse study where different grapevine growth and transpiration efficiencies were measured a range of 2.5 and 3.2 g dry matter/ kg H_2O transpired were reported (Gibberd *et al.*, 2001). Roux *et al.* (2014) reported cultivar differences in terms of FruitLook biomass production and biomass WUE in table grapes. In this particular study, Crimson Seedless had the highest biomass WUE, while Thompson Seedless indicated a higher biomass WUE among the white table grapes cultivars.

2.3.1.5 Leaf morphology

Leaf morphology is the study of the appearance of the leaf of plants. Leaves are the major sites for photosynthesis in most plants. Zephyris (2011) indicated that leaf morphology can be summarised as follows: A leaf consists of three major tissues, namely the epidermis, mesophyll and vascular bundles (Figure 2.2.). The epidermis is the external layer of cells covering the leaf surface and contains the stomates and guard cells. The stomates occur on either surface of the leaves even though they are abundant on the lower epidermis in woody plants. The stomata are comprised of two specialised epidermal cells, the guard cells, which surround the stomatal opening (pore). Stomata are tiny pores connecting the intercellular air spaces of the leaf with its surrounding environment. The mesophyll contains the palisade parenchyma cells and spongy parenchyma cells making up the internal leaf tissue. The palisade parenchyma cells are the principal photosynthetic tissues. While the vascular bundles are responsible for translocation of water into the leaf and photosynthetic products out of the leaf by microscopic cells. The leaf plays a big role in gaseous exchange between the environment and the plants therefore contributing significantly to grapevine WUE.

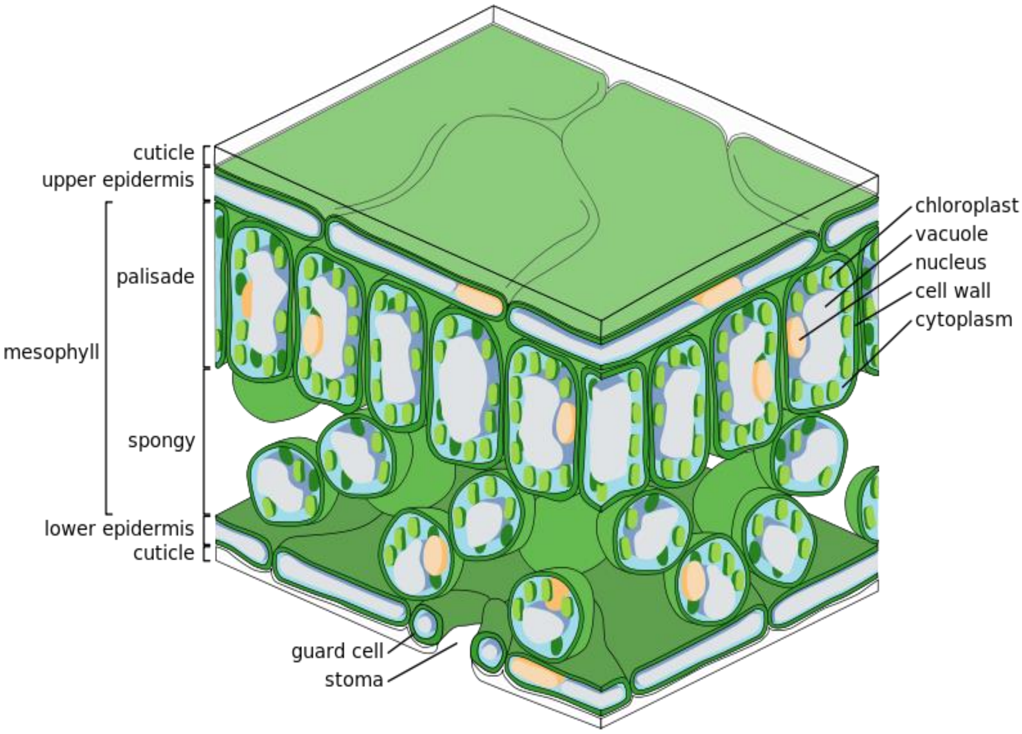

Figure 2.2: Leaf tissue structure (Zephyris, 2011).

Leaf size and thickness has an effect on carbon dioxide and water vapour fluxes in and out of the leaves due to the variation of the leaf boundary layers and enhancement of WUE. Thinner leaves are reported to have a lower WUE compared to thicker leaves (Stanhill, 1986). The lower WUE is reported to be caused by the lower ratio of internal volume in comparison to leaf surface area (Bacon, 2004). During water stress, leaf development is reduced, hence affecting transpiration efficiency (Bacon, 2004). Poni *et al.* (1994) and Cartechini and Palliotti (1995) reported a correlation between specific leaf mass and photosynthesis in grapevine. Leaf attributes such as leaf thickness, density and specific leaf mass can be used to explain the physiological performance of a leaf relating to its structure and environmental conditions (Witkowski & Byron, 1991).

2.3.2 Physiological mechanisms

The main physiological mechanism influencing WUE is reported to be photosynthesis, transpiration and respiration (Tomás, 2012). These physiological processes are affected by different factors such as stomatal conductance, plant, soil water status and root hydraulic conductivity that will be discussed under this section.

2.3.2.1 Photosynthesis and respiration

Photosynthesis is a process by which green tissues use energy from the sun to convert water and CO_2 into carbohydrates. This process is a complex process involving light and dark reactions. Light energy is changed into chemical energy during the light reaction to form adenosine triphosphate (ATP) and nicotinamide adenine dinucleotide phosphate (NADPH) (Iland *et al.*, 2011). In the dark reaction, CO_2 is joined by the carboxylation of ribulose-1,5-bisphosphate by ribulose 1,5-bisphosphate carboxylase-oxygenase (Iland *et al.*, 2011). The end result of these processes that are interlinked is the production of carbohydrates used in plant growth and development. Higher photosynthesis increases yields, quality and fruit size. Respiration is a chemical process whereby plants release energy from glucose in order to sustain itself. Therefore, it can be said that respiration is the inverse of photosynthesis since glucose produced in photosynthesis is used in respiration. Photosynthesis or carbon assimilation is one of the factors used to determine WUE.

2.3.2.2 Transpiration

Transpiration is the process by which water is lost by the plant through the leaf, stomata, stem and flowers. Water taken up by the plant through its roots is drawn through the xylem to the mesophyll cell walls, then it evaporates into the leaf air space before being lost to the atmosphere through the stomatal pores (Iland *et al.*, 2011). This is not a simple process since water vapour diffusion has to overcome stomatal and boundary layer resistances (Iland *et al.*, 2011). Resistance is the opposite of conductance, which is the commonly used term in botany. Transpiration is influenced by many interacting factors such as the environment and vine factors. Partial closure of stomata may increase transpiration efficiency while reducing photosynthesis as plants reduce their water loss compared to the CO_2 uptake (Flexas *et al.*, 2010; Iland *et al.*, 2011). Atmospheric conditions such as vapour pressure deficit, wind and temperature also affect transpiration.

2.3.2.3 Stomata and stomatal conductance

The main function of the stomata is to regulate gaseous exchange, particularly CO_2 and water vapour between the plant and the environment in order to optimise and regulate stomatal conductance of CO_2 and water vapour to balance photosynthesis with available water to the plant (Wang *et al.*, 2007; Casson & Gray, 2008). It is estimated that a typical C3 plant can lose 2000-3000 $\mu mol.m^{-2}.s^{-1}$ water vapour compared to 20-30 $\mu mol.m^{-2}.s^{-1}$ CO_2 (Bacon, 2004; Morison *et al.*, 2008). Hence, a lower stomatal opening reduces transpiration at the expense of photosynthesis with increased WUE (Jones, 2004a). Partial closure of stomata may increase transpiration efficiency while reducing photosynthesis due to the fact that plants reduce their water loss substantially compared to the CO_2 uptake (Flexas *et al.*, 2010; Iland *et al.*, 2011). Different factors such as light, temperature, humidity, CO_2 concentration, plant water status as well as plant hormones affect stomatal opening (Bacon, 2004). Reduction in stomatal conductance increases leaf temperature due to reduced evaporative cooling caused by reduced transpiration rate (Gibberd *et al.*, 2001). Furthermore, stomatal responses are linked to soil moisture content and leaf water status. Thus, higher soil moisture and plant water status increases transpiration. The guard cells open and close the stomatal pore in response to changes in turgor pressure within the guard cells. When there is sufficient water available, the guard cells swell and open the stomatal pores allowing transpiration to take place, while CO_2 is taken up by the plant. In water deficit conditions, the amount of abscisic acid (ABA) in xylem sap can increase significantly creating a high level of ABA concentration in the leaves that stimulates the closing of stomata (Bacon, 2004; Chaves *et al.*, 2004). Stomatal conductance is determined by the size and density of the stomata. Smaller stomata are reported to provide a higher conductance due to a shorter diffusion path length (Franks & Beerling, 2009). In a study by Xu and Zhou (2008) they reported that stomatal density of grass increased while stomata size decreased in order to control water loss. Stomatal conductance is positively correlated to stomatal opening: when stomata open, conductance will increase, allowing more water vapour loss from leaves.

Under water deficit conditions, plants respond by closing their stomata in order to control more water loss (Cifre *et al.*, 2005; Casson & Gray, 2008) making this indicator useful in irrigation scheduling. Stomatal conductance is a good indicator of plant water status and it can be used to determine water deficits early in plants before deficiency occur (Jones, 2004a; Cifre *et al.*, 2005). In a study conducted by Cifre *et al.* (2005) on grapevines, it was concluded that keeping gs between

0.05–0.15 mmol.$m^{-2}.s^{-1}$ could promote maximum WUE, optimal yield and good fruit quality. Some physiological indicator thresholds have been developed from different studies that can be used as guidelines for stomatal conductance (Medrano *et al.*, 2002; Cifre *et al.*, 2005). These tools can be used in improving WUE by determining concise water needs while preventing water constraints. Flexas *et al.* (1999) also reported that reduced stomatal conductance leads to less photosynthetic activity and yield. Furthermore, there have been some contrasting reports on the reduction of photosynthetic activity that might be caused by stomatal limitations and non-stomatal limitations (Flexas *et al.*, 1999; Cifre *et al.*, 2005; Tomás *et al.*, 2012). Stomatal regulation is critical to the WUE of plants. Different factors such as light, temperature, humidity, CO_2 concentration, plant water status as well as plant hormones affects stomatal opening (Bacon, 2004).

2.3.2.4 Plant water status

Lower water content in plant organs slows cell expansion, cell wall synthesis and cell division by reducing cell turgor (Buckley, 2005). Water stressed vines have lower leaf water potential, stomatal conductance, net assimilation rate and sap flow (Iland *et al.*, 2011). Additionally, water stress reduces leaf area, leaf number per shoot, leaf size and leaf thickness (Bacon, 2004). Grapevines respond to water deficit by reducing their plant growth as well as leaf area in order to reduce transpiration while increasing WUE (Iland *et al.*, 2011). Physiological indicators such as leaf and stem water potential (Williams & Matthews, 1990; Choné *et al.*, 2001; Deloire *et al.*, 2004; Girona *et al.*, 2006; Van Leeuwen *et al.*, 2007) and sap flow rate (Eastham & Gray, 1998) can give a reliable indication of the plant water status. These indicators can be used in grapevine water status assessment as well as in irrigation scheduling to improve WUE. Van Leeuwen *et al.* (2009) and (Myburgh, 2011) developed stem water potential thresholds that can be used as guidelines in order to reduce water use. These tools can be used in improving WUE by determining precise water needs whilst preventing excessive water constraints. Since water constraints in grapevines have negative impacts on lower stem water potential, stomatal conductance, sap flow and photosynthetic activity, proper irrigation management is needed. According to Jones (1990), plant physiology is highly affected by plant water status compared to soil water content. Thus, irrigation scheduling must be based on specific crop water need at the different phenological stages. Therefore, tools need to be refined to indicate when and how much to irrigate for optimal production. Tools such as leaf/stem water potential (Girona *et al.*, 2006) or sap flow sensors (Eastham & Gray, 1998) have the potential to aid in irrigation scheduling for improved WUE. Jones (2004b) and Cifre *et al.* (2005) indicated that stomatal conductance and plant leaf water potential can indicate plant water stress early in plant, making this tools also suitable for irrigation scheduling. At yield WUE level, it is important to note how water stress affects HI by reducing photosynthates for sinks and/or inhibition of pollination (Steduto, 1996). These observations are related to the period and magnitude of the stress and varies according to plant phenological stage (Williams & Matthews, 1990a).

2.3.2.5 Root hydraulic conductivity

Water movement throughout the vines is a passive process from a point of higher potential to one of lower potential. Grapevines take up water from the soil *via* their roots and distribute it to the rest of the plant through the xylem vessels. Water is moved up through the xylem vessels by adhesion of water molecules to the hydrophilic surface of leaf mesophyll cell walls (Iland *et al.*, 2011). The cell wall pores generate high tension to lift water from the roots to the leaves where it is lost to the atmosphere. Different factors such as soil water availability, atmospheric conditions and regulation of water by the vine itself affect the movement of water in the vine (Bacon, 2004). Soil available water is influenced by soil depth, texture, structure and root development. A well-developed root system is needed for a grapevine to be water use efficient. For maximum water extraction, deep and extensive roots are needed that can take up water deep in the soil especially with depleting soil moisture content (Bacon, 2004). Optimum root hydraulic conductivity is needed to extract maximum soil water and to optimise soil water extraction (SWE) (Iland *et al.*, 2011)**.** It has been reported that aquaporins can regulate root conductance in grapevines and, in some instances, aid in about 40% of the water flow (Iland *et al.*, 2011). However, it is reported that these mechanisms differ per variety (Lovisolo *et al.*, 2008).

2.3.2.6 Soil water potential

Soil water potential is the potential energy of water per unit volume relative to pure water (Iland *et al.*, 2011). Water potential (Ψ) consists of four components known as osmotic potential (Ψ_π), hydrostatic potential (Ψ_p), matrix potential (Ψ_M) and gravitational potential (Ψ_g) (Hillel, 1980). Of these different components, only the Ψ_π and Ψ_p are important in terms of grapevine water status. Living cells' Ψ_π is influenced by their composition. Therefore, it is reported that living cells have a high concentration of dissolved solutes contributing to Ψ_π of approximately -1.5 MPa (Iland *et al.*, 2011). On the contrary, xylem vessels consist mostly of dead cells and have a less negative Ψ_π compared to living cells. This negative potential is referred to as tension or water potential and it drives the uptake of water from the roots to the entire vine where it is used in different plant processes.

2.3.3 Climatic and environmental factors affecting WUE

2.3.3.1 Climatic factors

Climate is a complex term referring to an interaction of a variety of factors, such as temperature, humidity, soil moisture, wind speed, radiation and evaporation. All these factors have a direct or indirect influence on grapevine growth and productivity. Climate can be described in three different levels, namely the macroclimate, mesoclimate and microclimate (Iland *et al.*, 2011). Macroclimate refers to the differences between regions, mesoclimate is the differences between different vineyards in the same region while microclimate refers to the differences within the same canopy (Iland *et al.*, 2011).

2.3.3.2 Temperature and vapour pressure deficit

Temperature is a very important climatic factor that plays a major role in grapevine growth, berry development and composition (Iland *et al.*, 2011; Southey, 2016). Leaf temperature influences photosynthesis and carbohydrate accumulation as well as distribution to other plant parts. Berry temperature in turn affects enzyme activities, biochemical reactions and berry composition (Jackson *et al.*, 1993; Iland *et al.*, 2011). The optimal temperature for maximum photosynthesis is reported to be between 18^{o}C and 33^{o}C, if all the other factors are favourable (Iland *et al.*, 2011). Grapevine stomatal conductance is sensitive to air vapour pressure deficit (VPD) (kPa), (Poni *et al.*, 2009) which is similar to leaf VPD (VPD_L) that has a direct impact on WUE_{inst} (Schultz & Stoll, 2010). Schultz and Stoll (2010) reported a linear relationship between WUE_{inst} and VPD_L, with WUE_{inst} decreasing with an increase in VPD_L under water deficit conditions. However, WUE_i was higher for stressed plants compared to irrigated plants at different measurement times. Furthermore, the researchers also indicated that an increase in leaf temperature and VPD_L increased transpiration therefore reducing WUE_{inst} in grapevines (Schultz & Stoll, 2010). Hence, increasing leaf temperature reduces stomatal conductance due to reduction of evaporative cooling.

2.3.3.3 Light

Light absorbed by a leaf is used in photochemistry, ATP and NADPH production or re-emitted as fluorescence or dissipated as heat (Strever, 2014). A linear relationship between cumulative biomass and cumulative ET has been reported (Steduto, 1996). This implies two main functions in leaves; namely the photochemical role of intercepted radiation and the common pathway for water and CO_2 in gas exchange (Steduto, 1996). However, Hsiao (1973) reported that intercepted radiation plays a major role in the linear relationship between accumulated biomass and ET. Intercepted radiation depends on leaf area index (LAI) and the training system (Steduto, 1996). All absorbed radiation is used in transpiration; while only photosynthetic active radiation (PAR 400-700 nm) is used in CO_2 assimilation (Steduto, 1996).

2.3.3.4 Environmental impact on water use efficiency

Atmospheric CO_2 concentration is reported to increase at 1.5 ppm and slightly higher per year and this is expected to have an effect on agriculture (Steduto, 1996)**.** Some researchers such as Eamus (1991) and Prior *et al.* (2011) reported that an increase in plant WUE corresponded to an increase in atmospheric CO_2 concentration. This has been alluded to the fact that RuBP-ase might be playing a vital role and also improve nitrogen use efficiency (Hsiao, 1993).

Leaf N content plays a vital role in photosynthesis of which about three quarters of total leaf N is used in the photosynthetic apparatus (Steduto, 1996; Hikosaka, 2004). Furthermore, it was suggested by Field (1983) that the decline in photosynthesis with leaf ageing is due to translocation of N from leaves to sinks. Even though N is vital in photosynthesis, its interaction with other resources such as water and light is needed for optimal production (Mooney & Gulmon, 1979). For example, soil N might not be available to the plant if transpiration is limited and N can’t be transported to the leaves.

Salinity decreases osmotic potential and causes ionic imbalances that affect nutrient uptake (Grattan & Grieve, 1992). According to Lea-cox and Syvertsen (1993), salinity reduces N uptake and transpiration thereby reducing WUE. Increasing salinity and drought reduce WUE in salt sensitive crops while an increase is noted in salt tolerant crops.

2.3.4 Agronomic production practices affecting WUE

2.3.4.1 Cultivars

Cultivars are already discussed in Section 2.3.1.4. However, it is important to emphasize that cultivar choice is very important in table grape production. Table grape cultivation is a long-term investment therefore it is critical that the right cultivar should be selected for the specific production purpose and area in order to obtain optimum production and profitability.

2.3.4.2 Canopy management

Canopy management is a very important aspect in table grape production for increased production with an improved WUE. The main objective of canopy management is to maximise canopy light interception, optimise light distribution within the canopy, allow for proper fruit spacing and improvement of canopy microclimate of the canopy (Peacock *et al.*, 1994; Medrano *et al.*, 2015a). Canopy management is another strategy mostly used to regulate the vineyard microclimate (Medrano *et al.*, 2015a). The vineyard microclimate is regulated by the light intercepted through the canopy enhanced by the training system, shoot position and leaf area exposed to the light (Williams & Ayars, 2005; Medrano *et al.*, 2015a). Trellising systems play an important role in crop production and WUE since it determines light interception in the canopy (Buesa *et al.*, 2017). Leaf water use efficiency is mostly affected by light interception, with shaded leaves displaying lower WUE_i (Medrano *et al.*, 2012). It was also reported that leaf photosynthesis as well as WUE are affected by light interception and that there is variability with regard to light interception within the same canopy (Medrano *et al.*, 2012; Medrano *et al.*, 2015a). Canopy management also has an effect on crop growth, productivity as well as fruit quality (Williams & Ayars, 2005; Strydom, 2006; Medrano *et al.*, 2015a)**.** Furthermore, a vigorous vine trained to a restrictive trellis system tend to have a dense canopy restricting optimal light interception that can negatively impact on production and fruit quality (Peacock *et al.*, 1994).

2.3.4.3 Surface and soil management

Water use efficiency in vineyards can be realized with optimal crop management practices. The aim of these practices should be to increase the economic harvested yield per unit of water transpired, increase transpiration while reducing evaporation and maximise the use of rainfall water (blue water use) (Medrano, *et al.*, 2015a). It is therefore important to improve soil structure and organic matter to help retain more water for root uptake. Mulching in the form of straw, crop residue or compost can be used to prevent soil erosion as well as limit evaporation (Gregory, 2004). Besides the prevention of evaporation, mulches have also been reported to have other advantages in vineyards such as nutrient release, weed control and improvement of soil structure (Pou *et al.*, 2011). Cover crops are also recommended to control vigorous vegetative growth by the competition imposed on water and nutrient availability as well as prevention of soil erosion, runoff and reduced evaporation (Monteiro & Lopes, 2007; Pou *et al.*, 2011). However, there are inconsistencies in the benefits of cover crops, therefore careful cultivar selection must be made to avoid competition that might have a negative effect on grapevines while improving soil structure (Pou *et al.*, 2011; Medrano *et al.*, 2015a; Tomás, *et al.*, 2015). Dry and Loveys (1998) stated that cover crops grown in vineyards compete with grapevines during the vegetative stage, hence reducing leaf area that can be beneficial by reducing transpiration.

Table grapes can be grown in a wide variety of soil types. However, grapevines perform well under sandy loamy soils with average fertility (Strik, 2011). The soil must be well-drained with an adequate depth for optimal root growth. Waterlogged soils can have a negative impact on the grapevine growth and productivity (Myburgh & Howell, 2015). Soil types have different soil structure composition of which the main classes consist of sandy, clay and silt. Sandy soil has large soil particles which make it easy for water to leach out of the soil. It has a low water holding capacity and irrigation must be frequent. Clay soil types are also known as heavier soil because of small soil particles. Clay soil has a high water holding capacity and water scheduling must be properly done to avoid water-logged conditions that can negatively affect plant growth.

2.3.4.4 Irrigation systems and scheduling methods

Irrigation decisions are based on three important factors, namely soil water holding capacity, infiltration into the soil and crop water use. Table grapes are mostly grown under micro-sprinkler and drip irrigation systems in South Africa. The advantage with drip irrigation is that less water is applied directly to the root zone where it is needed and evaporation is limited in the process (Myburgh & Howell, 2012). Thus, drip irrigation systems use less water and are more efficient compared to micro-sprinklers (Ley, 1994; Saayman & Lambrechts, 1995). However, drip irrigation grapevines are prone to water constraints because of the smaller wetted area (Van Zyl & Van Huyssteen, 1988; Myburgh, 1996). Nonetheless, it was reported that if optimal irrigation scheduling is done and soil water content is monitored effectively and managed well, there should be no differences in growth, yield and quality between the two systems. Drip irrigation systems have a higher efficiency compared to micro-sprinklers since its water application targets the root zone and is effectively taken up with minimum loss to evaporation (Pereira *et al.*, 1996). For this reason, drip irrigation systems could be ideal in semi-arid to arid regions. An efficient irrigation system and proper scheduling is needed in table grape production in order to improve WUE. Grapevines in fertile soils produce equally high yield under any irrigation system if scheduling is properly managed (Van Zyl, 1984)**.**

The aim of irrigation scheduling is to provide the grapevine with enough water for growth and development and to minimise losses while increasing transpiration that has a direct link to photosynthesis (Green *et al.*, 2008; Annandale *et al.*, 2011). Optimum irrigation scheduling minimises water use without affecting production and quality (Green *et al.*, 2008). In order to schedule irrigation properly, the soil, climate and crop should be taken in account. Producers use different methods of irrigation scheduling, like soil water measurements, atmospheric based quantification of evapotranspiration (ET), subjective scheduling, integrated soil water balance methods and in fewer cases, plant based monitoring (Jones, 2004b; Stevens, 2006). However, in most cases water measurements or soil water balance calculations are used (Jones, 2004b). Using soil measurements only does not give an accurate indication of plant water status (Taylor & Gush, 2009), thus it is recommended that plant based measurement should be included in irrigation scheduling (Jones, 1990). Stevens, (2006), indicated that 18% of producers in South Africa are using “objective irrigation scheduling methods”. This relatively low figure is a reason for concern on WUE in the agricultural sector, given the pressure on scarce water resources.

In order to reduce water use and improve WUE, deficit irrigation strategies are gaining momentum (Costa *et al.*, 2007; Flexas *et al.*, 2010; Medrano *et al.*, 2015a). Most WUE studies focused on deficit irrigation, that have proven to be an efficient strategy by improving WUE and fruit quality, while controlling vine and fruit tree vigour (Myburgh, 2003; Girona *et al.*, 2006; Chaves *et al.*, 2007; Costa *et al.*, 2007 and Chaves *et al.*, 2010). Deficit irrigation scheduling is a method aimed at saving irrigation water, especially in semi-arid countries were water scarcity is a major concern. Grapevine water requirements differ during the different phenological stages; therefore, it is necessary to reduce water at less critical stages to control vine vigour in order to balance vegetative and reproductive development. There are three irrigation scheduling methods, namely sustained deficit irrigation (SDI), regulated deficit irrigation (RDI) and partial root zone drying (PRD) (Iland *et al.*, 2011). Sustained deficit irrigation is a scheduling strategy whereby water supply to vines is limited for the whole growing season. This limitation can be based on a percentage of calculated irrigation or ET. Regulated deficit irrigation restricts water supply to the vine for a specified period during the growing season. However, careful and regular soil and plant monitoring and visual assessment of vine water stress characteristics are required for successful implementation of SDI and RDI programmes. Partial root zone drying is a drip irrigation strategy that relies on the alternate wetting and drying of different sides of the vine root zone during the irrigation season (Flexas *et al.*, 2010; Iland *et al.*, 2011). Grapevines that are irrigated by means of the PRD strategy produce ABA in the drying half. The ABA travels in the xylem from the roots to the leaves thus causing the stomata to partially close (Bacon, 2004;Chaves *et al.*, 2007). This mechanism reduces transpiration water loss and vegetative plant growth, hence increasing WUE (Bacon, 2004; Du *et al.*, 2008; Flexas *et al.*, 2010). However, if not well managed the deficit irrigation strategies can negatively affect yield and fruit quality (Jones, 2004a). Bacon (2004) and Chaves *et al.* (2007) reported that PRD reduced leaf area hence reducing transpiration. However, there has been an inconsistency in literature about the leaf area reduction in PRD indicating that this irrigation strategy is affected by the soil and environmental conditions (Medrano *et al.*, 2015a). Dry and Loveys (1998) and Williams and Matthews (1990) also suggested inducing water stress for improved grape quality with careful consideration given to the stages and with which methods since not all methods give desirable results. Dry and Loveys (1998) indicated that imposing mild stress to the entire vineyard uniformly might be a problem, thus suggested that PRD might be a saver option. For optimal irrigation scheduling tools and methods need to be in place that will aid in the process.

2.4 Tools and methods used to measure plant and soil responses that have an effect on plant/crop water use efficiency

2.4.1 Leaf gas exchange measurements

Leaf water use efficiency is measured in the short term as instantaneous gas exchange (Bacon, 2004; Jones, 2004a; Morison *et al.*, 2008; Tomás *et al.*, 2012; Medrano *et al.,* 2015b) or long term as carbon isotope ratio to leaf dry matter (Farquhar & Richards, 1984). Instantaneous leaf measurements are measured by gas exchange systems, while the leaf is still attached as a non-destructive measurement. Field *et al.* (1989) reviewed protocols to assess photosynthesis. They indicated that photosynthesis is indirectly computed from measurements of several parameters such as CO_2 concentration and gas flow. Consequently, photosynthesis cannot be assessed by one specific instrument but rather by a system instead. These are either CO_2 or O_2 exchange systems. The CO_2 exchange systems utilizing infrared gas analysers (IRGA) are more appropriate for field measurements. Leaf dry matter carbon isotopes ratio (δ13C) are also used as a long term indicator for intrinsic WUE measurements (Farquhara & Richards, 1984).

Stomatal conductance (gs) is the measure of the quantity of CO_2 moving into the leaf through the stomata as well as the water vapour escaping through the stomata to the atmosphere and it is measured in mmol m^{-2} s^{-1} (Iland *et al.*, 2011). Stomatal conductance can be measured using a porometer or an IRGA (Iland *et al.*, 2011). Both measurements are taken while the leaf is still attached to the grapevine. Before measurements, the porometer is first calibrated and the calibration value is saved on the equipment. Thereafter, a small area of the leaf is inserted into the porometer chamber while still attached to the grapevine. The water evaporating from the leaf is trapped in the porometer chamber and on minute temperature differences close and very close to the leaf surface are measured.

2.4.2 Plant water potential measurements

Plant water potential measurements are used to determine the vine water status as well as to determine plant stress. Plant water potential in leaves and stems can be measured with a pressure chamber (Scholander *et al.*, 1965) or a psychrometer on leaves. Plant water potential can be determined by means of both leaf (uncovered leaves) and stem (covered leaves) measurements. Stem water potential is considered to be a more reliable indicator of plant water status (Choné *et al.*, 2001) since it is measured on non-transpiring leaf with less influence by environmental factors. Therefore, stem water potential can represent the whole vine water potential. Leaf water potential can be measured early in the morning at predawn or noon as a midday measurement. However, there has been contradiction in literature as to which leaf water potential is a better indicator of plant water status. Midday leaf water potential is used to determine plant water status even though it is believed that predawn leaf water potential is a better indicator of the beginning of water stress in plants (Annandale *et al.*, 2011). Under hot and dry conditions such as summers in South Africa, predawn leaf water potential becomes unreliable (Annandale *et al.*, 2011). Similarly, Williams and Trout (2005) reported that in warmer vine growing countries, midday water potential measurements perform better than predawn water potential. In contrast, Choné *et al.* (2001) indicated that predawn leaf water potential and stem water potential were better indicators of plant water stress compared to midday leaf water potential. This contradiction might be influenced by the phenomenon of ‘isohydric’ and ‘anisohydric’ responses. According to Rogiers *et al.* (2012), the near-isohydric and anisohydric differences in grapevine cultivars is related to hydraulic architectural variances. This might be due to the fact that leaf and soil water potential equilibrates before dawn. Plant water potential thresholds have been developed by Deloire *et al.* (2004), Van Leeuwen *et al.* (2009) and Myburgh (2011). Consequently, these tools can give a reliable indication of the plant water status to be used in irrigation scheduling in order to conserve water and improve WUE (Choné *et al.*, 2001; Girona *et al.*, 2006; Van Leeuwen *et al.*, 2007).

2.4.3 Methods of measuring evapotranspiration

Plant and crop WUE can be measured over a longer period, for example a week, month or the growing season. For this determination, biomass or yield and water use needs to be accurately determined. Evapotranspiration can be measured using a combination of instruments measuring evaporation and transpiration. Total evaporation can be estimated using micrometeorological methods such as Eddy Covariance (Thom, 1972) and the surface renewal techniques. Eddy covariance is recommended as a reliable technique to determine carbon and water fluxes especially under steady atmospheric conditions, with a consistent vegetation on a flat landscape (Baldocchi, 2003; Burba & Anderson, 2010). Evaporation can also be measured using cylindrical micro-lysimeters (Poblete-Echeverría *et al.*, 2012). Gravimetric methods or lysimeters are used to determine transpiration in potted plants making it possible for accurate estimations of biomass production (Tomás, 2012). For field grown grapevines, weighing lysimeters (Williams *et al.*, 2003; Green *et al.*, 2008; Tomás, 2012) or sap flow meters are used to determine transpiration (Eastham & Gray, 1998; Ginestar *et al.*, 1998; Escalona *et al.*, 2002; Myburgh, 2016). The heat pulse velocity technique is widely adopted and used in woody plants for sap flow measurements to determine transpiration (Dye & Olbrich, 1993; Dye *et al.*, 1996; Yunusa *et al.*, 1997; Burgess *et al.*, 2001; Gush *et al.*, 2008). Crop evapotranspiration (ET_c) can also be estimated based on reference crop evapotranspiration (ET_o) and a crop coefficient (K_c): $ET_c = K_c \times ET_o$ (Allen *et al.*, 1998; Williams & Matthews, 1990; Myburgh, 2016), water balance equations (Teixeira *et al.*, 2008) and remote sensing models (Bastiaanssen *et al.*, 1998; Vanino *et al.*, 2015). Allen *et al.* (2011) reviewed the advantages and disadvantages of the different methods used to calculate evapotranspiration (water balance, lysimeters, Bowen ratio, eddy covariance, scintillometry, sap flow & remote sensing). They concluded that all the measurement techniques need to be used with special care since an incorrect application can lead to errors. In addition, it was emphasized that having relevant knowledge of how a specific technique or concepts works is important and systems need to be calibrated and maintained properly. Lastly, researchers should clearly state the methodology used during measurements.

For sustainable table grape production, there is a need for proper irrigation scheduling to conserve scarce water resources and improve WUE in semi-arid countries. Consequently, there is a need to determine the quantity of water required to produce table grapes thus stressing the importance of water footprints. The following section will deal with WF concepts and methodologies needed for the calculations.

2.5 Water footprints of table grapes

2.5.1 Introduction

Water is a very important natural resource that plays a significant role in plant growth, metabolism and reproduction. There are few published results on seasonal total water use and water footprinting of table grape vineyards in South Africa. Results from studies regarding annual irrigation requirements/applications of table and raisin grape vineyards under South African conditions are inconsistent, since water use depends on different factors such as production regions, irrigation practices, canopy characteristics and grapevine vigour (Myburgh & Howell, 2007). Accurate estimation of seasonal crop water use is becoming a serious issue especially with climate change impacts on scarce water resources (Romaguera *et al.*, 2010). Climate change and human activities has had a serious impact on the global water cycle. This is posing a threat to human well-being and also negatively impacting the ecosystem (Pfister *et al.*, 2009). In view of this predicament, the 'Water Footprint' (WF) concept was introduced by Hoekstra (2003). More research and modification followed that lead to methodology development to assess WF (Hoekstra & Hung, 2003; Romaguera *et al.*, 2010; Hoekstra *et al.*, 2011; Mekonnen & Hoekstra, 2010). Taking above-mentioned into consideration, different approaches have been developed that can measure the impact that the extraction of freshwater has on a certain catchment, area or community and the damage it causes to the environment. Water footprint is a concept developed to account for water use along the production value supply chain and has a potential to indicate the impact a certain use has on the environment (Hoekstra *et al.*, 2011; Mekonnen & Hoekstra, 2010). Water footprint assessment is an analytical tool, which can assist in understanding the impacts different activities have on the water resource and the type of adjustments that can be done to avoid unsustainable freshwater use. Consequently, this tool provides awareness and indications but does not dictate what has to be done (Hoekstra *et al.*, 2011). Water footprint analysis can be a vital tool in improving WUE in agriculture since it estimates the total water needs with regards to irrigation scheduling, water conservation strategies as well as in policy formulation. With the gaining of momentum of WF assessment, critics also increased in the definitions of water footprint as well as the methodologies and interpretations used by the water footprint network (WFN). Thus, other approaches based on life cycle assessment were developed (Canals *et al.*, 2009; Pfister *et al.*, 2009). This is a clear indication that there are two schools of thought on the concept of WF as will be discussed in the different frameworks below.

2.5.2 Water footprint theoretical framework

2.5.2.1 Global standard of water footprint

The WF approach was developed in 2002 in the Netherlands (Hoekstra & Hung, 2003). Water footprint is defined as the total water needed to produce goods/products or needed for a specific service (Hoekstra *et al.*, 2011). The water use footprint shows water use at different stages along the supply change and can be used to raise awareness and aid in policy formulation that can lead to improved WUE. The global standard water footprint concept provides a suitable framework to determine the total freshwater used along a supply chain in a process step and product production. Water footprint indicates how freshwater resources are utilised and can measure direct and indirect water use (Hoekstra et al., 2011). It therefore also considers the sustainability of freshwater use. Water footprint results are reported in volumetric values, indicating freshwater use and pollution in a specific area. Methodologies on WF assessments have been improved since the first publication and more researchers made a contributions towards the WF research (Chapagain & Tickner, 2012). Reliable and updated databases of climate and hydrological information is used to account for local conditions (Chapagain et al., 2006) and updated data of flows of agricultural and other trades (Chapagain & Hoekstra, 2004; Mekonnen & Hoekstra, 2010). The WF concept is also refined to include terms such as 'net green WF' that differentiate between green WF of a crop and the natural land cover (Chapagain & Tickner, 2012). For consistency and transparent assessment the WFN developed the WF Assessment Manual (Hoekstra et al. (2011). The WF is categorised in three groups, namely the green, blue and grey water (Clothier *et al*., 2010; Mekonnen & Hoekstra, 2010). Green water refers to rainwater, blue water is the surface and ground water available for use, while the grey water is freshwater needed for chemical and fertiliser dilution (Mekonnen & Hoekstra, 2010).

2.5.2.2 Life cycle assessment

Life-cycle assessment (LCA) is a tool or technique used to analyse environmental impacts related to a product along the supply chain from the raw material to final production (Jefferies *et al.*, 2012). Different methods and models exist in life-cycle impact assessment (LCIA) that can assess global water resources and its availability (Kounina *et al.*, 2013), as well as water stress indicators (Vorosmarty, 2000; Alcamo *et al.*, 2003) making it possible to measure water shortages in water stressed environments. Thus, the LCIA can measure the quantity of water use but does not determine the water use type, source and geographical area of the water used (Pfister *et al.*, 2009) that can have an impact on sustainability assessment. Due to these limitations and also not being able to analyse the environmental impacts on freshwater use, the methodological development of environmental impact on freshwater consumption was motivated by Canals *et al.* (2009) and Pfister *et al.* (2009). In the LCA, terms such as "consumptive and degradative use" are used that can lead to confusion and therefore needs to be distinguished. Pfister *et al.*, (2009) defined consumptive water use as freshwater withdrawals in the form of evaporation, incorporated in products, moved to another area or even redeposited in the sea after usage. Degradative water use refers to change of quality that returns to the same unit. The LCA can assess the impact that degradative water use has on the aquatic environment, for example the toxicity levels, but cannot assess it in relation to freshwater resource loss (Pfister *et al.*, 2009).

2.5.3 Methodologies for measuring water footprints

2.5.3.1 Global standard for water footprint assessment

The global standard for WF assessment was developed by Hoekstra *et al.* (2011), and it is more aligned with the concepts of water-resources management (WRM) (Hoekstra *et al.*, 2009) and endorsed by the water footprint network (WFN). The main goal for WF assessment is to analyse how human activities or product production affects freshwater consumption and pollution and how it can be sustainably used. There are different levels of WF assessment to determine the impact human activities such as the process step, product, consumer, geographical area and business have on freshwater resources (Hoekstra *et al.*, 2011). Water footprint assessment consists of four stages for transparency and clarity to all interested parties (Hoekstra *et al.*, 2011). These stages are as illustrated in Figure 2.3.

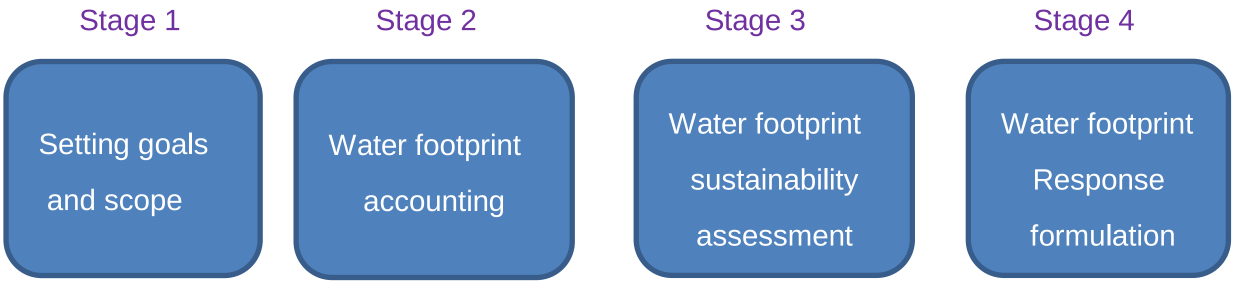

Figure 2.3: The four different stages of water footprint assessment according to Hoekstra *et al.* (2011).

Stage 1: Setting goals and scope

This stage is very important, since assessment can be done for various activities such as the process step, product, consumer/community, geographical area, national and business (Hoekstra *et al.*, 2011). The type of WF assessment to be conducted dictates the methodology to be followed, hence the need to clearly have the goal and scope set before conducting the relevant study. The following questions should be asked at this stage: 1) which WF should be included (blue, green & grey), 2) where along the supply chain should the analysis stop, 3) for what period should the analysis be conducted and finally 4) whether indirect water use should also be included or not?

Stage 2: Water footprint accounting

This is the stage where data is collected and calculated for the different WF analyses, depending on the level and scope already set in Stage 1. For this purpose of this review, the focus will only be on the WF of a process step and product WF assessment processes. Water footprint of a process step includes the blue, green and grey water footprints. The blue WF indicates the quantity of surface or groundwater evaporated, embedded into a product or settled in other areas than before (Hoekstra *et al.*, 2011). From all these forms, evaporation is normally the highest and consumptive use is often associated with evaporation. However, the other components must also be considered if applicable. The blue water is also known as an indicator of “consumptive blue water use”. Consumptive water use refers to water that is not available for other uses anymore in the specific area but can be available in a different area, e.*g.* evaporated and transpired water (Perry, 2007). Hoekstra *et al.* (2011) also recommended for a distinction to be made between the different types of blue water (surface water, flowing groundwater & fossil groundwater). A product’s WF is normally expressed as volume of water per unit of time. When a process WF is related to product quantity, it can be expressed as volume per quantity of product.

The following formula is used to calculate blue WF:

$$WF_{proc,\ blue} = \text{Blue water evaporation} + \text{blue water incorporation} + \text{lost return flow [volume/time]} \qquad \text{(Eq. 2.4)}$$

The green WF refers to evaporated rainwater, transpired or embedded in a product. This is the form of rainfall water that does not run off but rather settles on the soil surface or infiltrates into the soil and is taken up by plants for growth and carbohydrate formation. The following formula is used to calculate green water footprint:

$$WF_{proc,\ green} = \text{Green water evaporation} + \text{green water incorporation [volume/time]} \qquad \text{(Eq. 2.5)}$$

The authors indicated that it is important that distinctions be made between blue and green WF since the sustainability impact and production cost of the different WF differs (Falkenmark & Rockström, 2004; Hoekstra *et al.*, 2011). There are different methods to account for green water consumption in agriculture, such as using models that can estimate ET using climate data, soil and crop characteristics. The grey WF indicates the quantity of freshwater needed to integrate the load of pollutants to acceptable levels that won't be harmful to the environment (Hoekstra *et al.*, 2011; Mekonnen & Hoekstra, 2010). Thus, it is calculated by quantifying the volume of water needed to integrate the nutrients that reach ground water (Mekonnen & Hoekstra, 2010). For example, the N fraction that leached is multiplied by the applied amount then divided by the difference between the maximum acceptable concentration of N and the natural concentration of N in the water solution. The Health Organization and the European Union maximum recommended value for surface and groundwater nitrate is 50 mg nitrate (NO_3^-) per litre, while the maximum value for US-EPA is 10 mg per litre measured as nitrate-N (NO_3-N) (Chapagain *et al.*, 2006).

The following equation is used for grey WF assessment:

$$WF_{proc,\ grey} = \frac{L}{Cmax - Cnat} \ [\text{volume/time}] \qquad \text{(Eq.2.6)}$$

where L represents the pollutant load, Cmax the maximum acceptable concentration and Cnat the natural concentration in the receiving water body.

After the analysis of the different process steps, the blue, green and grey WF are added to determine the total WF. Thus, the following formula is used to determine the total WF of the process in crop production:

$$WF_{proc} = WF_{proc\ blue} + WF_{proc\ green} + WF_{proc\ grey} \ [\text{volume/mass}] \qquad \text{(Eq. 2.7)}$$

where $WF_{proc\ blue}$ stands for blue water footprint assessment, $WF_{proc\ green}$ is green water footprint assessment and $WF_{proc\ grey}$ is grey water footprint assessment

Distinctions can be made in the WF process assessment of crop production between the blue and green component by diving the green or blue component of crop water use (CWU) by the crop yield (Y). Hence the following formulas are used:

Green component: $WF_{proc,green} = \frac{CWUgreen}{Y}$ m^3/ton (Eq. 2.8)

where CWU green represent green crop water use and Y is yield

Blue component: $WF_{proc,blue} = \frac{CWUblue}{Y}$ m^3/ton (Eq. 2.9)

where CWU blue represent blue crop water use and Y is yield

The green and blue components in CWU, expressed in m^3/ha, are determined by adding the daily evapotranspiration (ET, mm/day) over the complete growing period (Hoekstra *et al.*, 2011).

The grey component in the WF of crop production (WF_{proc}, grey, m^3/ton) is determined by using the following formula:

$$WF_{proc,\ grey} = \frac{(\alpha * AR)/\ (Cmax - Cnat)}{Y} \ [\text{volume/mass}] \qquad \text{(Eq. 2.10)}$$

where α refers to leaching run off fraction, AR = application rate of the chemical per hectare, Cmax = maximum acceptable concentration, Cnat = pollutant natural concentration and Y = yield. In agriculture the pollutant of interest can be fertilizers, pesticides and insecticides and normally the leaching pollutant that can contaminate the freshwater is considered.

Water footprint of a product

The WF of a product is the total volume of freshwater used to produce a product. Similar accounting procedures are used for the different types of products from different sectors. The product WF includes the green, blue and grey WF as well as water used directly or indirectly in the production process (Hoekstra *et al.*, 2011). The WF of a product is alternatively referred to as 'virtual-water content' (Hoekstra & Hung, 2003). Hoekstra *et al.* (2011) indicated that product WF is a "multidimensional indicator", while 'virtual-water content' or 'embedded water' refers to a volume alone. The WF of a product is expressed in terms of water volume per unit of product. There are two approaches for product WF calculations, namely the chain-summation approach or the stepwise accumulative approach (Hoekstra *et al.*, 2011).

The chain-summation approach

The chain summation is a simpler approach normally used in cases where a production system produces single product. This calculation can be done by simply adding all the process WF divided by the production quantity of product. Thus, the following equation is used:

$$\mathrm{WF}_{\mathrm{proc}}[\mathrm{P}] = \frac{\sum_{s-1}^{k} WFproc[s]}{P\ [p]}\ \text{[volume/mass]} \qquad \text{(Eq. 2.11)}$$

where the $\mathrm{WF}_{\mathrm{proc}}$ [s] is the process WF (volume/time), and P[p] is the production quantity of product p (mass/time).

Unfortunately, such simplified production systems hardly exist in practice, and broader approaches such as the stepwise accumulative approach is needed for product WF calculations.

The stepwise accumulative approach

The stepwise accumulative approach is a broader approach used in production systems with complex inputs and outputs. Thus, the following formula is used:

$$\mathrm{WF}_{\mathrm{prod}}\ [\mathrm{p}] = \left(WFproc[p] + \sum_{i=1}^{y} \frac{WFprod[i]}{fp[p,i]}\right) xfv[p]\ \text{[volume/mass]} \qquad \text{(Eq. 2.12)}$$

were WFprod[p] is the output product water footprint, WFprod[i] is the input product WF and WFproc [p] is the process WF of the processing step, the fp [p,i] parameter is a 'product fraction' and fv [p] is a 'value fraction'. The value function of the output product, fv [p] is the monetary value as a ratio of the market value in relation to the aggregated market value of all the outputs products determined from input products

Stage 3: Water footprint sustainability assessment

The sustainability assessment phase is the phase where WF is evaluated from an environmental, social and economic perspective. Stage 1 and 2 guides to which type of sustainability assessments need to be conducted at this stage. If the goal and scope was to determine the process step or product WF, then sustainability assessment must be in line with your goal. Consequently, in the case of a process step or product WF, the focus will be on how the specific process step or product affects the environment, contribution to the social and economic activities of the production area. Hence, the following questions must be asked: (i) how does the specific process step or product WF contribution to the overall WF of humanity? (ii) how sustainable is the WF of the product? and (iii) what type of impact does this process step or product WF has on a specific geographic area? The sustainability of the WF of a process and product depends on the production area hence, cumulative effects of the different activities in the geographical area contributes to the water scarcity and pollution. Most of the irrigation water for agricultural production comes either from catchment areas or rivers in the production area or closer to the production, hence the need to consider the sustainability assessment of a catchment or river basin. Hoekstra *et al.* (2011) indicated four steps involved in sustainability assessment of a catchment or river basin as indicated in Figure 2.4.

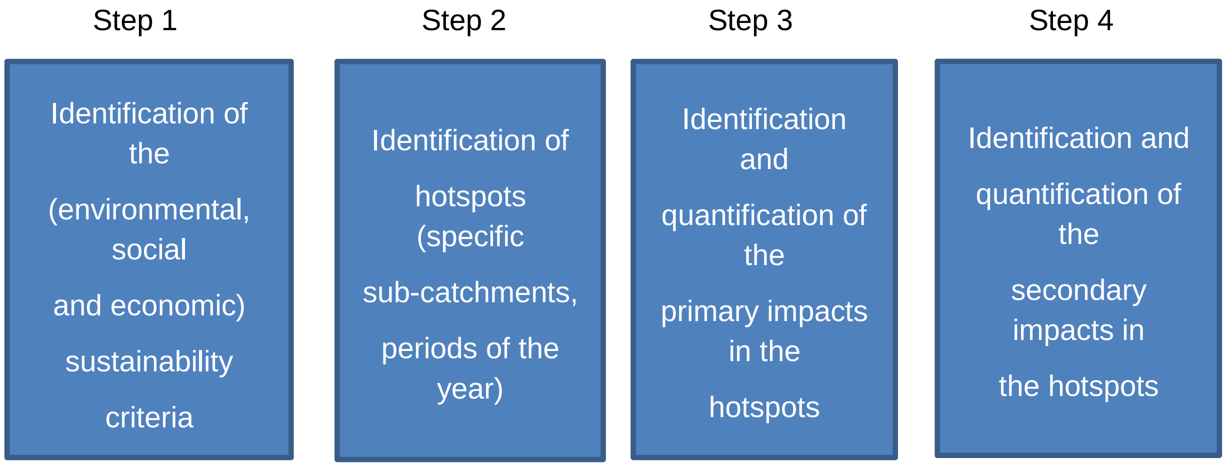

Figure 2.4: Four steps involved in the catchment or river basin sustainability assessment (Hoekstra *et al.*, 2011).

For the WF of a catchment to be sustainable, it needs to meet some criteria that satisfies the environmental, social and economic aspects. These criteria can only be satisfied if the water quality, rivers and ground water flows are within the certain limits where the natural ecosystem as well as the livelihood of people depending on it are not affected. Furthermore, the water needs to be used in an efficient way.

Stage 4: Water footprint response formulation

This is the final step where decisions are taken after calculating the WF and evaluating the sustainability of the different WF types. In this stage, response options are decided upon and strategies or policies are formulated. For example, in a catchment area, decisions on what can be done, by whom and how are formulated that can lead to reduced WF and increased sustainability.

2.5.3.2 Freshwater consumption impact assessment methods based on the Life cycle analysis

Two different approaches based on the LCA will be discussed in this section based on methodologies proposed by Pfister *et al.* (2009) and Canals *et al.* (2009).

Method 1: Pfister *et al.* (2009) developed environmental impact assessment methodologies for freshwater consumption that takes in to account human health, ecosystem quality and resource management. These methods are aligned with the current LCIA methods. The main focus of this methodology is the consumptive water use (WU consumptive) assessment, since it is considered a very important aspect of the hydrological perspective (Falkenmark & Rockström, 2004). For agriculture consideration, the “virtual water” database is used that can give a broader scope and information of a variety of crops from different countries (Chapagain & Hoekstra, 2004). Virtual water consists of “blue” and “green” water flows (Falkenmark & Rockström, 2004). The definitions of blue and green water flow are similar to the green and blue water use discussed above (Hoekstra *et al.*, 2011). However, in the methodology developed by Pfister *et al.* (2009), only the blue virtual water consumption is measured since its believed that green virtual water in its current form does not contribute to environmental flows. This methodology also uses the water stress index (WSI) determined with the WaterGAP2 global model (Alcamo *et al.*, 2003) to quantify the severity of the withdrawal impact. Water stress is defined as the ratio of freshwater withdrawal related to availability (Alcamo *et al.*, 2000; Vorosmarty *et al.*, 2000). The WaterGAP2 global model evaluates the hydrological and socio-economic aspects of the annual freshwater availability and withdrawals from the same unit (Pfister *et al.*, 2009). The hydrological part of the WaterGAP2 model is based on annual average data for the 1961-1990 period (Alcamo *et al.*, 2003). Thus, a variation factor is introduced that can effectively calculate the stress level to be incorporated into a modified WTA calculation to make a distinction between a strong regulated flows of catchments (SRF) (Pfister *et al.*, 2009). Thus, the following equations are used for strong regulated flow and non-strong regulated flow in a catchment:

$$\text{WTA} = \sqrt{VF} \times \frac{WU}{WA} \quad \text{for strong regulated flows (SRF)} \qquad \text{(Eq. 2.13)}$$

where $\sqrt{VF}$ is the square root of the variation factor, WU is withdrawn water and WA is available water in the catchment.

$$\text{WTA} = VF \times \frac{WU}{WA} \quad \text{for non-strong regulated flows (SRF)} \qquad \text{(Eq. 2.14)}$$

where VF is the variation factor, WU is withdrawn water and WA is available water in the catchment.

Pfister *et al.* (2009) defined VF as the combined measure of dispersion of the multiplicative standard deviation of monthly and annual precipitation, based on the long-term climatic data (1961-1990), the following equation is used:

$$\text{VF} = \text{e}\sqrt{In(S\ month)^2 + In(S\ year)^2} \qquad \text{(Eq. 2.15)}$$

where S month is the monthly precipitation and S year the annual precipitation.

The WSI is adjusted to a logistic function to achieve continuous values between 0.01 and 1, where a value of 1 indicates severe water stress. The following equation is used to determine the WSI:

$$\text{WSI} = \frac{1}{1+e^{-6.4*WAT\left(\frac{1}{0.01}-1\right)}} \qquad \text{(Eq. 2.16)}$$

where WSI is the water stress index and 0.01 represent the lowest value of WSI.

Method 2: According to Canals *et al.* (2009), LCA and virtual water analysis can indicate water used to produce a product but lack proper assessment methods to determine the water scarcity and water fitness for consumption. Therefore, methods are needed that distinguish and quantify blue and green water use, taking in account the environmental impact the extraction of freshwater has on a specific area or catchment. Thus, suitable indicators for the key pathways of freshwater ecosystem impact (FEI) and the freshwater depletion (FD) are proposed (Canals *et al.*, 2009). It is proposed that current freshwater use must be related to available water for the FEI. For FD, it is proposed that criteria used for abiotic depletion potentials be explored. Method 2 uses the environmental water stress indicators proposed by Smakhtin *et al.*, (2004), based on the river basin environmental water requirements (EWR) estimations. In their estimations, they consider EWR with available water resources (WR) and its use (WU) to determine the water stress indicator (WSI). The WSI values are then multiplied by the calculated blue water minus the green water. The following formula is proposed:

$$\text{WSI} = \text{WU}/(\text{WR}-\text{EWR}) \qquad \text{(Eq. 2.17)}$$

where WU is water use, WR is available water resources and EWR represent environmental water requirements.

Canals *et al.* (2009) acknowledged that this approach might be an accurate measurement for water resources available, but indicated that it is a new approach and lack of data might affect its acceptability to be used in LCA. The FD is calculated using an abiotic depletion potential (ADP) formula as follows (Canals *et al.*, 2009):

$$\text{ADPi} = \frac{ERi - RRi}{(Ri^2)}\ x\ \frac{Rsb^2}{DRsb} \qquad \text{(Eq. 2.18)}$$

where ADPi is the abiotic depletion potential; ERi is the extraction rate i; RRi is the regeneration rate i; Ri is the ultimate reserve i; DRSb is the accumulation rate of the reference for ADP (Sb, Antimony) and RSb is the ultimate reserve of the reference resource for ADP (Sb, Antimony).

It should be noted that Method 2 is an upgrade of Method 1.

2.5.3.3 Hydrological water balance method

The hydrological water balance methods as proposed by Deurer *et al.* (2011) consider all components of the water balance (inflows, outflows & storage changes) and determines the green, blue and grey WF like the WFN. Different methods or approaches on determining green and blue WF are proposed by these authors. However, they adopted the WFN methodology for the grey WF. The following formulas are used for green and blue WF:

$$\text{Green WF} = D^r + ET_c^r + RO^r - RF^* \qquad \text{(Eq. 2.19)}$$

where D^r is drainage, ET_c^r represent evapotranspiration from rainfed crops, RO^r is runoff in rainfed fields and RF* is effective rainfall.

$$\text{Blue WF} = -\Delta GW - IR + D^r + \Delta D^{i,r} + RO^r + \Delta RO^{i,r} + \Delta ET_c^{i,r} \qquad \text{(Eq. 2.20)}$$

where $-\Delta GW$ represent the net flux of groundwater, IR is the irrigated volumes, $\Delta D^{i,r}$ is the difference between drainage from irrigated and rainfed conditions, $+\Delta RO^{i,r}$ and $\Delta ET_c^{i,r}$ is the differences between runoff and evapotranspiration between irrigated and rainfed conditions.

2.5.4 Assessment methodological differences or challenges

The WFN have developed methods/approaches to measure grey water WF, but challenges still exist due to variation in standards and water quality in different areas. Furthermore, grey water normally remains in the hydrological system, and can be re-used if treated properly (Chapagain & Tickner, 2012). Thus, it causes confusion whether to treat it as effectively 'lost' from the local system in the same way that evapotranspirated blue or green water is considered lost (Chapagain & Tickner, 2012). Another concern with the WFN method is that the output of the WF assessment is a volumetric value indicating the water consumption and pollution (Hoekstra *et al.*, 2011), which is considered as confusing to the other research communities.

Uncertainties exist in the impact assessment in LCA, hence a more detailed assessment is needed for water withdrawal and its effect on the environment. Most importantly, local conditions must be considered and appropriate mitigation strategies identified (Pfister *et al.*, 2009). Most of the LCA research focused more on water use impacts on the local environment but does not consider the global water scarcity issue (Pfister *et al.*, 2009; Ridoutt & Pfister, 2010). Thus, more studies are needed that focus on the impact water withdrawal has on a specific catchment/river and the impact it will have on a specific community. Ridoutt *et al.* (2015) indicated that using footprint in environmental impact assessments can be problematic due to the different approaches used in the determinations. The authors further indicated that the inconsistency in the assessment methods can cause confusion among public and business communities and can have a negative impact in policy making. Therefore, it was recommended that international standards such as the ISO 14040 and 14044 foundations (Finkbeiner, 2013) be used in footprint assessments in order to use the same principles that can be comparable (Pfister & Ridoutt, 2014; Ridoutt *et al.*, 2015). The ISO 14014 and 14044 is based on the environmental management concept from the life cycle viewpoint (Ridoutt *et al.*, 2015).

2.5.5 FruitLook as a tool for water footprint assessment

FruitLook is an open web portal funded by the Western Cape Department of Agriculture with eLeaf (eleaf.com) generating and providing the spatial data provided on fruitlook.co.za. FruitLook data is derived from a combination of algorithms, satellite data products, field based weather data and other ancillary data. FruitLook uses the surface energy balance to estimate total evapotranspiration (ET) or the latent heat flux density (λE), biomass production, water deficit and biomass water use efficiency spatially (Pelgrum *et al.*, 2010; Bastiaanssen *et al.*, 2012). On the FruitLook portal, fruit and grape producers in the Western Cape can access satellite-based information on plant growth, water use and nutrient status. FruitLook was initiated in the 2011/12 season to provide this data following a feasibility study of the GrapeLook trial (2010/11). Remote sensing data has the potential to aid in optimal water management that can lead to improved WUE (Jarmain *et al.*, 2014). Algorithms such as Surface Energy Balance Algorithm for Land (SEBAL) and ETLook has been applied in agricultural field water management and have also been evaluated (Jarmain *et al.*, 2014). Remote sensing data is reported to have several advantages such as allowing for near real-time monitoring, providing automatic, and continuous measurements, can be used over a big area and is not time consuming (Alvino & Marino, 2017). This data can be used in irrigation scheduling to also improve water use efficiency (Alvino & Marino, 2017). Remote sensing data such as precipitation, water storage, runoff and land use also has the potential to be used in global or national WF assessments of crops (Romaguera *et al.*, 2010). These researchers suggested that derived remote sensing data can be used in a mass water balance to quantify blue and green water. One of the benefits of using remote sensing data is that crop water use is determined spatially, for each pixel of a satellite image, and there is no need to rely on generalised crop coefficients.

2.6 Conclusions

Water scarcity has become a major concern, especially in arid and semi-arid countries due to the decreasing rainfall distribution and seasonal drought experienced during the growing season that leads to a stronger competition between the different water use sectors. Table grapes are cultivated in warm and arid areas and harbour large canopies with large crops, therefore there is the necessity to limit water whilst optimising plant efficiency. Irrigated agriculture contributes significantly to the economy of the region, but is also the sector that uses a lot of water. Hence, the reason for advocacy for improved WUE, therefore there is a need to quantify water needs and to investigate ways of reducing water use, without compromising yield and quality. Factors are reviewed that have an effect on WUE. Of these, canopy management and irrigation scheduling are factors that can easily be manipulated. Therefore, proper care must be taken in order to minimise unnecessary water loss in order to improve transpiration which is linked to carbon production and fruit quality. Deficit irrigation strategies are also reviewed. These strategies have a potential to reduce water use and increase WUE. However, careful management is needed to avoid negative impact on production and fruit quality. There are also contradictory results as to which deficit irrigation strategy is best, thus more studies are needed to give proper guidelines.

Physiological WUE has been studied widely in a number of studies. However, few studies have focused on crop or WUE_y. Most of the available studies scale up from leaf to crop WUE.

Unfortunately, this has its own complications since data does not always correlate due to the effect that different leaf positions have on carbon gain and water loss. In addition, carbon losses through dark respiration is not accounted for in leaf measurements. Thus, more studies are needed to fill that knowledge gap.

In order to improve WUE, there is a need to quantify proper irrigation requirements. There is inconsistency in literature regarding table grape water requirements. Consequently, clearer indications or monitoring tools are needed for scheduling of irrigation. With the increasing pressure on natural water resources, a more holistic approach is necessary that will allow precision irrigation scheduling that relies on soil and crop variability. One way of providing such guidelines is through WF assessments. There have been very few studies in South Africa on table grape WF assessments, thus the need for more studies. Remote sensing derived data also has a potential to be used in WF assessments. In this regard, FruitLook could add value in irrigation management and water footprint determination.

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Zephyris, 2011. Leaf tissue structure. Wikimedia Commons.

Chapter 3

Research results

Investigating Crimson Seedless grapevine phenology and vegetative growth performance under differing cultivation conditions

CHAPTER III: INVESTIGATING CRIMSON SEEDLESS GRAPEVINE PHENOLOGY AND VEGETATIVE GROWTH PERFORMANCE UNDER DIFFERING CULTIVATION CONDITIONS

3.1 Introduction

The South African table grape industry is export driven and comprised a total of 382 production units on 18 575 ha in 2016 (SATI, 2016). Since the industry is export driven, it contributes valuable foreign exchange to the economy and directly employs more than 7 000 permanent and 16 000 seasonal workers (SATI, 2016). A water footprint analysis conducted in the Breede Catchment revealed that table grapes offer producers the highest gross income per cubic meter of water and also creates the highest number of jobs per unit of water compared to all other crops produced in the area (Pegasys, 2010). *Vitis vinifera* L. *cv*. Crimson Seedless is one of the major table grape cultivars produced in South Africa. It is a late-season red seedless table grape cultivar with elongated berries and a crispy excellent flavour (Dokoozlian *et al.*, 2000). This cultivar can be grown well in different soil types under different growing conditions. However, deep and fertile soils should be avoided since it stimulate vigorous vegetative growth (Dokoozlian *et al.*, 2000). Optimal vineyard management in terms of fertilisation and irrigation strategies is needed to control canopy size. Rootstock choice also plays an important role in table grape production. Ramsey rootstock perform well on unfertile sandy soils, like the ones in the Hex River Valley, because it is a strong vigorous rootstock with good root distribution (Teubes, 2014). The good root branching contributes to effective water extraction from the soil. However, it is not advisable to use this vigorous rootstock with a strong growing scion cultivar such as Crimson Seedless in fertile soils, since it will result in problems with bud fertility and set (Skinkis, 2013).

Table grape phenological stages are divided into vegetative and reproductive stages. The vegetative growth cycle is characterised by bud break and the active growth of shoot, leaves and roots, whereas the reproductive cycle comprises initiation of flower clusters, flowering, berry set and berry ripening (Coombe, 1995). The grapevine's irrigation and fertilizer requirements differ from stage to stage and needs to be adhered to in order to obtain high productivity and excellent fruit quality. Table grape phenological stages coincide with high temperature, high evapotranspiration and limited water resources in semi-arid countries (Chaves *et al.*, 2007). Therefore, there is a need to know the phenological stages to make sound management decisions in terms of soil, water, pest and disease control. Plant water stress reduces shoot vigour, resulting in shorter shoots and decreased leaf area per grapevine (Iland *et al.*, 2011) and leaf number per shoot, leaf size and leaf thickness (Bacon, 2004). Excessive irrigation strategies stimulate more vegetative growth at the expense of reproductive development, leading to lower yields with poor fruit quality. Hence, the introduction of deficit irrigation strategies in order to control vegetative growth to improve fruit quality as well as to improve water use efficiency (Bacon, 2004; Girona *et al.*, 2006; Chaves *et al.*, 2007; Fereres & Soriano, 2007; Howell *et al.*, 2013). Thus, accurate estimation of vineyard water use is important for irrigation scheduling in order to optimise yield, growth and quality (Suvočarev *et al.*, 2013; Myburgh, 2016).

The Hex River Valley is the largest producer of table grapes in South Africa, contributing significantly to the economy of the region and job creation. This study therefore seeks to evaluate the effects of differing cultivation conditions (different soil texture & irrigation system scenarios) on Crimson Seedless phenology and vegetative growth.

3.2 Materials and methods

3.2.1 Site description

Plant based measurements were conducted in four different table grape vineyard blocks during the 2013/14 and 2014/15 growing seasons in the Hex River Valley of the Western Cape, South Africa. The location of the experimental blocks is indicated on the Google® map (Figure 3.1). More details of the respective blocks are given in Table 3.1.

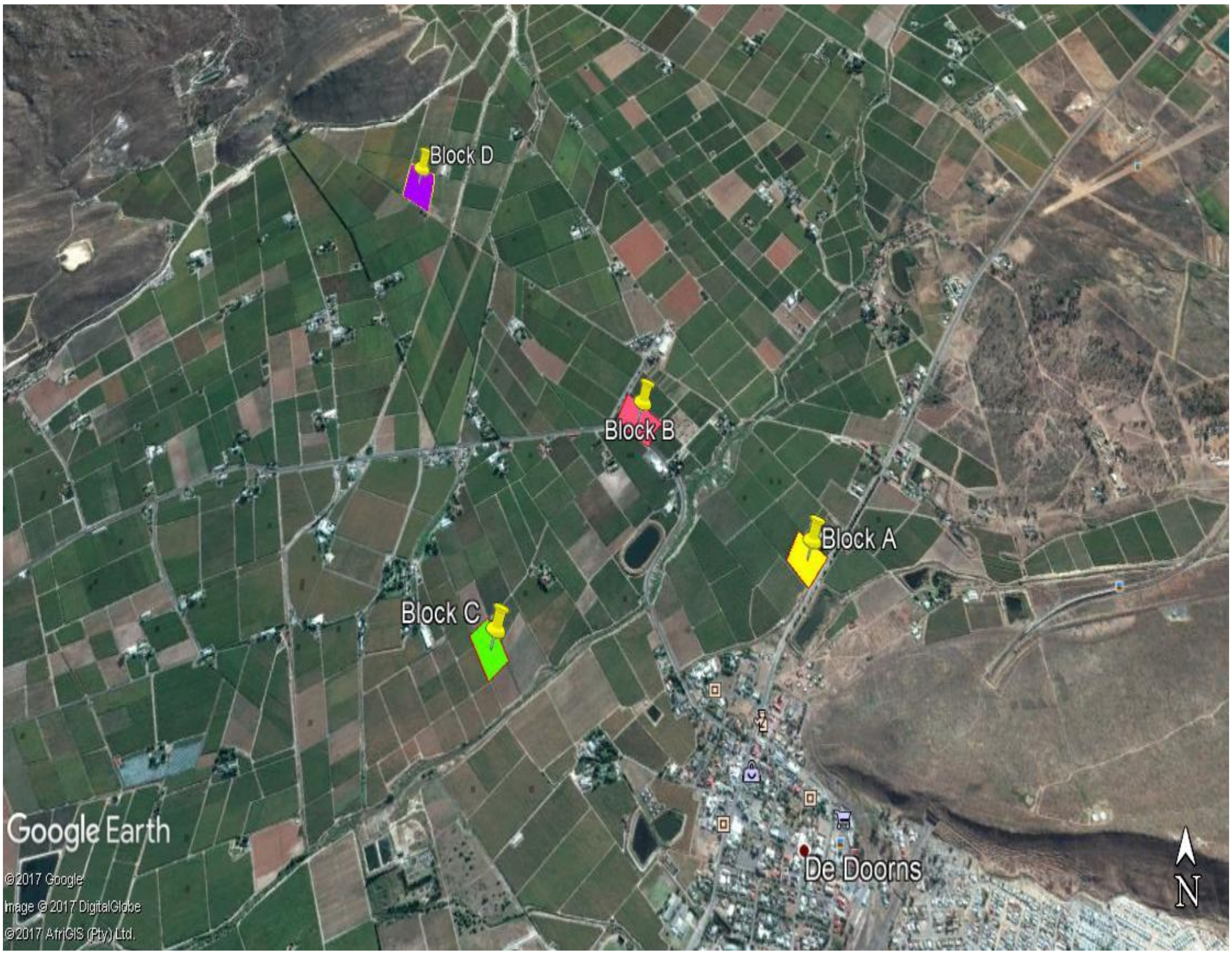

Figure 3.1: Location of the four 'Crimson Seedless' experimental blocks in the Hex River Valley.

Table 3.1: Block details of the four sites in Hex River Valley.

Descriptor	Block A	Block B	Block C	Block D
Climate	Mediterranean			
Grapevine species	*Vitis vinifera*			
Cultivar	Crimson Seedless			
Rootstock	Ramsey			
Year established	2001	2002	2000	2004
Block size (ha)	1.8	1.3	1.0	1.5
Row orientation	NE-SW	NE-SW	NNW-SSE	NNE-SSW
Grapevine spacing (m × m)	3 × 1.8	3 × 1.8	2.75 × 1.8	3 × 1.8
Trellis system	Trentina			
Soil type	Sandy clay loam	Sandy clay loam	Loamy fine sand	Sandy clay loam
Irrigation system	Drip	Micro-sprinkler	Micro-sprinkler	Drip
Pruning system	Cane (10 buds per cane)			

3.2.2 Experiment layout

This study was conducted in established vineyards and, due to practical reasons, more blocks could not be included in order to have a specified statistical layout. Therefore, only four blocks with different scenarios were selected. Thus, the experiment consisted of four fixed blocks. The scenarios were as follows: (1) drip on sandy clay loam; (2) micro-sprinkler on sandy clay loam; (3) micro-sprinkler on loamy fine sand and (4) drip on sandy clay loam. No treatment was applied for this study. In each vineyard block, ten experimental units were replicated (randomly selected) for measurements. All ten experimental units consisted of four vines, of which one representative data vine was selected according to its stem diameter for plant based measurements. These measurements were deemed representative of the entire block. It should be noted that standard viticulture management practices as recommended for the production of export quality Crimson Seedless table grapes (SATI, 2015) were applied in each block by the specific farm .

3.2.3 Automatic weather stations (AWS)

Weather data for the 2013/14 season was obtained from a weather station on the Hex River experimental farm, within approximately 4 km from the experimental blocks (De Doorns, Lat 33.4667˚S, Long 19.6667˚E; Alt 457 m, courtesy of the Agro-Climatology Division of the Institute of Soil Climate and Water of the Agricultural Research Council: Agro-Climatology, ARC – ISCW, Pretoria, ZA). The ARC weather station was not working during the 2014/15 season and an alternative station in the same area was used instead. Hence, 2014/15 season's weather data was obtained from the Modderdrift weather station (Lat 33.1122˚S, Long 22.5345˚E; Alt 1020 m, courtesy of iLeaf, Hortec (Pty) Ltd). Growing degree days (°C.day^{-1}) were calculated daily from 1 September to 31 March to accommodate the different budburst dates in the different blocks (Jones & Davis, 2000).

3.2.4 Soil analysis

Soil samples were collected at five experimental units in each block at the following soil depths: 0-30, 30-60 and 60-90 cm. A soil auger was used to sample Block A and C, while profile holes were made in Block B and D due to the high stone content of these blocks. All samples were analysed by a commercial laboratory (Bemlab, Strand). Textural and chemical analysis was conducted by a commercial laboratory (Bemlab, www.bemlab.co.za). Average soil textural analysis (sand, clay and silt) of the five samples per block were determined and the soil texture classification for each block was derived from the soil texture calculator triangle (www.nrcs.usda.gov).

3.2.5 Soil water measurements

Soil water content was determined with the neutron scattering technique using a 503 DR Hydroprobe Neutron Depth Moisture Gauge (Campbell Pacific Nuclear International Inc., CA, USA). Soil water monitoring access tubes were installed a few centimetres from the data vine at two experimental units per block at the beginning of December 2014. Block A was measured at the following soil depths: 0-30 cm; 30-60 cm and 60-90 cm, whereas Blocks B, C and D were measured at 0-30 and 30-60 cm soil depths due to the high stone content of these blocks. The neutron probe was placed on its box close to the data vine to be measured. Three measurements were taken to obtain a standard reading for the probe before it was placed on the access tube. The probe was lowered to each specific depth and a measurement taken. Count ratios (CR) were determined by dividing the neutron probe reading at each soil depth by the machine standard reading, which was 7950. Soil water content was measured every second week during the active growing season, *i.e.* December to April. In the post-harvest period, soil water content was measured monthly of the 2014/15 season.

A field calibration was carried out during the 2014/15 season to convert neutron counts to volumetric soil water content, soil water content was determined as described below and used in the estimated ET calculations. Soil samples were collected at each of the two data vines where the soil water monitoring access tubes were installed in each block. Samples were collected at the same depths where neutron probe readings were taken. Soil samples were collected at three different phenological stages, namely pea size berries, post-harvest and at dormancy. Samples were taken at these stages to obtain a range of different levels of soil wetness. Soil samples were taken to the laboratory and weighed immediately. The samples were put in an oven dried at 105ºC to dry to constant weight. At constant weight, samples were weighed again to determine the dry weight in order to determine the water loss. Calculation of the gravimetric soil water content was done using the following equation of Hillel (1980):

$$\text{Water content (\%) } P_w = ((M_w - M_d)/(M_d)) \times 100 \qquad \text{(Eq. 3.1)}$$

where M_w is the mass of the wet soil and M_d is the mass of the dry soil.

From gravimetric calculations, volumetric soil water content was calculated using the following equation:

$$\text{Volumetric } (\theta_v) = (P_w/100) \times (\rho_b) \qquad \text{(Eq. 3.2)}$$

where ρ_b is bulk density. The bulk density value used in Eq. 3.2 was obtained from values reported by Myburgh and Howell (2007) and Myburgh (2012).

Volumetric soil water obtained by Eq. 3.2 was multiplied by the soil depth layer of 300 mm to express the soil water content in mm/mm. A universal global relationship between soil water content (mm/mm) and count ratios were set up. The R^2 of the relationship was 0.72. The correlation obtained between the two parameters was used to calculate the soil water content in mm/m for the other neutron probe readings. The correlation equation used to convert neutron probe readings to soil water content was as follows:

$$\text{Soil water content} = \text{slope} \times \text{Count ratio} + \text{intercept} \qquad \text{(Eq. 3.3)}$$

Where slope and intercept are the values of 64.6671 and – 9.2926, respectively, obtained in the correlation between the soil water content of the field calibration samples and neutron probe readings.

3.2.6 Estimated evapotranspiration

Estimated evapotranspiration was determined from the second week of December 2014 to August 2015 during the 2014/15 season based on water balance calculations. Irrigation data supplied by the producers and rainfall data obtained from the AWS nearest to the blocks were used in these calculations. Estimated evapotranspiration was then calculated by using the following equation:

$$ET = \Delta GW + I + P \qquad \text{(Eq. 3.4)}$$

where ΔGW is the change in soil water content during the period of measurement, and I + P is irrigation and rainfall, respectively. The assumption was made that there was no substantial drainage in these blocks and therefore it was not accounted for in this calculation. Water Balance estimated ET (ETWB) was corrected with published crop factors (CF) from Lategan (1996) ($ETWB_{(L)}$), Myburgh (2003a) ($ETWB_{(M)}$) that was determined under the Orange River conditions and FruitLook (fruitlook.co.za) ($ETWB_{(FL)}$) to estimate the actual plant water use. FruitLook data is derived from a combination of satellite and field data and the ETLook algorithms is used (Bastiaanssen *et al.*, 2012). The FruitLook crop factor was determined from the FruitLook ET and ETo obtained from the Modderdrift AWS by using the following equation:

$$CF_{FL} = \text{FruitLook Actual ET} / ET_o \qquad \text{(Eq.3.5)}$$

FruitLook data is available on a weekly basis during the main growing season (September/October – April), thus the average CF per month was used. FruitLook CF values are not estimated in winter, because the product does not run then. However, it can be assumed that CF_{FL} would be constant in winter, because it corresponds with the dormant period of the grapevine. The September CF could have been the preferred one to use since growth is most likely going to be the same from May to September but unfortunately this season's Fruitlook data only started in October and therefore the April CF was used instead. The different CF used for these calculations is presented in Table 3.2.

The irrigation scheduling was based on commercial setups whereby producers use defined irrigation hours per week according to the different phenological stages. Irrigation records were obtained from the producers and irrigation volumes were calculated according to the delivery rates, irrigated areas and total irrigated hours.

Table 3.2: Crop factors used to correct the ET estimated from the water balance method (2014/15 season).

Reference	Block	Crop factor							
		January	February	March	April	May	June	July	August
Lategan (1996)		0.50	0.60	0.60	0.30	0.20	0.20	0.20	0.20
Myburgh (2003a)		0.98	0.88	0.68	0.41	0.33	0.21	0.16	0.25
FruitLook	A	0.78	0.59	0.76	0.67	-	-	-	-
	B	0.73	0.65	0.74	0.68	-	-	-	-
	C	0.83	0.75	0.84	0.73	-	-	-	-
	D	0.94	0.90	0.94	0.74	-	-	-	-

3.2.7 Phenology

Grapevine phenological stages were determined by visual observations throughout the growing season using the modified E-L system of Coombe (1995), as well as obtaining records of the experimental vineyards from producers.

3.2.8 Stem water potential

Five mature, healthy and fully expanded leaves in two experimental unit per block were measured at the different phenological stages. Stem water potential (Ψ_S) was determined using a pressure chamber according to Choné *et al.* (2001). Mature, healthy leaves were covered with plastic zip lock bags covered by aluminium foil at least 45 minutes prior to measurement. For the 2013/14 season, Ψ_S was measured in all blocks at the same time as the leaf gas exchange measurements (Refer to Section 4.2.1, Chapter 4). In the 2014/15 season, Ψ_S was measured over the course of a day in Blocks B and D. Measurements were taken every two hours from 06:00 to 18:00. The Ψ_S in Blocks A and C were measured between 12:00 and 14:00 so that all blocks were measured at midday.

3.2.9 Vegetative measurements

3.2.9.1 Shoot growth and plastochron index (PI) measurements

Shoot growth measurements were conducted on all the selected data vines in the 10 experimental units per block. Two shoots on the 3rd cane (left & right side on the same vine) between node position 4 and 9 were tagged and non-destructive shoot and leaf measurements taken throughout the growing seasons. Due to wind damage, shoot removal and topping early in the season, shoots used for measurements had to be changed during the season where required. Shoot growth measurements were done weekly from when the shoots were 15 cm long up to the termination of shoot growth. Shoot length and nodes per shoot were measured for each marked shoot. Main leaf vein lengths were also recorded from the leaf petiole attachment to the tip of the leaf for leaves with a vein length L-1 (shorter than 2.5 cm) and L1 (longer than 2.5 cm) in order to determine the

Plastochron Index (PI) (Erickson & Michelini, 1957) as adapted by (Strever, 2012). The following equation was used to calculate PI:

$$\mathrm{PI} = n + \frac{\log(Ln) - \log(2.5)}{\log(Ln) - \log(Ln+1)} \qquad \text{(Eq.3.6)}$$

where n is the number of nodes equal to or longer than the reference length, Ln is the length of the leaf longer than the reference (2.5 cm) and Ln+1 is the length of the leaf shorter than the reference.

Plastochron is defined as the interval of time between formulation of two successive internode cells or leaves. Therefore, a plastochron gives an indication of the developmental scale when successive plastochrons are equal in duration (Erickson & Michelini, 1957).

3.2.9.2 Leaf area

Leaf area (LA) was measured destructively for five data vines per block. For each data vine, three representative shoots were collected for the measurements. The following measurements were taken: main and lateral shoot length, number of nodes for both shoots, number of laterals on the main shoot, and LA. Main and lateral shoot leaf area was measured using an electronic leaf surface area meter (Delta-T devices Ltd, Cambridge, UK). Leaf L1 length and thickness were also determined for three experimental units per block.

Measurements were done at the following phenological stages to determine main and lateral shoot LA per stage: pea size berries, véraison, harvest and in winter (pruning) for the 2013/14 season and only at pea size berries for the 2014/15 season. The winter (pruning) data was collected in order to determine the total grapevine LA for the different stages. Unfortunately, during the 2013/14 season pruning, in Blocks A and D was done before detailed cane measurements and total main and lateral shoots per vine were counted. Therefore, leaf areas per main and lateral shoot on the measured main shoot were determined in all blocks, while total grapevine LA could only be determined in Block B and C. Grapevine LA was determined by using shoot lengths (main and laterals) to derive the leaf area from the 2013/14 season calibration curve to show seasonal differences (Addendum A, Figs. A.4 & A.5). Hence, multiplying the 2013/14 season main and lateral shoot leaf area and shoot length correlation equation with the total number of main and lateral canes at pruning for both seasons. The following equations were used for the main and lateral LA calculations:

Main canes: $y = 27.8672 + 7.8837x$ (Eq. 3.7)

Lateral canes: $y = 25.2359 + 6.9937x$ (Eq. 3.8)

3.2.9.3 Leaf morphology

The same leaves used for leaf gas measurements (Refer to Section 4.2.1, Chapter 4) were removed and used for morphological studies. In addition, two more small and shaded, lateral optimal and sunny and hardy leaves were sampled in order to have a total of three leaves per leaf category. Five disks were punched from the inter-vein areas of the leaf using a cork borer with an area of 2.0109 cm^2. The leaf disks were immediately put into weighed micro-centrifuge tubes to avoid any moisture loss. Thereafter, the tubes were weighed to determine leaf fresh mass (FM). The leaf material was oven-dried at 65°C until constant dry mass (DM). Leaf thickness measurements were conducted with a Sundoo digital thickness gauge (Model LP-D1030, Wenzhou Sundoo Instruments, Wenzhou, China). Mean leaf thickness was calculated from the five positions measured per leaf. The following leaf disk measurements were calculated: specific leaf mass (SLM), specific leaf area (SLA), leaf density, leaf water content relative to dry mass (LWC_d) and leaf water content relative to leaf area (EWT) (Strever, 2012).

3.2.9.4 Pruning measurements

During winter all grapevines in the experimental units were cane pruned and weighed. Detailed cane measurements were performed on five data vines in each block. Four canes per data vine were sampled and the following measurements were taken: main cane length, number of nodes per main cane, number of lateral shoots per main cane, lateral cane length and number of nodes per lateral cane. After sampling the remaining canes were counted.

3.2.10 Statistical analysis

Statistical analysis was done and graphs were prepared using Statistica 10 ® software (Statsoft, Tulsa, UK). Due to the fact that this study was executed in 4 established commercial vineyards, presenting 4 commercial scenarios with their irrigation scheduling and irrigation application practices (no treatments were applied) and a specified statistical layout could not be done. Thus, no ANOVA analysis was possible and data were analysed using regression analysis, as well as graphs with 95% confidence intervals and standard errors.

3.3 Results and Discussion

3.3.1 Climatic conditions

Monthly average values of temperature, rainfall, wind speed, relative humidity and accumulated rainfall for the 2012/13, 2013/14 and 2014/15 seasons are depicted in Figure 3.2 and 3.3. As expected, temperatures increased during summer, followed by a decline thereafter, reaching a minimum of 4^oC during winter (Fig. 3.2). Temperatures tend to peak during November and December, remaining high until March each year. Average monthly minimum temperature in the winter for the 2012/13, 2013/14 and 2014/15 seasons were 4.70°C, 4.40°C and 3.98°C respectively. The average maximum temperatures were 30.70˚C, 33.00°C and 32.43°C during 2012/13, 2013/14 and 2014/15 respectively. Winter rainfall weather conditions were noted during these three seasons (Figure 3.2). Seasonal rainfall (September to April) was 69.7 mm, 187.1 mm and 164.8 mm for 2012/13, 2013/14 and 2014/15 seasons respectively. As expected, it rained predominantly during winter, with the 2013/14 season having higher rainfall, whereas the 2012/13 season had the lowest rainfall. Accumulated annual rainfall (September to August) recorded for 2012/13, 2013/14 and 2014/15 season was 311 mm, 1114 and 883 mm respectively (Fig. 3.3). Wind speed was, on average, very low at the blocks. Maximum and minimum relative humidity for the three seasons are also displayed in Figure 3.3. Growing degree days are presented in Figure 3.4. The 2014/15 season was slightly warmer, with higher GDD compared to the 2013/14 season. The 2014/15 season had a faster accumulation of heat units, because of average higher temperatures at the beginning of the season compared to the 2013/14 season. This resulted in the 2014/15 season being approximately a week earlier in terms of phenology from budburst to harvest, compared to the previous season. Prevailing weather conditions affect table grape physiology as well as productivity. Hence the need to study grapevine growth and productivity, taking into account the effect weather conditions have on plant performance.

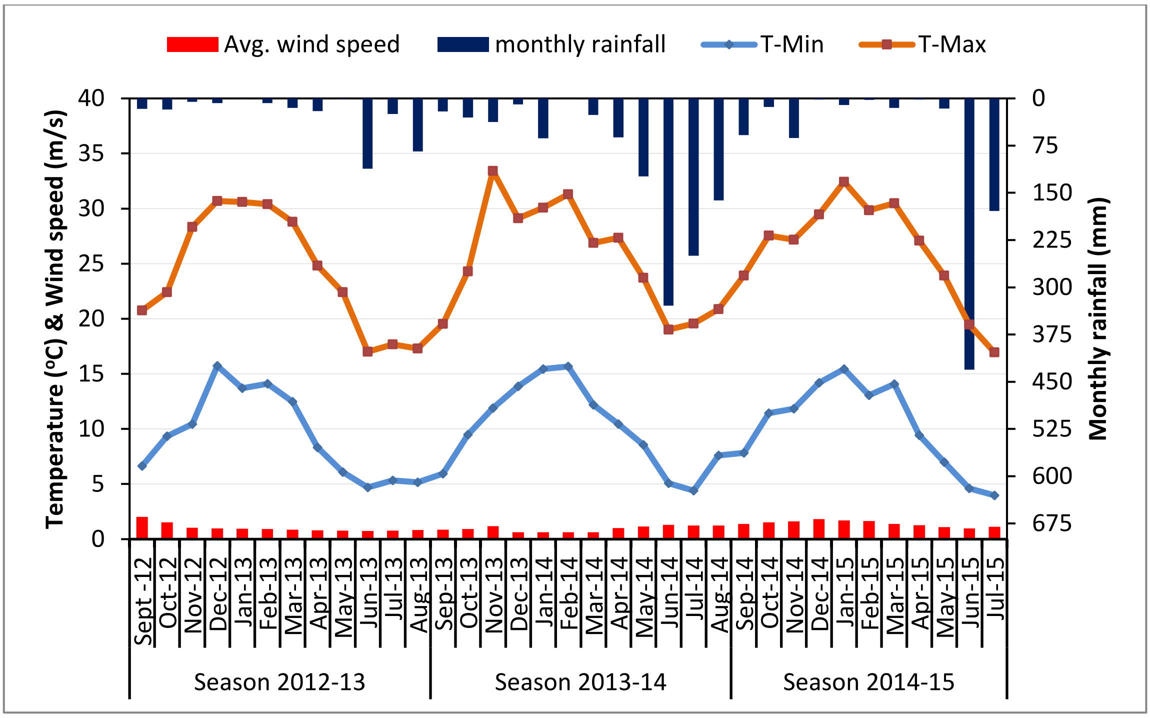

Figure 3.2: Monthly values of meteorological variables recorded at De Doorns between September 2012 and July 2015.

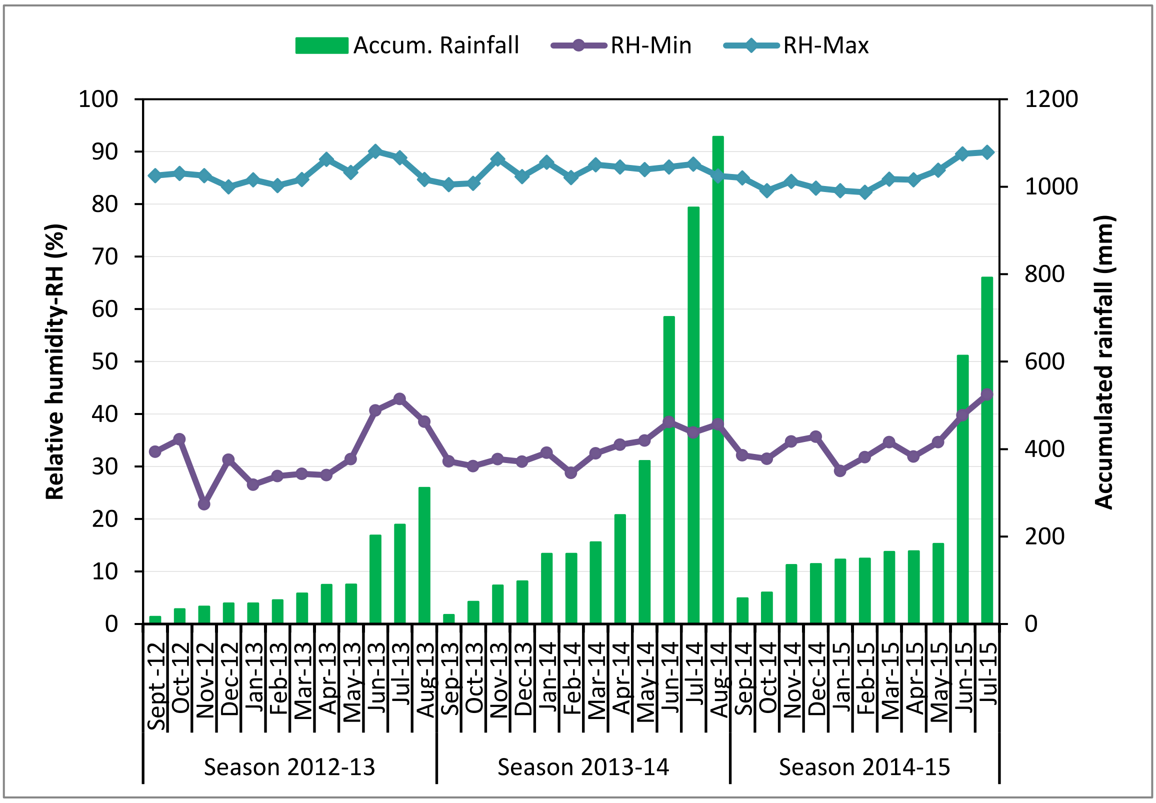

Figure 3.3: Relative humidity (%) and accumulated rainfall (mm) recorded at De Doorns between September 2012 and July 2015.

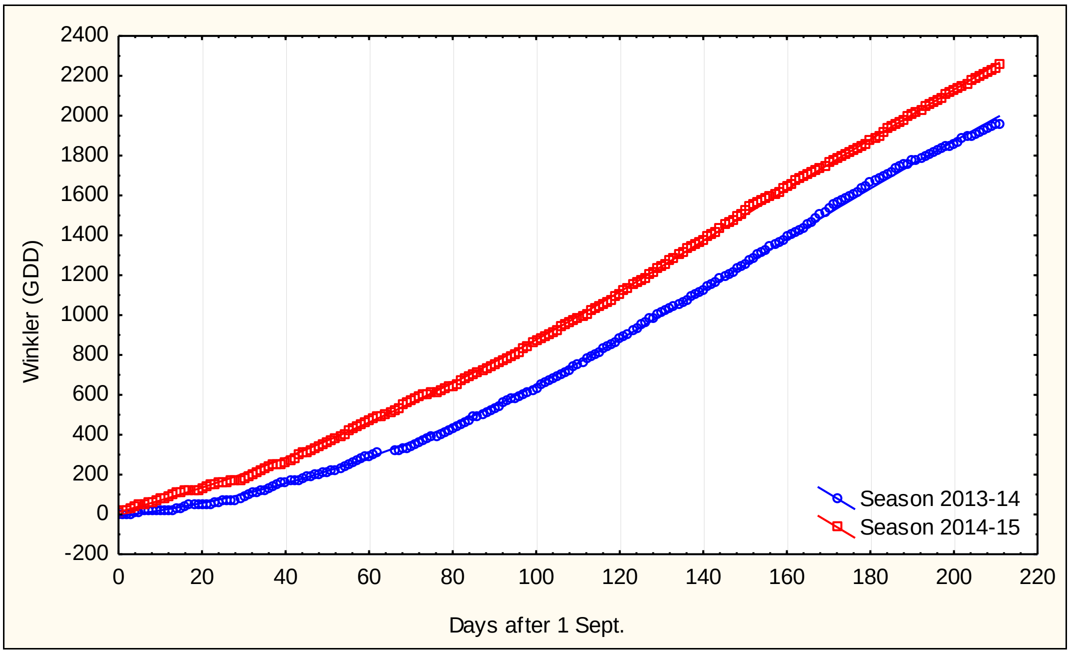

Figure 3.4: Growing degree days (GDD) relative to days after 1st September calculated for the different seasons at De Doorns.

3.3.2 Soil analyses

3.3.2.1 Soil textural analysis

The textural analysis indicated that Blocks A, B and D were sandy clay loam whereas Block C was a loamy fine sand block. The loamy fine sand had the lowest clay and silt contents at all soil depths (Table 3.3), while the sandy clay loam had the highest clay content at the different soil depths with a range of 24-34%. Similarly, the sandy clay loam sand seemed to have a higher fine sand fraction as shown in Table 3.3, whereas the loamy fine sand block had a higher medium and coarse sand at all soil depths. Lower stone volume was measured in the loamy fine sand block compared to the sandy clay loam blocks at all measured soil depths. Block B had the highest stone volume at 30-90 cm soil depth followed by Block D. This means the deeper in the prolife, the higher the stone volume found in Blocks B and D. Although the analysis indicated that Block B had a higher stone fraction in the 30-60 cm and 60-90 cm soil layers compared to Block D, it was contrary to what was visually observed in the two blocks (Figure 3.5). This is possibly due to a sampling issue as large stones were not included in the samples. Different soil types have different water holding capacities, for example sandy soils have a lower ability to hold water compared to clay soils (Bemlab, 2015). The nature of the soil structure, organic matter and soil particle size determine its ability to retain water (Bemlab, 2015). Water holding capacity (WHC) is arguably one of the most important soil characteristics in irrigated table grape production. The WHC of the different soil depths ranged between 78 mm/m and 117 mm/m. Block A had the highest WHC (Table 3.3). The WHC of the different soil layers at Block C was similar. In contrast, WHC in the sub-soil of Block B was low and this was probably the result of the high measured stone fraction in the sample (small stones were included in this sample).

Table 3.3: Soil textural analyses of the four experimental blocks (values are means of five samples). Increasing shades of green indicates higher values while increasing shades of red indicates lower values.

Block	Depth (cm)	Clay %	Silt %	Fine Sand %	Medium Sand %	Coarse Sand %	Stone Volume (v/v)	Water holding capacity (mm/m)
Block A	0 - 30	15.76	13.60	50.03	11.59	9.04	12.10	116.90
	30 - 60	21.36	9.60	54.56	9.17	5.32	15.98	115.60
	60 - 90	23.60	13.20	44.42	11.36	7.51	14.40	106.94
Block B	0 - 30	26.80	12.00	46.88	7.90	6.43	15.32	109.52
	30 - 60	29.20	11.60	48.50	5.79	4.92	25.16	98.52
	60 - 90	29.20	10.00	50.60	6.45	3.77	42.26	78.12
Block C	0 - 30	10.00	10.40	38.82	28.42	12.37	3.42	97.70
	30 - 60	10.40	8.80	41.82	28.45	10.56	5.00	98.60
	60 - 90	10.80	7.60	40.86	27.84	12.93	4.22	97.60
Block D	0 - 30	24.00	10.80	45.26	9.62	10.32	18.26	102.46
	30 - 60	29.60	14.00	38.62	7.04	10.76	18.78	98.58
	60 - 90	34.80	12.80	37.02	5.89	9.51	21.64	93.10

Figure 3.5: Images of soil profiles in Blocks B (left) and D (right), with the high stone fraction visible.

3.3.2.2 Soil chemical analyses

The soil $pH_{(KCl)}$ of all blocks was within the acceptable required norms of 5.5-6.5 for grapevines (Addendum A, Table A.1.) (Conradie, 1994; Van Schoor *et al.*, 2000). Most of the macro and micro elements analysed were also within the norms recommended by Conradie (1994) and Van Schoor *et al.*(2000) (Addendum A, Table A.1). Block A had a lower resistance at the different soil depths indicating higher salinity levels (Addendum A, Table A.1.). Block A also had a higher Mn content at all soil depths. For optimal production, the carbon percentage must be between 0.8 - 1.5% (Bemlab, 2015). Block D had a higher carbon percentage at all measured depths, and it was also the only block with a carbon percentage higher than 0.8%, whereas the carbon % was lower in Block B at all soil depths.

3.3.3 Soil water measurements

The neutron probe measurements revealed that Block A was the wettest, while Block D was the driest throughout the season (data not shown). There were no differences between different soil depths per block. However, there was a tendency towards higher count ratios observed deeper in the soil profile. A global relationship between soil water content (mm/mm) of the sampled soils and count ratios taken at the same time was determined and the correlation equation was applied to all the other count ratio measurements in order to determine soil water content. A positive correlation was obtained (Fig. 3.6) and water content determined from the correlation equation was used in the water balance equation as already explained in Section 3.2.6.

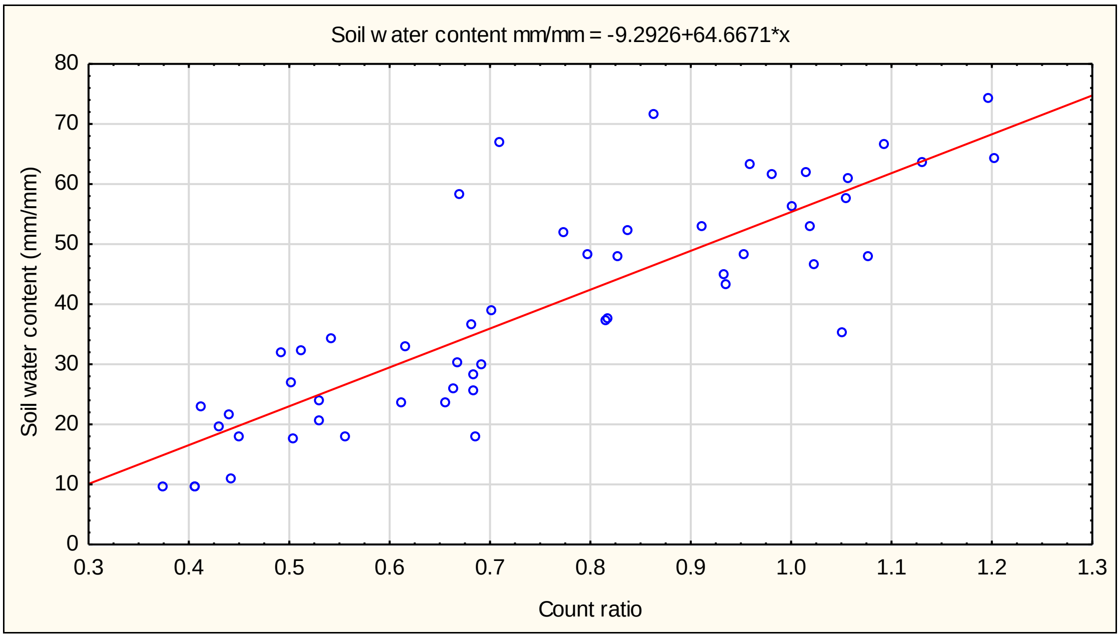

Figure 3.6: Relationship between soil water content and count ratio measured for all blocks during the 2014/15 season. Regression results: r= 0.85; p= 0.00; r^2= 0.72.

3.3.4 Estimated evapotranspiration

Estimated ET was calculated from the water balance method from which four different ET calculations (ETWB, ETWB(L), ETWB(M) and ETWB(FL) were made for the 2014/15 season as already explained in Section 3.2.6. Three different CF were used to make a comparison between them and to determine the effect of the different CF on the ET calculation. For accurate estimation of plant water use, it is very important to use the optimal CF that takes the different growing stages and canopy development into account. From the three different CF used, the Myburgh (2003a) factors were the highest, since they was determined from a full cover canopy, followed by the FruitLook values and lastly the Lategan (1996) CF values between January and February. FruitLook CF was higher during March and April since its calculation is based on above and below ground biomass accumulation while the published values consider the active growth and post-harvest period. There was not such a vast difference between the published CF during the post-harvest period. Interestingly, Block D FruitLook CF during January and February was not so different to Myburgh (2003a) raising a concern whether the Lategan (1996) CF is not too low and if it is indeed capturing the crop growth relation to ET well. The lower CF determined by Lategan (1996) might have been attributed by the smaller canopy caused by the slanting trellising system used in their study. The estimated ET corrected with the different crop factors indicated that the ETWB(L) was the lowest for all calculations as shown in Table 3.3. Block C had the highest ET, while Block D had the lowest ET (Table 3.3). The higher ET in Block C is probably due to its lower clay content and higher medium and course sand necessitating more frequent irrigation. This observation is also supported by the higher seasonal irrigation volume given in Block C (Table 3.4). As expected, the two drip irrigated blocks, *i.e.* Blocks A and D, had the lowest seasonal irrigation volumes in both seasons (Table 3.4). The lower seasonal irrigation volume measured and the high stone fraction observed in Block D might have contributed to the substantially lower estimated ET.

Table 3.3: Estimated evapotranspiration (mm) calculated for the four Crimson Seedless blocks using the water balance method from the second week of December 2014 to August 2015 during the 2014/15 season.

						Evapotranspiration (mm)								
ET calculated from water balance equation	Block	1/2/2015	1/20/2015	2/19/2015	3/5/2015	3/21/2015	4/8/2015	4/30/2015	5/29/2015	7/1/2015	7/31/2015	8/21/2015	Dec- AprTotal	Dec- Aug Total
Estimated ET (no crop factor used)	Block A	97.43	99.51	201.90	86.77	47.63	37.98	63.21	18.51	160.99	60.71	15.16	634.44	889.81
ETWB	Block B	138.28	93.90	149.97	71.89	63.91	63.38	93.39	-11.30	165.00	56.01	21.12	674.72	905.55
	Block C	139.55	117.84	137.57	127.48	21.70	90.25	35.47	34.34	159.74	58.24	30.43	669.85	952.60
	Block D	75.16	102.77	160.75	55.51	48.22	49.98	33.97	19.29	150.24	54.53	24.56	526.35	774.97
ET corrected with a Crop Factor														
Lategan, 1996	Block A	48.72	49.76	121.14	52.06	28.58	11.39	18.96	3.70	32.20	12.14	3.03	330.61	381.68
$ETWB_{(L)}$	Block B	69.14	46.95	89.98	43.13	38.34	19.02	28.02	-2.26	33.00	11.20	4.22	334.58	380.75
	Block C	69.77	58.92	82.54	76.49	13.02	27.07	10.64	6.87	31.95	11.65	6.09	338.46	395.01
	Block D	37.58	51.38	96.45	33.31	28.93	15.00	10.19	3.86	30.05	10.91	4.91	272.83	322.56
Myburg, 2003a (30% depletion)	Block A	95.49	97.52	177.67	59.00	32.39	15.57	25.92	6.11	25.76	9.71	3.79	503.56	548.93
$ETWB_{(M)}$	Block B	135.52	92.03	131.97	48.88	43.46	25.99	38.29	-3.73	26.40	8.96	5.28	516.13	553.04
	Block C	136.76	115.48	121.06	86.69	14.75	37.00	14.54	11.33	25.56	9.32	7.61	526.29	580.10
	Block D	73.66	100.71	141.46	37.75	32.79	20.49	13.93	6.37	24.04	8.72	6.14	420.78	466.05
FruitLook (www.fruitlook.co.za)	Block A	76.00	77.62	119.12	65.95	36.20	25.45	42.35	12.40	107.86	40.68	10.15	442.68	613.78
$ETWB_{(FL)}$	Block B	100.94	68.55	97.48	53.20	47.29	43.10	63.51	-7.69	112.20	38.09	14.36	474.07	631.03
	Block C	115.82	97.81	103.18	107.08	18.23	65.88	25.90	25.07	116.61	42.51	22.21	533.89	740.30
	Block D	70.65	96.60	144.67	52.18	45.33	36.99	25.14	14.27	111.18	40.35	18.18	471.55	655.53

Table 3.4: Seasonal irrigation volumes applied to the four experimental blocks for the 2013/14 and 2014/15 seasons.

Block	A		B		C		D	
Season	2013/14	2014/15	2013/14	2014/15	2013/14	2014/15	2013/14	2014/15
Irrigation (mm) (September - April)	455	755	963	913	1051	996	639	606

3.3.5 Phenology

Grapevine phenology is the study of the natural process that takes place in the life cycle of a vine and how it is influenced by climate and its growing environment. The seasonal cycle in grapevines begin with bud break, normally late winter to early spring, ending with leaf fall in autumn followed by winter dormancy. Plant growth and water requirements change as the season progresses. Therefore, there is a need to know the phenological stages in order to supply correct irrigation volumes to improve water use efficiency. Important phenological stages for the two seasons were recorded and are presented in Table 3.5. Bud break was a week earlier in the 2014/15 season compared to the 2013/14 season and this might have been due to a higher or faster accumulation of GDD due to higher average temperature at the beginning of September 2014 (Fig. 3.4).

Table 3.5: Important phenological stages and occurring dates for the 2013/14 and 2014/15 seasons of the four experimental blocks.

Block	Phenological stage dates							
	Bud break		Full bloom		Véraison		Harvest (start)	
	2013/14	*2014/15*	*2013/14*	*2014/15*	*2013/14*	*2014/15*	*2013/14*	*2014/15*
A	25/09/2013	17/9/2014	28/10/2013	23/10/2014	25/12/2013	20/12/2014	12/02/2014	6/2/2015
B	10/09/2013	5/9/2014	2/11/2013	27/10/2014	17/12/2013	26/12/2014	13/02/2014	8/2/2015
C	15/09/2013	8/9/2014	7/11/2013	30/10/2014	22/12/2013	29/12/2014	18/02/2014	11/2/2015
D	18/09/2013	14/9/2014	25/10/2013	20/10/2014	20/12/2013	15/12/2014	05/2/2014	28/1/2015

3.3.6 Stem water potential

3.3.6.1 Season 2013/14

Stem water potential at pea size berries was between -1200 and -1400 kPa in all blocks, indicating a similar stress level. Nevertheless, at véraison Block B was the most stressed (< -1400 kPa) followed by Block A (< -1200 kPa) (Fig. 3. 7). The Ψ_S at Block A remained lower than the other three blocks at harvest. Likewise, at post-harvest, Block A's and B's Ψ_S was lower than those of Block's C and D. A general increase in Ψ_S was noted between harvest and post-harvest in Blocks A, C and D, indicating a crop effect on Ψ_S. Despite the increase in Ψ_S at this stage, Ψ_S at Block A and B was still the lowest. This finding supports the slow shoot growth (Refer to Section 3.3.7.1) and lower yield (Refer to Section 4.3.4.1, Chapter 4) observed in these blocks during the 2013/14 season. Jones (1990) and Myburgh and Howell (2012) reported that grapevine growth and yield is influenced by plant water status.

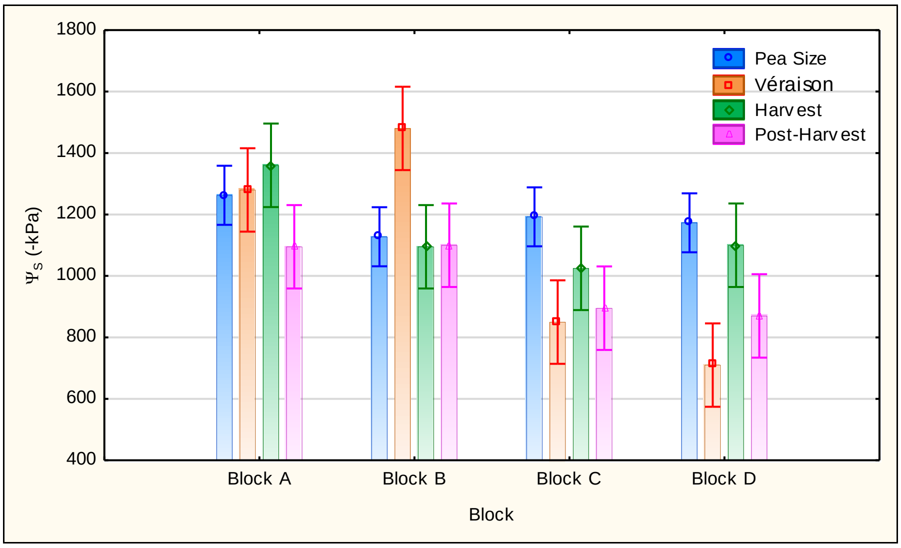

Figure 3.7: Stem (Ψ_S) water potential of the four experimental blocks at different phenological stages (pea size, véraison, harvest and post-harvest) for the 2013/14 season. Vertical bars denote 95% confidence intervals.

3.3.6.2 Season 2014/15

At pea size, Ψ_S at Block B was lower than Block D (Fig. 3.8). However, at harvest Block D had a tendency towards lower Ψ_S. This corresponded with the low soil water content observed with the neutron probe measurements (data not shown). Similar patterns were observed in these two blocks at post-harvest. The diurnal cycle measurements showed high Ψ_S in the early morning, followed by a steady decline to midday and partial recovery for the remainder of afternoon at all phenological stages. At pea size, the Ψ_S at 06:00 was -400 kPa and -200 kPa for Blocks B and D, respectively, declining to -1400 kPa and -900 kPa at 14:00 followed by an increase to about -820 kPa in both blocks towards the late afternoon (Fig. 3.8). The Ψ_S remained constant in Block D between 14:00 and 16:00 while Block B indicated an increase between 14:00 and 18h00. The lowest Ψ_S was measured at harvest with Block D reaching a minimum of -2000 kPa at 12:00 and recovering slightly to -1200 kPa by late afternoon. This is supported by the high temperature and radiation measured at harvest. Post-harvest diurnal course of Ψ_S indicated a slightly lower Ψ_S in Block B between 06:00 and 13:00 followed by an increase to values higher than those of Block D in the late afternoon (Fig. 3.8). This is in agreement with other researchers who indicated that the point of lowest water potential is reached at midday (Choné *et al.*, 2001). The diurnal cycle measurements at pea size and harvest indicated that Ψ_S was lowest between 12h00 and 14h00. In the post-harvest period, the lowest Ψ_S was observed at midday. This could have been influenced by the prevailing higher temperatures combined with lower RH resulting in high VPD values at that particular time.

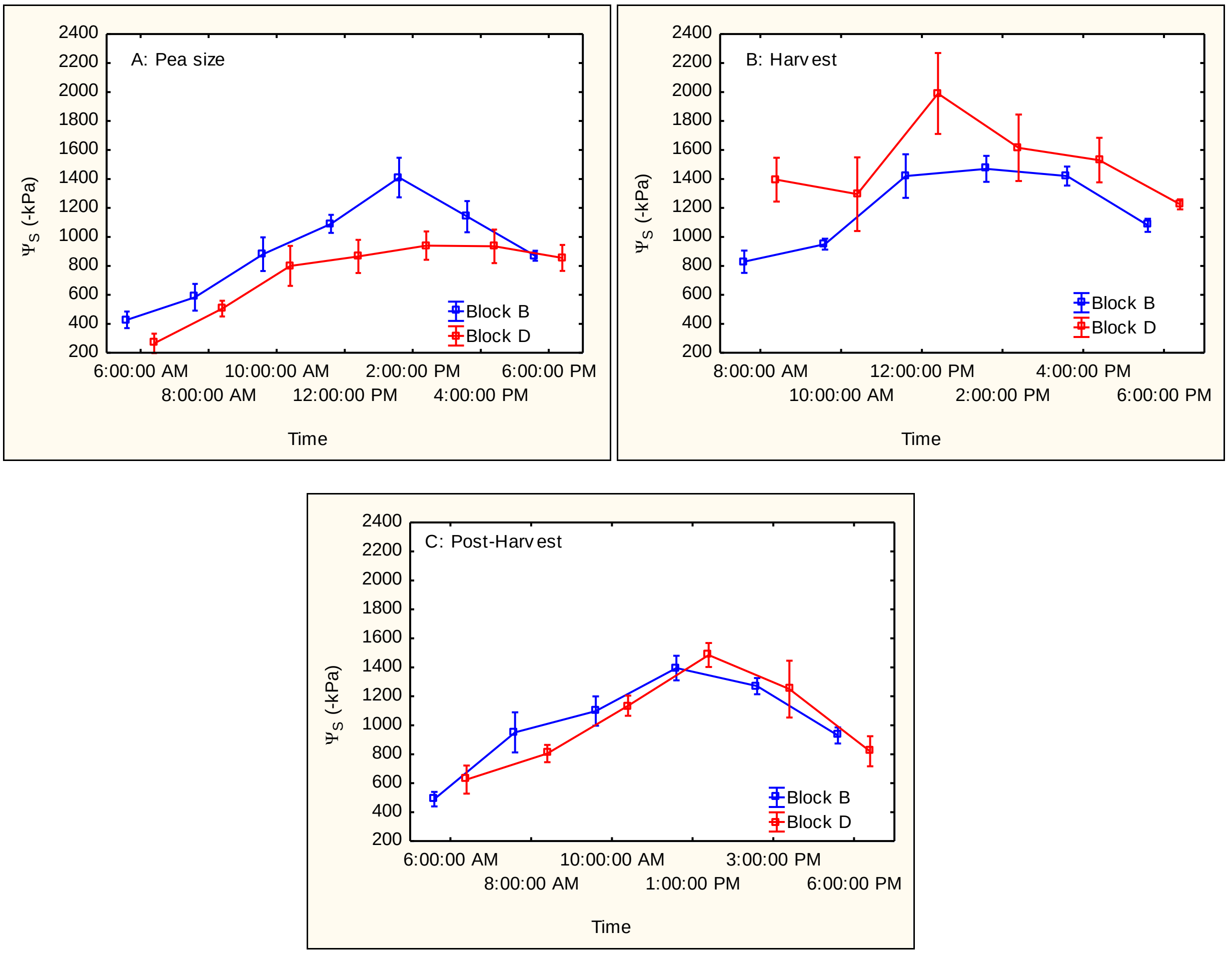

Figure 3.8: Diurnal course of stem (Ψ_S) water potential of Block B and D at pea size (A), harvest (B) and post-harvest (C) for the 2014/15 season (means with +/- standard error shown).

Midday Ψ_S (12:00-14:00) was lower in Blocks A and B compared to Blocks C and D at pea size (Fig. 3.9). However, Blocks C and D had a tendency towards lower Ψ_S at harvest. At post-harvest, Blocks A and D had similar low Ψ_S. Relatively low Ψ_S was measured in Block D at harvest (-2100 kPa) and post-harvest (-1600 kPa). This was probably due to the low soil water content measured in the block as well as the larger transpiring leaf area (Fig. 3.9). Researchers such as Williams and Trout (2005) and Schultz and Stoll (2010) reported that larger leaf areas deplete soil water faster through transpiration, causing low plant water status. Van Leeuwen *et al.* (2009) and Myburgh (2011) proposed the following thresholds for stem water potential as an indication of plant stress: -400 > -1000 kPa (mild), -1000 > -1400 kPa (moderate), -1400 > -1600 kPa (strong) and < -1600 kPa (severe). Based on these thresholds, the midday stem water potential at pea size measured in this study was within the mild to moderate stress threshold, while at harvest and post-harvest it was in the moderate to severe stress thresholds.

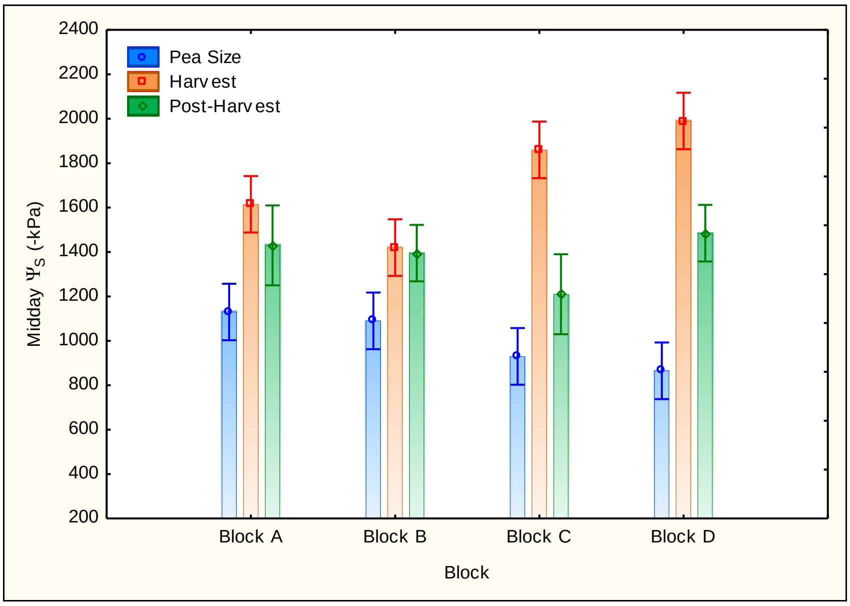

Figure 3.9. Midday stem (Ψs) water potential (-kPa) of the four experimental blocks at different phenological stages (pea size, harvest and post-harvest) for the 2014/15 season. Vertical bars denote 95% confidence intervals.

Stem water potential was high at pea size indicating optimal conditions, followed by a reduction in all blocks at harvest, showing a crop effect. After harvest, Ψs increased in almost all the blocks as in the previous season. The low Ψs in Block D suggest that this block was stressed for a large part of the growing season.

3.3.7 Vegetative measurements

3.3.7.1 Shoot growth

Block D had vigorous shoot growth, more node development with longer average internode length in both seasons (Figs. 3.10 & 3.11 and Addendum A, Figs. A.1 & A.2). During the 2013/14 season, Block A shoot length growth started off faster, but its growth subsided compared to the other blocks as the season progressed (Figure 3.10). During the 2014/15 season, an improvement in Block A's shoot growth was noted, with longer shoot length and more node development than in Blocks B and C (Figure 3.11). This was probably due to an increase of 300 mm in the seasonal irrigation applied to Block A in the 2014/15 season (Table 3.4). Shoot growth per day during the 2013/14 season showed a similar range of 2 cm to 2.5 cm growth per day in Blocks B, C and D from the beginning of the season to 60 DAB, while Block A had a shoot growth rate per day of only 1 cm for the same period (Fig. 3.12). A peak in growth tempo was noted in Blocks A (2 cm) and C (3 cm) while in the other two blocks it steadily decreased up to cessation of shoot growth. Block A had a tendency towards a lower growth tempo in both seasons, indicating a slower growth (Figure 3.12 & Figure **3.13**). This could be due to two factors. Firstly, the block seemed wet throughout the 2014/15 growing season and this could have affected growth negatively. Secondly, the soil chemistry indicated that a salinity problem may have also been prevalent in this block (Addendum A, Table A.1). Comparing the two seasons' shoot growth per day from bud burst up to 60 DAB showed that the shoot growth rate in the 2014/15 season was higher than in the 2013/14 season. This was expected as the GDD was higher in the 2014/15 season. Furthermore, the soil water content at the beginning of the first season (2013/14) started off quite dry, whereas after winter in the second season (2014/15) the soil was quite wet, hence the uneven and slow initial growth in the first season.

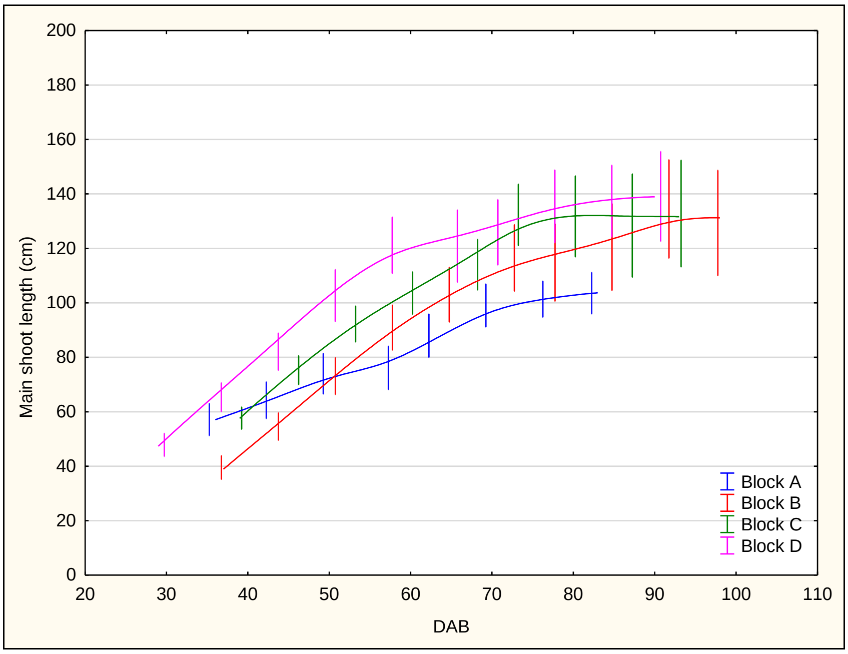

Figure 3.10: Main shoot length (cm) relative to date after budburst (DAB) of the four experimental blocks for the 2013/14 season. A distance weighted least squares fit was drawn. Spreads indicate standard errors.

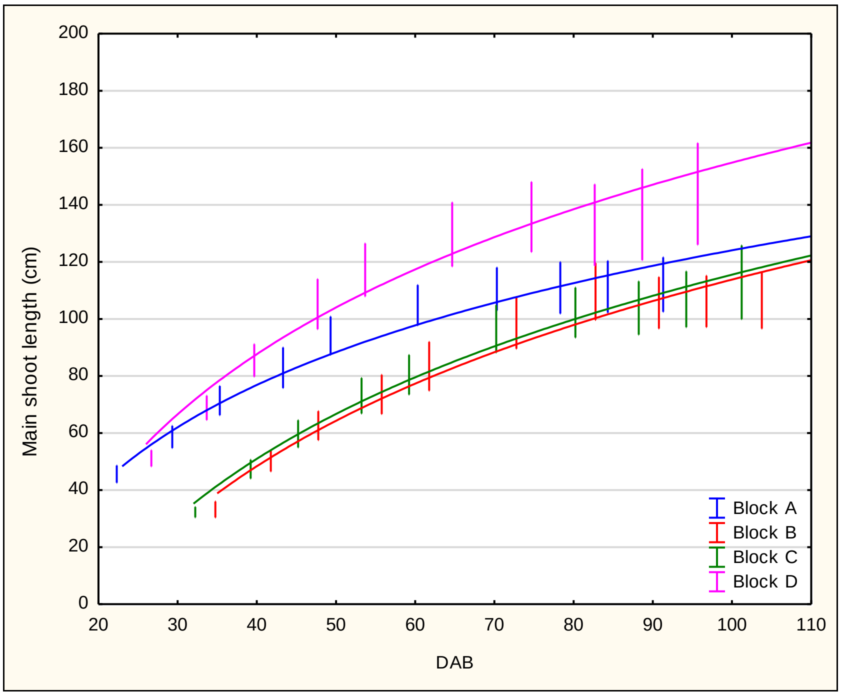

Figure 3.11: Main shoot length (cm) relative to date after budburst (DAB) of the four experimental blocks for the 2014/15 season. A distance weighted least squares fit was drawn. Spreads indicate standard errors.

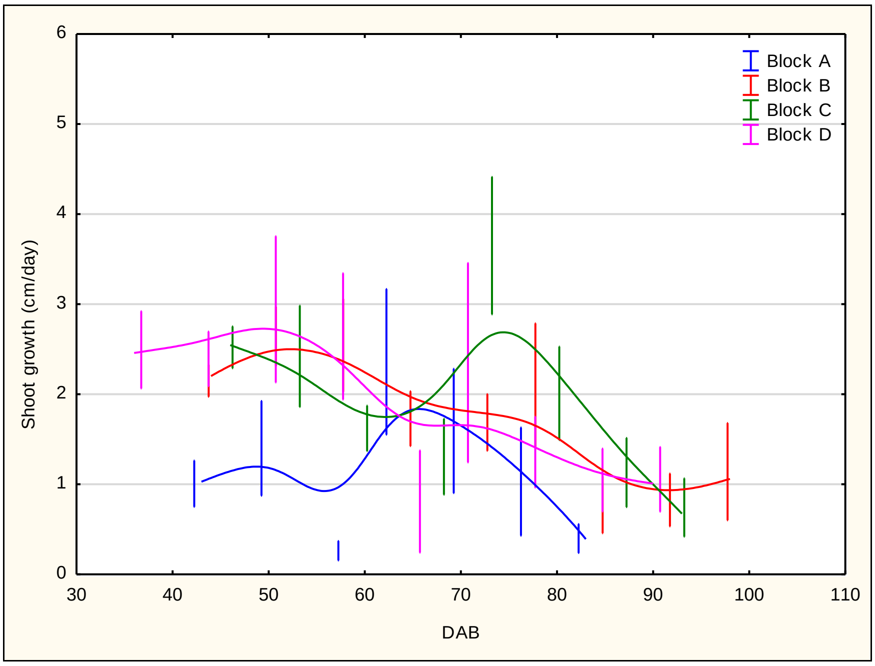

Figure 3.12: Shoot growth per day (cm) relative to date after budburst (DAB) of the four experimental blocks for the 2013/14 season. A distance weighted least squares fit was drawn. Spreads indicate standard errors.

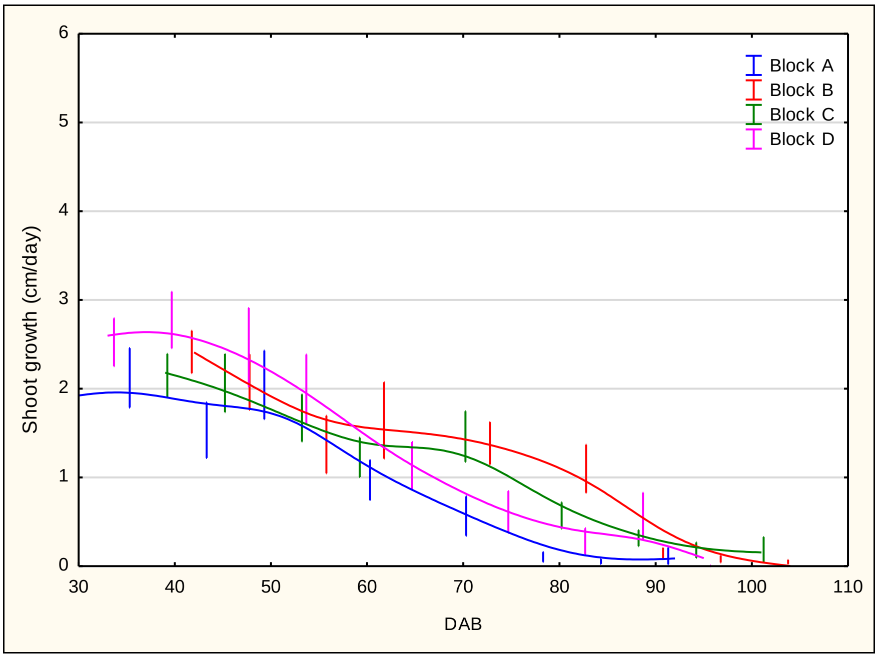

Figure 3.13: Shoot growth per day relative to date after budburst (DAB) of the four experimental blocks for the 2014/15 season. A distance weighted least squares fit was drawn. Spreads indicate standard errors.

Main shoot topping around véraison to allow more sun penetration in the bunch area for growth and proper colour development is a normal practice in table grape production (SATI, 2015). Consequently, an adjustment was necessary to account for topped shoot growth. Therefore, around véraison developing lateral shoots on marked topped shoots were measured to determine the topping effect on shoot growth. During the 2013/14 season, lateral shoot development was observed from 65 to 92 DAB. Thereafter, lateral shoot development stabilised until termination of shoot growth (Addendum A, Fig. A.3). In Block D, topping was done in a standardised way by cutting away all shoots that went over the last wire in order to allow proper sun penetration in the dense canopy of this block (Figure 3.14). The effect of this practice could clearly be seen in the lateral shoot measurements that indicated a rapid growth from 65 DAB until 80 DAB followed by a steady growth to termination of shoot growth (Addendum, Fig. A.3). During the 2014/15 season, Block C had fewer lateral shoots with less node development than the rest of the blocks, supporting the lower growth observed in this block (data not shown). This may be attributed to the fact that this is a vineyard block growing in loamy fine sand with low clay content. In addition, vigour could have been affected by little or not frequent enough irrigation. This is in agreement with Iland (2011) who reported that lateral shoot growth is restricted when the vineyard has low soil water content.

Figure 3.14: Images illustrating the standardised topping system in Block D.

3.3.7.2 Plastochron Index (PI)

In order to calculate the Plastochron Index (PI), nodes from the beginning of the shoot up to leaf L1 (more than 2.5 cm) were needed. Unfortunately, at the beginning of the 2013/14 season total shoot nodes were not recorded and PI could therefore not be determined up to 58 DAB (Figure 3.15). The PI in Blocks C and D was the highest, followed by Block B and lastly Block A during the 2013/14 season. An improvement in the PI for Block A was noted in the following season. In both seasons, Block A seemed to cease developing new nodes earlier than the other blocks. This might have been due to improper irrigation scheduling. Furthermore, this block had a salinity problem and it is highly likely that the irrigation scheduling was done in such a way that the block remained wet in summer to be able to control the salinity. Unfortunately, that had a negative effect on the block growth. Lower PI tempo was recorded for the 2014/15 season compared to the previous season (Fig. 3.16). Similar observations were observed for PI tempo as for the shoot growth tempo, of which Block A had a lower tempo compared to the other blocks during both seasons (Fig. 3.16).

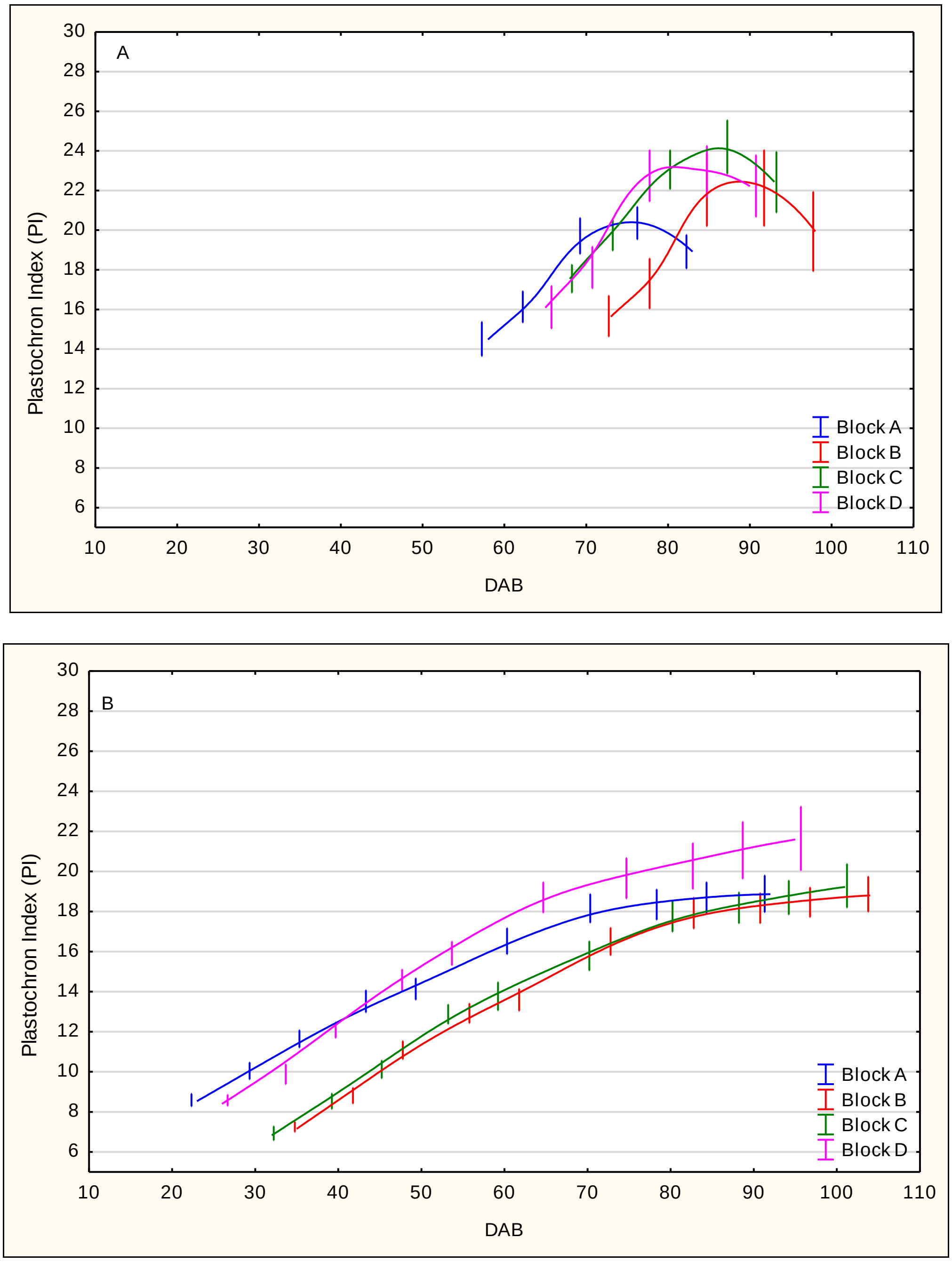

Figure 3.15: Plastochron Index (PI) relative to date after budburst (DAB) of the four experimental blocks for the (A) 2013/14 and (B) 2014/15 seasons. A distance weighted least squares fit was drawn. Spreads indicate standard errors.

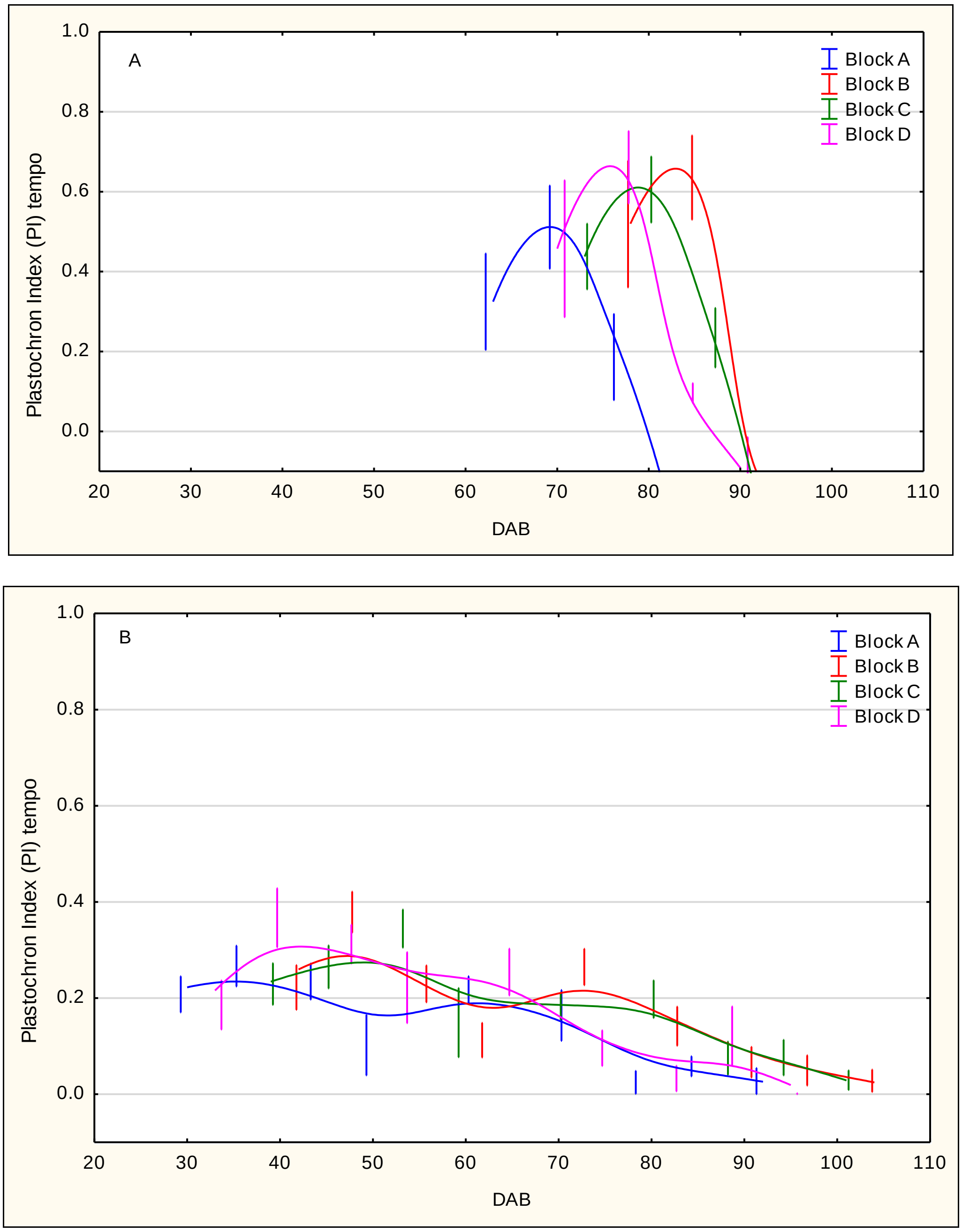

Figure 3.16: Plastochron Index (PI) tempo relative to date after budburst (DAB) of the four experimental blocks for the (A) 2013/14 and (B) 2014/15 season. A distance weighted least squares fit was drawn. Spreads indicate standard errors.

3.3.7.3 Leaf area

Shoot growth and LA increases as the season progress with weather conditions affecting it (Howell, 2001; Iland *et al.*, 2011). Detailed shoot and LA measurements at the different phenological stages during the 2013/14 season are presented in Table 3.6. Block A had shorter main shoots with fewer nodes at pea size and véraison (Table 3.6), whereas differences between Blocks B, C and D in terms of length and node number seemed insignificant. At harvest, Block A had more main shoot nodes than Block C and D. This is in support of the higher PI values recorded in Block A at this stage (Figure 3.15). Block D had longer main shoot internode length at véraison and harvest, confirming the vigorous growth in this block.

During the 2013/14 season, Block B showed larger main shoot LA than Block A and D at pea size (Table 3.6). Block C and D had vigorous shoot growth, therefore more canopy opening and shoot topping was done to improve sunlight interception to enhance colour development after véraison. The topping action had an effect on the shoots collected for LA measurements at harvest since most shoots in these blocks were topped. In a study on Redglobe (Strydom, 2006) reported main shoot LA in the range of 7.9-9 m^2. The reported LA values was higher than in the current study during the 2013/14 season but comparable to Block B and D's LA at pea size during the 2014/15 season. At pea size, Blocks A and D had shorter lateral shoots with fewer nodes on the selected main shoots (Table 3.6). Results indicated that Block A had slower vegetative growth and this might have been affected by the soil chemistry as well as the high soil water content. Block A also had a problem with berry colouring during the 2013/14 season and more canopy opening was done after véraison to aid berry colour development. This practice may have reduced LA in this particular block. Lateral shoots were stimulated by main shoot topping therefore vigorous growing blocks had more LA on their lateral shoots compared to the slower growing blocks. The lateral shoot LA of 6.94 m^2 reported by Strydom, 2006, was higher than all measured lateral LA in the current study.

Block B had a higher total LA at pea size and harvest during the 2013/14 season (Table 3.7). Total grapevine LA for Block B was 8.30 m^2, 8.70 m^2 and 10.50 m^2 at pea size, véraison and harvest, respectively. Block C had a total grapevine LA of 8.17 m^2, 9.98 m^2 and 9.83 m^2 at pea size, véraison and harvest respectively. During the 2014/15 season, the total grapevine LA at pea size for Blocks A, B, C and D was 6.69 m^2, 11.12 m^2, 9.31 m^2 and 11.83 m^2, respectively (Table 3.8). Total grapevine LA for Blocks B and C at pea size was higher in the 2014/15 season compared to the 2013/14 season. This can be ascribed to the higher GDD in the 2014/15 season which stimulated more vegetative growth. The total grapevine LA was lower than values reported by Links (2015) for the same cultivar in the same region. However, total LA in the current study was similar to values reported for a 33% shoot removal treatment, where the total LA for the 2011/12 season was10.41 m^2 (Links, 2015). The S33 treatment compared well with Block B's total grapevine LA at harvest in the 2013/14 season and was lower than Blocks B and D's grapevine LA at pea size during the 2014/15 season. Values of 8.57m^2, 8.49m^2, 8.08m^2 and 9.56m^2 for total grapevine LA, have been reported for Pirobella, Bien Donné, Ronnelle and Italia, respectively (Avenant,(1994). It was evident that the total LA at pea size and veraison for Blocks B and C during the 2013/14 season was in the same range. However, for the 2014/15 season Block B and D had higher grapevine LA at pea size.

Block B had a higher main to lateral LA ratio at all measured stages during the 2013/14 season (Table 3.7). Main to lateral LA ratio was highest in Block B and lowest in Block C in the 2014/15 season. The main to lateral LA ratio was higher in the 2014/15 season compared to the 2013/14 season, and this was most probably due to higher temperatures that stimulated more vegetative growth during the latter season. Blocks A, B, C and D lateral LA contributed about 18%, 15%, 27% and 22%, respectively, towards the total grapevine LA during the 2014/15 season. A slightly higher value of 29%, on average, was reported by Links (2015) for lateral leaf area contribution towards total grapevine LA for two shoot removal treatments over two seasons. In another study, lateral LA contribution towards total grapevine LA of 19%, 12%, 19% and 11% for Pirobella, Bien Donné, Ronnelle and Italia, respectively, was reported by Avenant (1994). Results from the current study are also in agreement with Iland *et al.* (2011), who reported that lateral shoots contributes approximately 6% to 40% towards total leaf area. It should be noted that, there are several factors such as cultivar, canopy manipulation and irrigation scheduling strategies which can affect the contribution of the lateral LA towards the total LA.

Table 3.6: Detailed shoot and leaf area measurements of the four experimental blocks at different phenological stages (pea size, véraison and harvest) for the 2013/14 season.

Phenological stage	Block	Main shoot length (cm)	Main shoot nodes	Main shoot internode length (cm)	Main shoot leaf area (cm^2)	Lateral shoot length per main shoot (cm)	Lateral shoot nodes per main shoot	Lateral internode length per main shoot (cm)	Lateral leaf area per main shoot (cm^2)
Pea size	Block A	86.85±12.87(1)	16±1.69	5.02±0.40	718.85±102.46	24.66±10.09	12±3.94	2.10±0.33	181.22±86.83
Pea size	Block B	133.63±12.28	18±1.53	7.56±0.58	1054.83±109.40	78.80±17.38	20±3.89	3.89±0.94	552.29±124.65
Pea size	Block C	133.95±15.20	18±1.12	7.23±0.58	890.09±119.06	94.86±30.01	22±5.89	3.71±0.41	543.32±196.04
Pea size	Block D	126.63±17.08	19±1.23	6.52±0.63	793.96±96.59	45.89±14.64	12±1.54	3.16±0.93	196.88±52.07
Véraison	Block A	122.04±11.98	21±1.23	5.79±0.36	1003.93±105.45	75.07±20.15	25±6.39	2.71±0.43	617.87±179.22
Véraison	Block B	144.49±17.28	21±1.66	7.01±0.56	1230.88±150.30	75.58±26.12	26±6.36	2.57±0.34	672.23±221.43
Véraison	Block C	161.63±20.76	24±2.31	6.45±0.56	1357.64±175.12	122.21±32.78	32±6.90	3.18±0.34	943.03±258.41
Véraison	Block D	172.62±18.65	22±1.74	7.71±0.59	1299.35±143.18	60.26±31.62	18±6.76	2.43±0.38	461.31±219.99
Harvest	Block A	158.43±16.50	25±1.78	6.04±0.33	1428.77±138.92	49.69±14.14	19±3.48	2.28±0.34	417.58±100.69
Harvest	Block B	166.36±21.19	22±2.01	7.31±0.50	1400.92±206.43	107.05±28.95	25±5.51	3.59±0.67	830.06±213.50
Harvest	Block C	151.87±17.77	21±1.60	7.27±0.65	1324.28±169.35	134.65±34.82	33±6.34	2.98±0.54	987.93±227.79
Harvest	Block D	152.69±13.95	20±1.31	7.77±0.65	1321.27±147.68	159.56±31.95	29±5.34	4.59±0.68	1079.71±253.68

(1) Values are means (n=15) ± standard errors of mean

Table 3.7: Grapevine shoot and leaf area measurements of two experimental blocks at different phenological stages (pea size, véraison and harvest) for the 2013/14 season.

Vegetative growth parameter	Phenological stage					
	Pea size		Véraison		Harvest	
	Block B	Block C	Block B	Block C	Block B	Block C
Mean main shoot length (cm)	134	134	144	162	166	152
Mean main area (m^2)	0.11	0.11	0.12	0.13	0.13	0.12
Main leaf area per vine (m^2)	6.16	5.96	6.65	7.16	7.63	6.74
Mean lateral length (cm)	79	95	76	122	107	135
Mean lateral leaf area (m^2)	0.06	0.07	0.06	0.09	0.08	0.10
Lateral leaf area per vine (m^2)	2.13	2.20	2.05	2.82	2.86	3.09
Total leaf area per vine (m^2)	8.30	8.17	8.70	9.98	10.50	9.83
Ratio main: lateral leaf area	2.89	2.71	3.25	2.54	2.67	2.18

(1) Leaf area was calculated from the 2013/14 season calibration curve

Table 3.8: Grapevine shoot and leaf area measurements of the four experimental blocks at pea size for the 2014/15 season.

Vegetative growth parameter	Phenological stage			
	Block A	Block B	Block C	Block D
Mean main shoot length (cm)	171	173	191	206
Mean main area (m^2)	0.14	0.14	0.15	0.17
Main leaf area per vine (m^2)	5.50	9.44	6.76	9.26
Mean lateral length (cm)	48	67	85	77
Mean lateral leaf area (m^2)	0.04	0.05	0.06	0.06
Lateral leaf area per vine (m^2)	1.19	1.68	2.55	2.58
Total leaf area per vine (m^2)	6.69	11.12	9.31	11.83
Ratio main: lateral leaf area	4.64	5.62	2.65	3.59

(1) Leaf area was calculated from the 2013/14 season calibration curve

3.3.7.4 Leaf morphology

In both seasons, there was an increase in DM, SLM, leaf thickness and leaf density as the season progressed (data not shown). In contrast, there was a reduction in SLA, LWCd and EWT as the season progressed, with higher values at pea size and lower values at post-harvest (data not shown). The SLM, DM, leaf thickness, leaf density and EWT increased with leaf size and light exposure, with small and shaded leaves being the lowest and sunny and hardy leaves being the highest (Table 3.9). This is in agreement with Strever (2012) who reported that the region in the canopy of high specific leaf mass shift from the lower parts to the apical parts as the season progresses. For the 2013/14 season, Blocks A and B had a tendency towards higher DM and SLM in the small and shaded as well as the sunny and hardy leaves at pea size. During the 2014/15 season no comparable differences were found in the DM and SLM at the different stages in the lateral optimal as well as the sunny hardy leaves. However, Block A had a tendency towards higher DM and SLM at harvest in the optimal leaves (Table 3.9). Block D indicated tendencies towards lower DM and SLM in all its leaf types in both seasons. This is probably due to shading in the dense canopy as well as the low soil water content measured during the 2014/15 season. Poni *et al.* (1994) and Cartechini and Palliotti (1995) has shown a correlation between SLM and photosynthesis in grapevine. Niinemets (1999) also reported a positive correlation between photosynthesis and leaf thickness as well as leaf dry mass in woody plants.

During the 2013/14 season, Blocks C and D had a tendency towards higher SLA at pea size in the small and shaded, as well as the optimal leaves. Furthermore, Block D indicated higher tendencies of SLA in the small and shaded, as well as the optimal leaves at pea size and post-harvest in both seasons. No comparable differences in SLA were observed in the sunny and hardy leaves among the different blocks at all stages in both seasons.

Leaf thickness and density increased with an increase in leaf size throughout the season (data not shown). The hardy sun exposed leaves were thicker and denser than the small and shaded, optimal and lateral optimal leaves at the different phenological stages in both seasons. Measured leaf thickness was in the range of 0.27 to 0.40 mm in both seasons. Blocks A and B had a tendency towards thinner leaves during the 2013/14 season that could have been affected by the lower Ψ_S measured in those blocks at the different phenological stages. Blocks B and D had thicker leaves during the 2013/14 season (Table 3.9). Conversely, Block C and D indicated higher tendencies in leaf thickness in all the leaf types, compared to the other blocks during 2014/15 season. At post-harvest in the 2014/15 season, all leaf types in Blocks B and D tended to be thinner leaves with the exception of sunny, hardy leaves of Block B (Table 3.10). Leaf size and thickness affects CO_2 and water vapour fluxes in and out of the leaves due to the variation of the leaf boundary layers and enhancement of WUE (Stanhill, 1986). Thinner leaves are reported to have a lower WUE compared to similar thicker leaves (Stanhill, 1986). The lower WUE of thinner leaves is believed to be caused by the lower ratio of internal volume in comparison to leaf surface area (Bacon, 2004). Block D had tendencies towards lower leaf density in all the leaf types at the different stages probably due to the denser canopy (Table 3.9 & 3.10). This is in agreement with Witkowski and Byron (1991) who reported that higher light intensity may increase leaf density. Block A had tendencies towards higher leaf density during the 2013/14 season. In Block C, leaf density tended to be lower in all leaf types at all stages, whereas Block D indicated lower tendencies at harvest during 2014/15 season (Table 3.10).

Small and shaded leaves and optimal leaves had tendencies towards higher LWCd compared to sunny hardy leaves while the opposite was observed for EWT in all blocks (Table 3.9). Block D tended to have higher LWCd in all the leaf types, while similar tendencies of EWT were observed among the different leaf types in all blocks during the 2013/14 season. No comparable differences were found in the EWT between the blocks at the different phenological stages, except for Block A that had lower tendencies at post-harvest during 2013/14. During the 2014/15 season, Blocks A and C had apparent lower LWCd and EWT in all its leaf types at harvest (Table 3.10). Furthermore, there was no comparable difference between the optimal and lateral optimal leaf attributes during the 2014/15 season. However, lateral optimal leaves seemed to be higher. Blocks B and D had a higher LWCd and EWT during both seasons. Since leaf water content is influenced by the specific leaf mass, this attribute could be a possible good indicator of plant water status. This study revealed that leaf water content decreases with an increase in SLM. Similar tendencies for leaf water content and SLM was reported by Strever (2012). Water deficits reduce leaf area, leave number per shoot, leaf size and thickness (Witkowski & Byron, 1991), affecting transpiration efficiency (Bacon, 2004). Witkowski and Byron (1991) also indicated the important role leaf morphological attributes such as leaf thickness, density and specific leaf mass can play in determining plant physiological responses to environmental conditions.

Table 3.9: Leaf attributes of the four experimental blocks at harvest in the 2013/14 season. Increasing shades of green indicates higher values while increasing shades of red indicates lower values.

Block	Leaf type	DM (g)	Leaf thickness (mm)	Leaf density	SLM (g/cm^2)	SLA (cm^{-2}. g)	LWCd (%)	EWT (g/cm^2)
A	Small and shaded	0.0075(1)	0.3063	0.0124	0.0037	273.9552	290.5072	0.0106
	Optimal	0.0147	0.3070	0.0241	0.0073	142.5573	172.4514	0.0121
	Sunny and hardy	0.0144	0.3530	0.0207	0.0072	151.0509	204.6555	0.0132
B	Small and shaded	0.0066	0.2927	0.0113	0.0033	322.0925	319.5368	0.0102
	Optimal	0.0101	0.3727	0.0137	0.0050	206.2927	254.1192	0.0124
	Sunny and hardy	0.0149	0.3987	0.0190	0.0074	139.0998	196.7933	0.0142
C	Small and shaded	0.0072	0.2927	0.0126	0.0036	283.3050	297.1234	0.0106
	Optimal	0.0122	0.3033	0.0202	0.0061	166.5105	185.6593	0.0111
	Sunny and hardy	0.0154	0.3767	0.0207	0.0076	133.5588	177.3462	0.0133
D	Small and shaded	0.0059	0.2657	0.0113	0.0029	343.1823	341.8596	0.0100
	Optimal	0.0099	0.3220	0.0153	0.0049	211.5255	271.1512	0.0128
	Sunny and hardy	0.0130	0.4040	0.0165	0.0065	163.5015	223.6563	0.0136

(1) Values are means of 3 leaves

Table 3.10: Leaf attributes of the four experimental blocks at harvest for the 2014/15 season. Increasing shades of green indicates higher values while increasing shades of red indicates lower values.

Block	Leaf Type	DM (g)	Leaf thickness (mm)	Leaf density	SLM (g/cm^2)	SLA (cm-^{2}. g)	LWCd (%)	EWT (g/cm^2)
A	Optimal	0.0139(1)	0.3077	0.0226	0.0069	146.6134	72.6987	0.0049
	Lateral Optimal	0.0124	0.2867	0.0213	0.0062	175.7141	80.4536	0.0050
	Sunny and hardy	0.0167	0.3790	0.0220	0.0083	122.2921	79.3978	0.0065
B	Optimal	0.0105	0.2723	0.0192	0.0052	193.6198	205.8843	0.0106
	Lateral Optimal	0.0138	0.3020	0.0227	0.0068	152.5345	153.8560	0.0103
	Sunny and hardy	0.0162	0.3570	0.0228	0.0080	124.7448	140.4935	0.0113
C	Optimal	0.0126	0.3456	0.0181	0.0062	165.7510	89.8603	0.0055
	Lateral Optimal	0.0129	0.3243	0.0198	0.0064	162.3959	82.5196	0.0053
	Sunny and hardy	0.0143	0.3617	0.0196	0.0071	142.3611	75.8742	0.0054
D	Optimal	0.0113	0.3510	0.0161	0.0056	179.0140	226.9818	0.0127
	Lateral Optimal	0.0116	0.2820	0.0202	0.0058	183.5054	192.6501	0.0107
	Sunny and hardy	0.0144	0.3787	0.0188	0.0071	146.3221	184.7541	0.0128

(1) Values are means of 3 leaves

There was a strong positive linear correlation between leaf density and SLM (Figure 3.17), while a weak correlation was noted between the average leaf thickness and SLM (data not shown). There was a strong negative correlation between LWCd and SLM (Figure 3.18). Block A leaf density had a strong correlation to SLM (r^2 = 0.81) compared to Blocks B and D with r^2 of 0.63 and 0.64, respectively. Based on the strong correlation of LWCd and SLM observed in all the blocks, it can be concluded that LWCd increases with a reduction in SLM (Fig. 3.18).

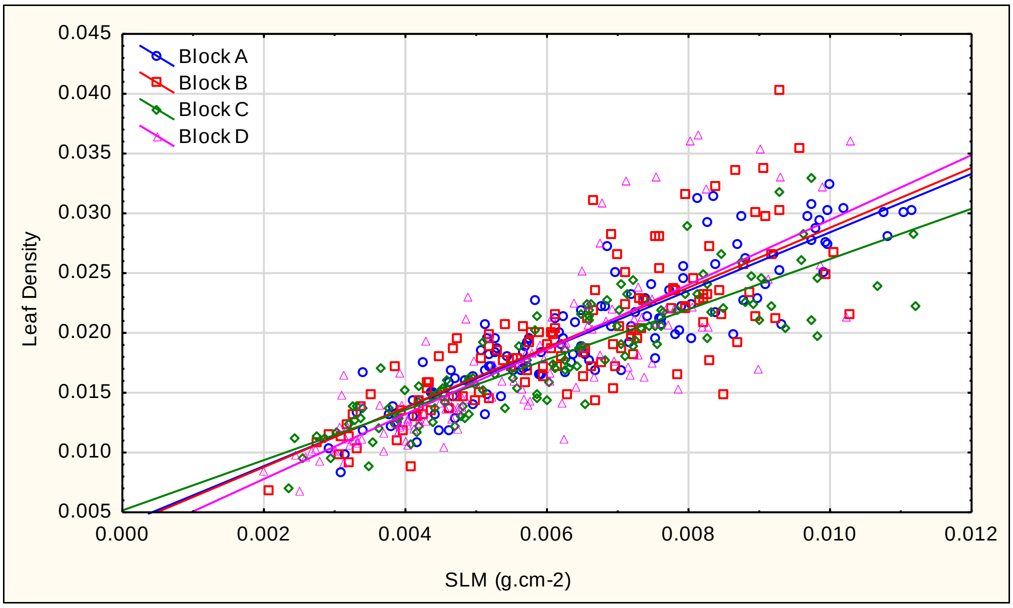

Figure 3.17: Relationship between leaf density (LD) and specific leaf mass (SLM) of the four experimental blocks for combined seasons 2013/14 and 2014/15 (Block A: r^2 = 0.81; Block B: r^2 = 0.63; Block C: r^2 = 0.77; Block D: r^2 = 0.64).

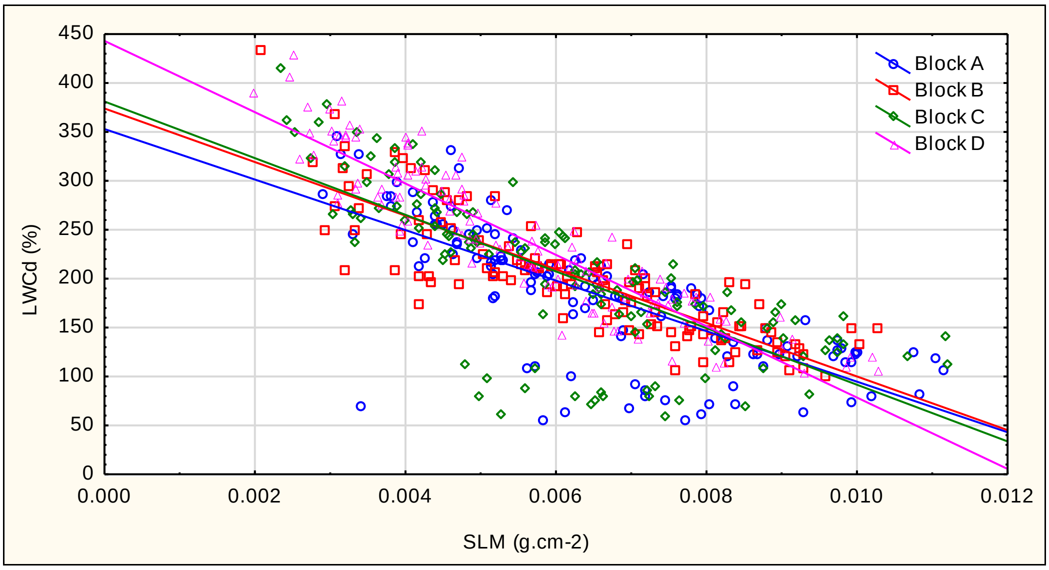

Figure 3.18: Relationship between leaf water content (LWCd) and specific leaf mass (SLM) of the four experimental blocks for combined seasons 2013/14 and 2014/15 (Block A: r^2 = 0.75; Block B: r^2 = 0.85; Block C: r^2 = 0.75; Block D: r^2 = 0.92).

3.3.7.5 Pruning measurements

In both seasons, Block D had higher average winter pruning mass compared to the other blocks (Figure 3.19). Despite the fact that the neutron probe measurements indicated that this block had lower water content, it had vigorous growth. This can be attributed to the fact that this block's soil had a higher carbon percentage and is probably managed well. Furthermore, Block D soil has higher clay content irrespective of the large stones, and may have very good root distribution and buffer capacity that contributed to this block's productivity. Blocks A, B and C indicated similar average pruning mass for both seasons. Pruning cane mass obtained in this study during both seasons was higher than the pruning cane mass reported by Links (2015) for the same cultivar in the same area. There have been very few studies done on Crimson seedless grapes, therefore pruning mass were compared to comparable mature vigorous growing table grape cultivars such as Sultanina and Festival Seedless (Sugraone). The cane mass at winter pruning was higher than the 1.26 kg/vine reported for ungrafted Sultanina (Clone H4) by Myburgh (2003b) and 1.20 kg/vine for own-rooted Sultanina (Clone14/2) reported by Myburgh and van der Walt (2005). However, Avenant (1998) reported 3.61 kg/vine for Festival.

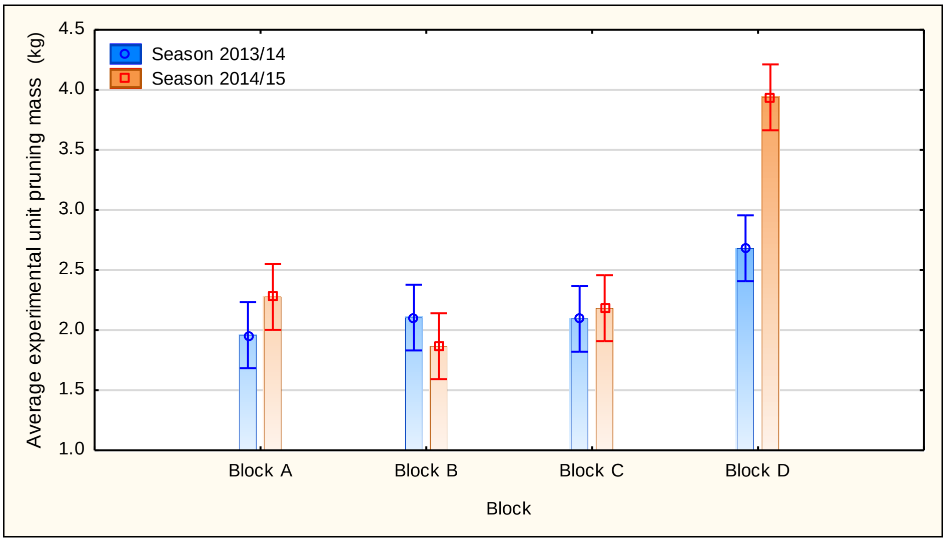

Figure 3.19: Average experimental unit pruning mass (kg) of the four experimental blocks for the 2013/14 and 2014/15 seasons. Vertical bars denote 95% confidence intervals.

3.4 Conclusions

Since the 2014/15 season had a faster accumulation of heat units compared to the 2013/14 season, it was approximately a week earlier in phenology from bud burst to harvest. The four selected blocks showed great variability in terms of their soil and vegetative growth responses. Block A was the wettest block throughout the growing season, whereas Block D was the driest. This was likely due to its high stone fraction. Block C had the highest seasonal irrigated volumes and a higher ET, followed by Blocks B, A and lastly D. Block D had vigorous vegetative growth in both seasons and that was confirmed by higher average winter pruning. Higher clay carbon and contents, combined with good management practices, probably contributed to the higher vegetative growth. In contrast, Block A had poor vegetative growth. The wetness of the soil as well as saline soil conditions probably caused the poor growth. It appeared as if irrigation system had an effect on vegetative growth. In this regard, grapevine growth in Blocks B and C was slower in the 2014/15 compared to the 2013/14 season. Micro-sprinkler irrigation systems were used to irrigate these two particular blocks. The second season was drier and warmer than the first, leading to more water loss through evapotranspiration. Hence, there was a negative impact on vegetative growth.

Stem water potential was highest at pea size and lowest at harvest. Results showed that Ψ_S was highest in the early morning, followed by a steady decline until 14h00 and partial recovery for the remainder of the day. At harvest, midday Ψ_S was lower in Blocks C and D. There was an increase in DM, SLM, leaf thickness, leaf density as the season progressed but SLA, LWCd and EWT decreased. Specific leaf mass, DM, leaf thickness, leaf density and EWT were related to leaf size and light interception. Block D tended to have lower DM and SLM in all leaf types probably due to the denser canopy, whereas Blocks B and D had higher SLA and LWCd. Blocks A and B had a tendency towards thinner leaves that could have been affected by the lower Ψ_S in those blocks phenological stages.

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Chapter 4

Research results

Selected physiological parameters, reproductive indicators and yield water use efficiency of Crimson Seedless grapevines

CHAPTER IV: SELECTED PHYSIOLOGICAL PARAMETERS, REPRODUCTIVE INDICATORS AND YIELD WATER USE EFFICIENCY OF CRIMSON SEEDLESS GRAPEVINES

4.1 Introduction

Due to the increasing pressure on scarce water resources especially in semi-arid countries, sustainable table grape production calls for higher water use efficiency (WUE) (Howell, 2001b; Tomás *et al.*, 2012). In order to increase WUE at farm level, a more holistic approach on irrigation scheduling is needed that will take into account: a) quantification of crop water use, b) yield response to applied water and c) the right tools to determine when to irrigate as well as plant stress indicators (Williams *et al.*, 2010). Thus, optimal irrigation is needed for improved WUE. Optimal irrigation can be defined as a strategy that would minimise drainage and evaporation while improving WUE. Stringent water budgets are required in table grape production to improve WUE. The need to optimise WUE is aggravated by the fact that table grapes, which are mostly cultivated in warm and dry conditions, have large canopies with large leaf area indices. Grapevine growth and yield are influenced by different factors such as climate, soil moisture, grapevine nutrient status and vineyard management (Myburgh, 1996; Chaves *et al.*, 2007; Jones, 2007). Proper management is therefore required to conserve scarce water resources and improve WUE in table grape production, thus the need to reduce irrigated water while maintaining the table grape industry economically sustainable (Jarmain *et al.*, 2007).

There is a need to balance vegetative and reproductive growth, since vigorous vegetative growth can have a negative impact on fruit quality (Chaves *et al.*, 2007). In addition, Chaves *et al.* (2007) indicated that under optimal irrigation (therefore no over-irrigation), vegetative parts of the grapevines are not strong sinks, therefore assimilates are channelled towards reproductive development. Plant water status plays an important role in the physiological processes of a grapevine, since stressed vines have lower plant water potential, transpiration, stomatal conductance and photosynthetic activity (Iland *et al.*, 2011). A reduction in photosynthesis due to limited soil water availability is reported to reduce net carbon assimilation, grapevine growth and yield (Medrano *et al.*, 2003). In addition, Flexas *et al.* (2010) reported that prolonged plant moisture stress, high vapour pressure deficits (VPD), high irradiance and temperature can have a negative impact on yield and quality. It is also important to allocate the correct crop load to obtain a high percentage of export quality grapes. An excessively high crop load results in grapes of inadequate berry size, poor colour development, low sugar, flaccid grapes, poor taste and poor shelf life (SATI, 2015). Furthermore, high crop loads can lead to increased water consumption and water stress (Saayman & Lambrechts, 1995). Moreover, grapevines respond to water deficit by reducing leaf area and plant growth in order to reduce transpiration while increasing WUE (Xu & Zhou, 2008).

Few studies have been conducted on table grape yield WUE relating yield to water use either as evapotranspiration or irrigated volumes (Araujo *et al.*, 1995; *Yunusa et al.*, 1997a; Yunusa *et al.*, 1997b; Myburgh, 2003b; Jarmain *et al.*, 2007). Therefore, the aim of this study is to determine the effects of differing soil texture classes and differing irrigation systems on Crimson Seedless table grapes physiology, yield, fruit quality and yield water use efficiency (WUE_y). Selected physiological parameters such as net carbon assimilation rate, stomatal conductance and leaf temperature will be linked to berry size, yield and WUE_y to compare the performance under the differing cultivation conditions.

4.2 Materials and Methods

The experiment layout, scenarios, climatic conditions, soil conditions and soil water status measurement methodology are described in Chapter III. Therefore, only relevant additional details are given here.

4.2.1 Infrared gas analyser measurements

Photosynthetic capacity and leaf gas exchange were measured during the 2013/14 and 2014/15 seasons. Net carbon assimilation rates (A), stomatal conductance (gs) and transpiration rates (E) were measured with an infrared gas analyser (IRGA) chamber (LI-6400, Li-Cor, Lincolin, Nedbraska, USA). The flow rate to the sample cell, reference CO_2 and quantum flux on the IRGA was controlled to the following values, respectively: 500 µmol.s^{-1}, 380 µmol CO_2.mol^{-1} and 1500 µmol.m^{-2}.s^{-1} for all measurements. During the 2013/14 season, two vines that were randomly selected based on the stem diameter in all blocks (A, B, C & D) were measured during four different phenological stages (pea size berries, véraison, harvest & post-harvest). Due to logistical constraints regarding available equipment, it was decided to only conduct diurnal cycles at two of the four blocks for the next season. Consequently, only one vine in Blocks B and D were measured to determine diurnal cycles at the above-mentioned phenological stages for the 2014/15 season. The diurnal cycle measurements were done on the same leaf from 08:00 to 16:00 at two-hour intervals. Five leaves per grapevine were selected for the IRGA measurements in both seasons. These leaves were selected in categories as follows: one small shaded leaf, three fully expanded leaves, and a hardy sun exposed leaf for the 2013/14 season. Since there were no apparent differences between the small shaded leaves in all blocks in the 2013/14 season, it was decided to replace the small shaded leaf with a lateral fully expanded leaf for the 2014/15 season. In addition to the IRGA measurements, stomatal conductance was measured with a leaf porometer (Delta-T AP4, Cambridge, England and Decagon Devices, Inc., Pullman, WA). Leaf temperature (TLeaf) and vapour pressure deficit (VPD) measurements were also measured using the IRGA.

4.2.2 Light measurements

Canopy light measurements were conducted with an AccuPAR LP-80 ceptometer (Decagon Devices, Inc., Pullman, WA) in both seasons. Measurements were taken at the end of leaf gas exchange measurements per block and are expressed as a ratio of ambient radiation measured in units of µE.m^{-2}.s^{-1}. Four above canopy measurements were taken to calibrate the instrument where after measurements below the canopy (30 cm below the trellising wire) were done at three positions. Selected positions were as follows: 1st wire (low), 4th wire (middle) and 6th wire (high). During the 2014/15 season, ceptometer readings were taken with the midday measurements (12:00-14:00) for all four blocks. In the 2014/15 season, the ratio of red: far red (660:730 nm) radiation was also measured around the leaf where gas exchange was measured using an R:FR sensor (Skye instruments, Powys, UK). These measurements were taken in conjunction with the IRGA measurements.

4.2.3 Reproductive measurements

4.2.3.1 Yield and its components

At harvest, yield (kg/vine) and export mass (kg/vine) of the marked data vines in all experimental units were determined. Grapes were sorted and classified according to the industry quality standards into the following classes: Class 1 (Export), Class 2 (Local) and Class 3 (Cull) (Department of Agriculture, 2016).

4.2.3.2 Berry sampling and analysis

A random sample of 50 berries for each of the ten experimental units at each block was collected weekly from véraison to harvest for monitoring progression of berry ripening and quality evaluation in both seasons. However, for the 2014/15 season, berry sampling was done few weeks before harvesting (two to four weeks) in order to capture the final ripening stage before harvesting. After sampling, grapes were transported to the laboratory. Berry fresh mass (g) was determined with a digital scale, while the diameters (mm) were measured in the centre of the berry with a digital calliper. Grape samples for each of the ten experimental units were homogenised with a blender and juice was sieved into a clean measuring glass, from which 50 mL juice sample was extracted with a pipet for analysis. Total soluble solid concentration (TSS) was determined using a digital pocket refractometer (Atago PAL-1, Tokyo, Japan). Total titratable acidity (TTA) and pH was measured with an automatic titration device (Metrohm 785 DMP Titrino, Herisau, Switzerland). During the 2014/15 season, berry volume (mL) was also determined by water displacement.

4.2.3.3 Total anthocyanin analysis

Random samples of 50 berries per five experimental units were sampled as already described in Section 4.2.3.2. Samples collected throughout ripening were frozen at -20°C until further processing. An extraction solvent ethanol/water 50/50 (v/v) adjusted to pH 2 with 37% HCl was prepared. Anthocyanin extraction from berry skins (Iland/AWRI method – adapted) was used to determine the total anthocyanins (Iland *et al.*, 2000). Berries were defrosted to facilitate the peeling process and 25 of the 50 berries were randomly selected. Berry skins were removed from the pulp using blades. Thereafter, berry skins were weighed. After extraction solvent (5 mL) was added to the berry skins, samples were homogenised with a homogeniser (IKA T18 basic, Germany) until smooth. Samples of 2 g homogenate were transferred to 50 mL Falcon tubes. The extraction solvent was then added to the Falcon tube at a ratio of 10 mL of solvent for 1 g of berry skin. Tubes were capped and the contents were mixed periodically by inverting the tube every 10 minutes over a period of 1 hour. After an hour, the tubes and contents were put in a centrifuge (Hermle Labortechnik GmbH, Germany) and centrifuged at 10 000 rpm for 5 min. During the 2013/14 season, the extract was scanned in an Analytic Jena Specord 50 UV−vis spectrophotometer (Jena, Germany), using a 10 mm path length quartz cuvette. A cuvette with extraction solvent was used as the reference blank. Unfortunately, during the 2014/15 season, the Specord spectrophotometer was not working so a Thermo Scientific Multiskan GO (Thermo Fisher Scientific Oy, Vantaa, Finland) spectrophotometer was used instead. As in the previous season, a 10 mm path length quartz cuvette, with extraction solvent as the reference blank, was used. In both seasons, absorption of the extract was read at 520 nm wavelength.

4.2.4 Yield water use efficiency and irrigation water use efficiency

Evapotranspiration was only determined from the second week of December until August during the 2014/15 season and did not account for the whole season. Therefore, the seasonal irrigation volumes for both seasons were determined in order to calculate irrigation WUE. The WUE_y is defined as total harvested yield per unit of water use (ET) (kg/m^3 or mm), whereas the irrigation water use efficiency (WUE_{irr}) is defined as total harvested yield per unit of irrigated volume (kg/m^3 or mm).

Estimated ET and seasonal irrigation volumes (m^3) were divided by the yield (kg/ha) per block to determine WUE_y and WUE_{irr}. The following equations were used to calculate WUE_y and WUE_{irr}:

$WUE_y = Y/ ET\ (kg/m^3)$ (Eq. 4.1)

$WUE_{irr} = Y/ I\ (kg/m^3)$ (Eq. 4.2)

where Y is yield, ET is estimated ET from the water balance calculations (December–April) and I is seasonal irrigation volumes (September–April), respectively. Four different WUE_y calculations were done based on the type of ET correction used (Refer to Chapter 3). Thus, the following abbreviations were used for the uncorrected water balance method ($WUE_{y(ET)}$), ET corrected with published crop factors from Lategan (1996) ($WUE_{y(ETL)}$) and (Myburgh, 2003b) ($WUE_{y(ETM)}$) and ET corrected with FruitLook derived crop factor ($WUE_{y(ETFL)}$) as already discussed in Chapter 3.

4.2.5 Statistical analyses

Statistical analyses and graphs were done using Statistica 10 ® software (Statsoft, Tulsa, UK).

4.3 Results and discussion

Results will be presented with the physiological measurements results including net carbon assimilation rate, stomatal conductance and leaf temperature being presented first, in order to link them to the reproductive parameters such as berry size, yield and then finally WUE_y.

4.3.1 Infrared gas analyser measurements

In the 2013/14 season, four blocks were measured per day and it was only possible to measure two blocks in the morning. Hence, Blocks B and D were measured before midday while Blocks A and C were measured in the afternoon. Stomatal conductance measured in these blocks were much lower than values reported in literature (Cifre *et al.*, 2005; Chaves *et al.*, 2007) for both seasons. There was probably a calibration issue with the IRGA that affected the vapour measurements that might have affected stomatal conductance, transpiration and leaf VPD values. Therefore, only the net carbon assimilation rate is reported here. To explain the differences observed in the physiological measurements, it is important to consider the prevailing weather conditions at the specific measuring time. Thus, during the 2013/14 season, the duration of the measurements in a block was recorded and mean temperature, radiation, vapour pressure deficit, wind speed and relative humidity for the specific period was calculated. Most of the physiological measurements during the 2013/14 season lasted for about two hours and an average between two hours intervals (hourly data) was calculated for the data presented in Table 4.1. For the 2014/15 season, day cycle's measurements were done in Blocks B and D and prevailing weather conditions for that season is given in Table 4.2. The weather data for the 2013/14 season was obtained from the ARC automatic weather station (AWS) except for the wind speed and radiation values. The latter mentioned values seemed to be incorrect and thus obtained from the De Vlei AWS (5 km from the ARC AWS). Since the ARC AWS was not working during the 2014/15 season, the 2014/15 season's data was obtained from the Modderdrift AWS (3 Km from the ARC AWS). The 2014/15 season's vapour pressure deficit (VPD) was calculated using the following equation:

$VPD\ (Pascals) = \{1-(RH \div 100)\} \times SVP$ (Eq. 4.3)

where RH is the relative humidity and SVP is the saturated vapour pressure.

$SVP = 610.7 \times 10^{7.5T/(237.3+T)}\quad (kPa)$ (Eq. 4.4) where T is the ambient temperature.

Table 4.1: Mean$^{(1)}$ temperature, radiation, vapor pressure deficits, wind speed and relative humidity at the specific block measurement time as obtained from the ARC and De Vlei weather stations (De Doorns) at the different phenological stages in the 2013/14 season.

Phenological stage	Block	Temperature (°C)	Radiation (w/m^2)	VPD $^{(2)}$ (kPa)	Wind Speed (m.s^{-1})	Relative Humidity (%)
Pea size	A	28.47	0.40	2.70	1.34	30.74
	B	18.62	0.90	1.24	1.36	42.51
	C	23.56	0.90	1.95	2.34	33.16
	D	24.30	0.40	1.70	2.55	44.59
Véraison	A	34.09	3.39	3.88	1.18	27.46
	B	30.85	3.46	2.80	1.18	37.80
	C	33.75	2.29	3.60	2.17	31.76
	D	25.87	2.05	1.56	1.55	53.54
Harvest	A	33.42	2.98	3.90	1.05	24.87
	B	18.84	1.28	1.00	1.14	54.58
	C	31.03	3.25	3.25	1.18	28.22
	D	24.94	1.71	1.72	1.61	46.58

(1) Values are means (n = 2)

(2) Vapour pressure deficit.

Table 4.2: Hourly temperature, radiation, vapour presure deficit, wind speed and relative humidity at the specific phenological stage measurements as obtained from Modderdrift weather station (De Doorns) in the 2014/15 season.

Phenological stage	Time	Temperature (°C)	Radiation (w/m^2)	VPD (kPa)	Wind Speed (m.s^{-1})	Relative Humidity (%)
Pea size	06:00	13.70	0.02	0.22	0.55	86.10
	08:00	18.90	0.63	0.70	0.76	68.00
	10:00	24.80	2.83	1.68	1.02	46.30
	12:00	27.10	3.57	2.03	2.05	43.40
	14:00	28.60	3.56	2.21	3.26	43.40
	16:00	28.90	2.81	2.24	3.36	43.80
	18:00	27.60	1.48	2.07	3.28	43.90
Harvest	06:00	15.20	0.00	0.25	0.44	85.50
	08:00	18.60	0.09	0.36	0.62	83.40
	10:00	28.30	2.16	1.98	1.04	48.50
	12:00	33.10	3.29	3.26	1.16	35.50
	14:00	35.10	3.54	3.71	2.59	34.30
	16:00	38.00	3.03	5.29	2.66	20.10
	18:00	36.80	1.80	4.69	2.41	24.40
Post-harvest	06:00	12.00	0.00	0.18	0.71	87.00
	08:00	13.30	0.01	0.27	1.05	82.20
	10:00	19.30	0.73	0.78	1.06	65.10
	12:00	24.70	2.37	1.70	1.20	45.20
	14:00	29.70	2.76	2.80	0.95	32.90
	16:00	30.40	2.30	2.88	1.90	33.60
	18:00	28.30	0.76	2.33	2.99	39.30

Season 2013/14

Block D had a tendency towards a higher net carbon assimilation rate at pea size, véraison and harvest (Fig. 4.1). This block was measured mid-morning and the weather condition (Table 4.1) might have been favourable for the net carbon assimilation rate. Leaf type analysis did not show apparent differences in the net carbon assimilation rate between the small shaded and optimal leave types in the different blocks at all measured phenological stages (Fig. 4.1). However, sunny hardy leaves in Block D had a tendency towards a higher net carbon assimilation rate at véraison and harvest compared to Blocks A and B. Block C's net carbon assimilation rate at harvest, as well as all measurements in Block D were within ranges reported by Cifre *et al.* (2005) and Chaves *et al.* (2007). The sunny hardy leaves in Blocks B, C and D had a higher net carbon assimilation rate, followed by the optimal and lastly the small shaded leaves. On the contrary, Block A's optimal leaf indicated a higher net carbon assimilation rate at véraison and harvest compared to sunny hardy leaf type. This is an indication that larger and sun exposed leaves are more productive than smaller shaded leaves.

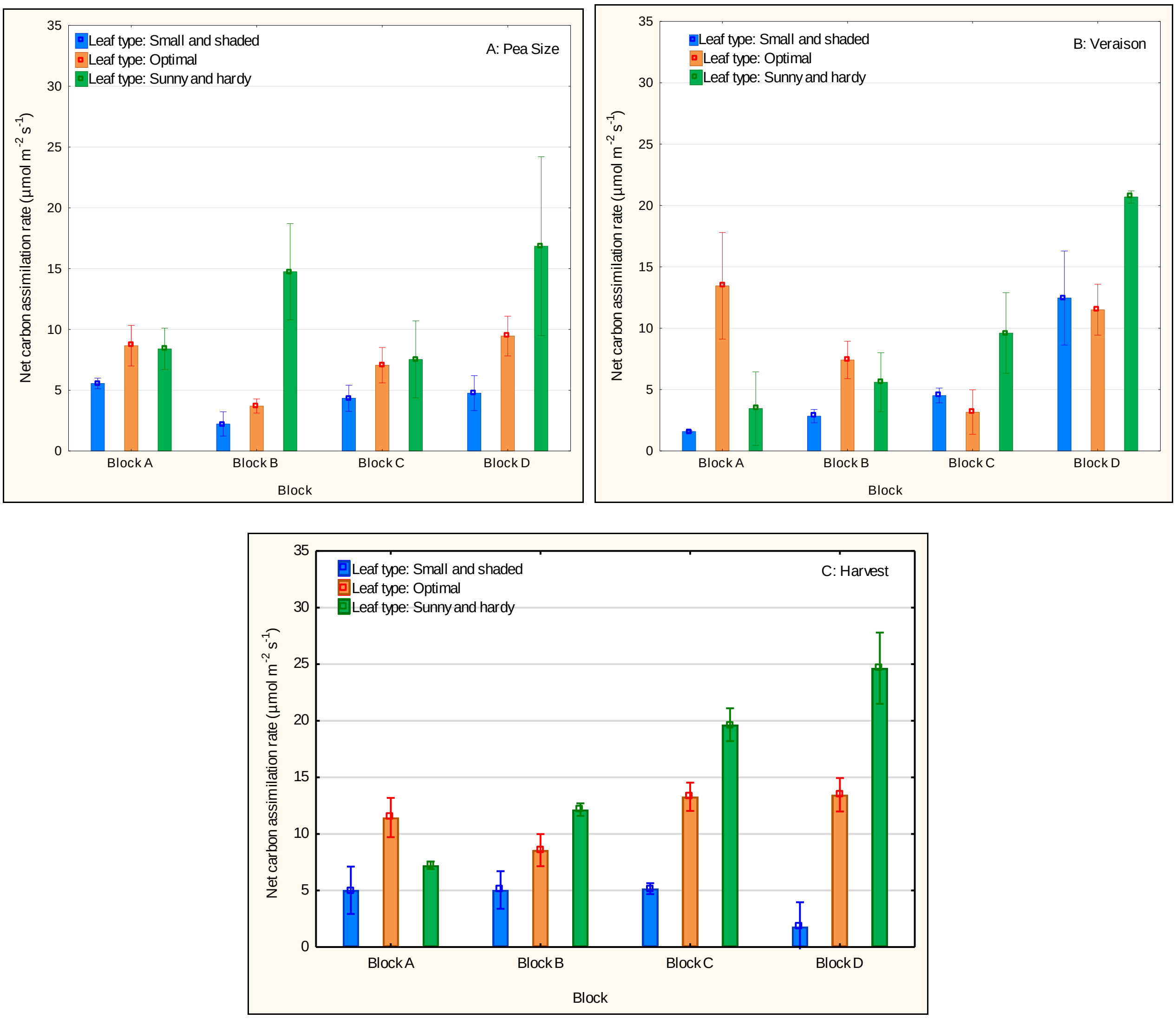

Figure 4.1: Net carbon assimilation rate (µmol m^{-2} s^{-1}) of the four experimental blocks at (A) pea size, (B) véraison and (C) harvest measured on different leaf types (small shaded, optimal & sunny hardy) for the 2013/14 season (means with +/- standard error shown).

Stomatal conductance (gs) indicated a trend of higher conductance in Blocks B and D at véraison (Fig. 4.2). Moreover, Blocks C and D had higher gs trends at harvest, while Block C's conductance remained higher at post-harvest. During the measurements, it was observed that net carbon assimilation rates and gs were declining midday due to higher temperature and higher VPD (Table 4.1). Other researchers also found similar trends in their studies (Lebese, 2008; Schultz & Stoll, 2010; Rogiers *et al.*, 2012). Block A had a tendency towards lower gs at véraison and harvest. This is likely due to the prevailing afternoon weather conditions, combined with the low stem water potential measured in this block. Previous studies by Lakso (1985), Jones (2008) and Schulze et al. (1993) indicated that plant water deficits affect both net carbon assimilation and gs as noted in this block. Since the gs at Block C was higher than that at the other blocks at véraison and harvest, it appeared that measuring this particular block in the afternoon did not affect measurements. This was probably because the grapevines at Block C were not experiencing water stress. Stomatal conductance of the small shaded and optimal leave types indicated similar lower trends among the different blocks. Most leaf types in Block A had a tendency towards lower conductance at all stages. Leaf type's gs indicated similar results as to what was observed for net carbon assimilation rate. Therefore, it can be concluded that larger and sun exposed leaves are more productive than smaller shaded leaves.

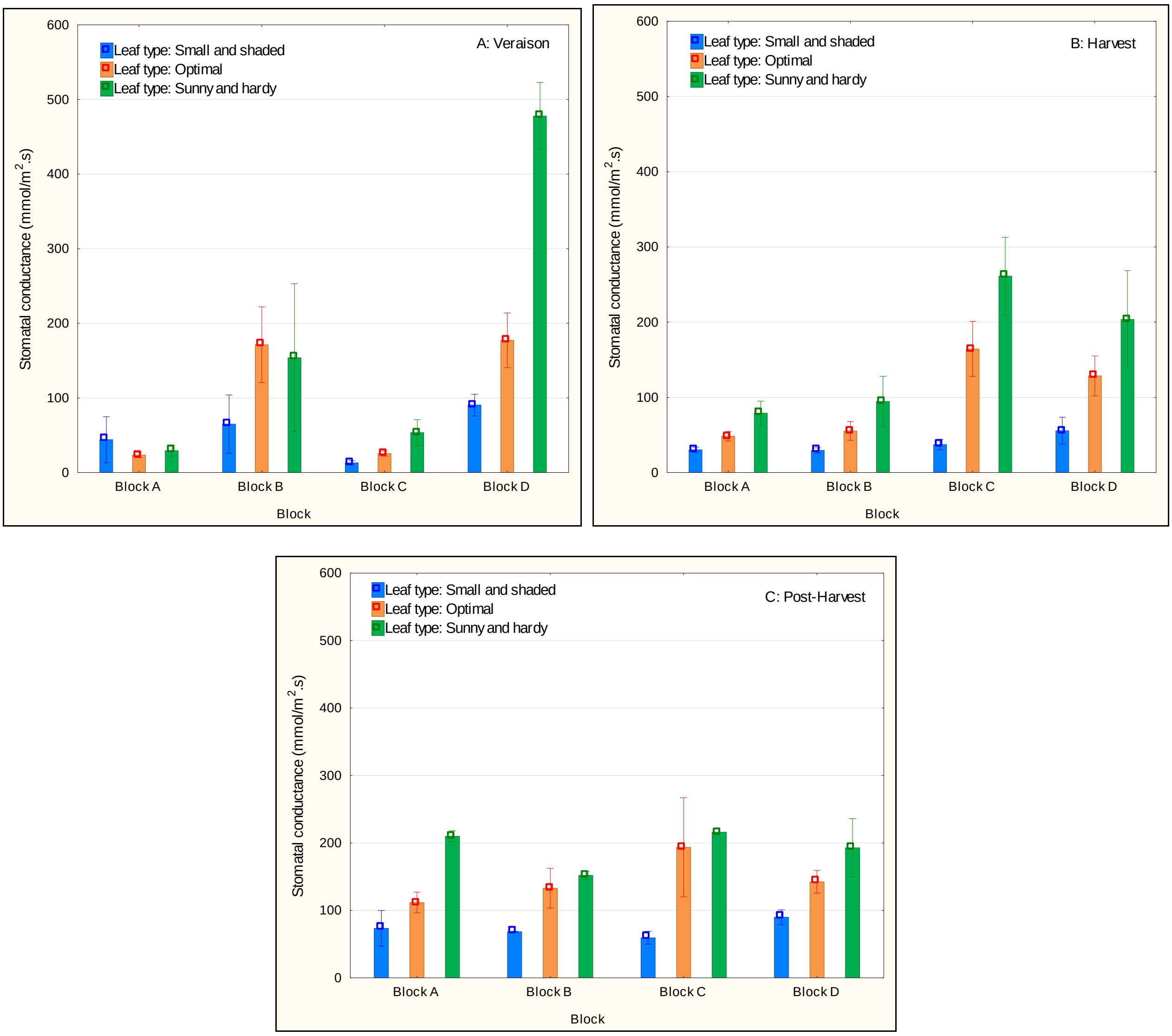

Figure 4.2: Stomatal conductance (mmol m^{-2} s^{-1}) of the four experimental blocks measured with a porometer at véraison (A), harvest (B) and post-harvest (C) measured on different leaf types (small shaded, optimal and sunny hardy) for the 2013/14 season (means with +/- standard error shown).

Leaf type analysis indicated similar trends for the small and shaded leaf net carbon assimilation rates and gs. No conclusion could be made from the differences seen in the 2013/14 leaf gas exchange data since measurements were done at different times and the weather conditions might have had an influence. Therefore, it was decided to only include two blocks for 2014/15 season that will be measured as diurnal cycles between 08:00 and 16:00 in order to determine/evaluate the grapevine's response to environmental conditions within the two blocks (scenarios).

Season 2014/15

At pea size, Block B had a tendency towards higher net carbon assimilation rate in all its leaf types compared to Block D (Figure 4.3). Furthermore, Block D had a tendency to slightly higher net carbon assimilation rate at harvest. Net carbon assimilation rate was the lowest at post-harvest stage in both blocks (Figure 4.3). This could have been due to the lower temperature and lower radiation (Table 4.2) measured at this stage, as well as crop removal. Net carbon assimilation rate during this season was comparable to the findings of Cifre *et al.* (2005), Chaves *et al.* (2007) and Chaves *et al.* (2010). The diurnal courses of net carbon assimilation rate at pea size and harvest indicated mid-morning and midday peaks in most of the leaf types, followed by an afternoon recovery with decreasing temperature and VPD. This is in agreement with the findings of Flexas *et al.* (1999) and Lebese (2008). In the post-harvest period, net carbon assimilation rate in Block D was the highest early in the morning, declined thereafter to 14:00 and then remained constant. No recovery after the midday depression was observed. Similar findings were reported by Flexas *et al.* (1999) for grapevines experiencing drought treatment. The lack of recovery of the net carbon assimilation rate in Block D could have been influenced by the low stem water potential noted at harvest (Refer to Chapter 3), combined with the lower temperature at post-harvest (Table 4.2). Even though the sunny hardy leaves had the highest net carbon assimilation rate before midday at the various phenological stages, the effect of partial stomatal closing was evident by the substantial reduction between 12:00 and 14:00. A similar trend was noted in the leaf type analysis with sunny hardy leaves having a tendency towards higher net carbon assimilation rate in both blocks, followed by optimal and, lastly, the lateral optimal leaves. This was in agreement with Greer (2012) who reported that net carbon assimilation and transpiration rate measured during the season varied according to the node position on the shoot, development and maturity of the leaves. The findings of the current study ascertained that earlier developing leaves had a higher net carbon assimilation and transpiration rate early in the season while later developing leaves were more productive as the season progressed. This was also in support with the similar net carbon assimilation rate shown between the optimal and lateral optimal leaf types later in the season. Results indicate the importance of not removing too many actively photosynthesing leaves during canopy management that could have a negative impact on productivity (Avenant, 1994; Strydom, 2006). Net carbon assimilation rate decreased from harvest to post-harvest in both blocks. This could be due to the influence of high daily temperature and sink effects. Considering the response of the different types of leaves over the progression of the season, it was clear that there were differences amongst the different leaves performance at pea size and harvest. However, at post-harvest all leaves had similar net carbon assimilation rate because leaves had aged and were similar with respect to functionality. The diurnal sequence for net carbon assimilation rate was lower early in the morning, reaching a peak at mid-morning (10:00) or midday (12:00), thereafter showing a slight afternoon recovery (16:00) in some cases. This result supports the low net carbon assimilation rate and gs found in Block A during the 2013/14 season. Diurnal gs was also measured in the two blocks with different porometers, unfortunately one porometer had calibration issues and those data were excluded.

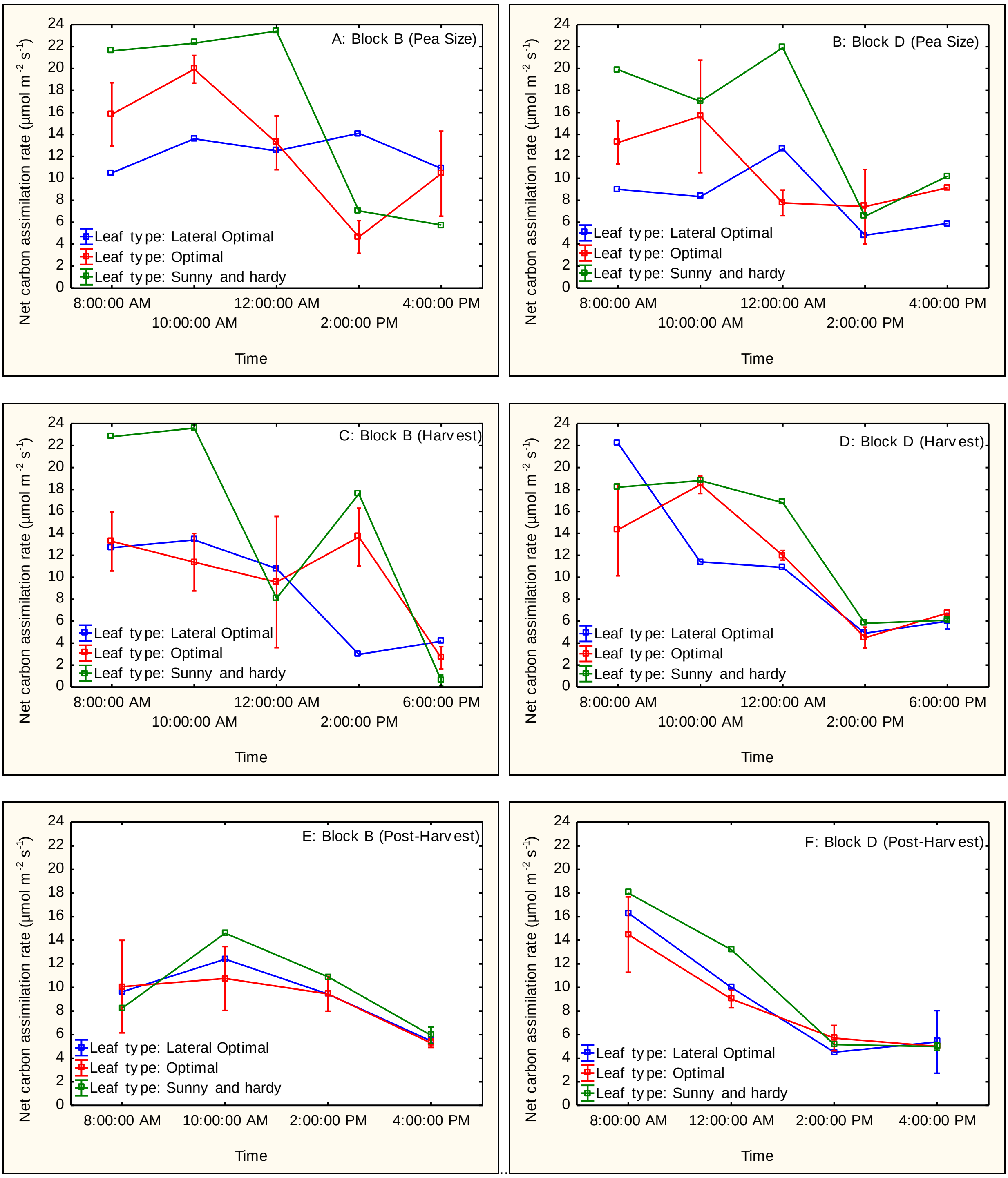

Figure 4.3: Diurnal course of net carbon assimilation rate (µmol m^{-2} s^{-1}) of Blocks B and D at (A & B) pea size, (C & D) harvest and (D & F) post-harvest measured on different leaf types (optimal, lateral optimal & sunny hardy) for the 2014/15 season (means with +/- standard error shown).

4.3.2 Leaf temperature

Season 2013/14

Leaf temperature (Tleaf) was very high throughout the season and was in the range of 26 to 46°C in the 2013/14 season (Fig. 4.4). Optimum leaf temperature for photosynthesis is in the range of 25 to

30ºC and temperatures outside this range can negatively affect net carbon assimilation rate, gs and transpiration (Williams & Trout, 2005; Chaves *et al.*, 2010; Iland *et al.*, 2011). Most of the blocks in this study experienced temperatures outside the optimum range for photosynthesis. However, Block B had lower temperatures at pea size and harvest that was optimal. Increasing temperature and VPD increased transpiration rate influencing stomata to close partially (Schultz & Stoll, 2010), leading to low gs observed in most of these blocks. At pea size, Block B had a tendency towards lower Tleaf, while Blocks C and D indicated similar trends in all the leaf types. At véraison, Block D had a tendency towards lower Tleaf in all its leaf types compared to the other blocks. As the season progressed, the effect of prevailing weather conditions could be seen on measurements. In this regard, afternoon Tleaf was higher than Tleaf measured in the morning. Also at véraison, Tleaf was the highest and corresponded to the high atmospheric temperature measured on the same day by the weather station (Table 4.1). At harvest, the two blocks (A & C) that were measured in the afternoon tended to have higher Tleaf (Fig. 4.4). Leaf type categories also indicated that Tleaf in all leaf types in Block A, was higher than the other three blocks at all measured phenological stages. Apart from Block A being measured in the afternoon, this block also had lower stem water potential throughout the season and this might have had a negative effect on growth and productivity. Additionally, Block A had a less vigorous growth, sparser canopy with more direct sun exposed leaves that could also have contributed to the higher Tleaf. Even though leaf vapour pressure deficit (VPDL) has been excluded from this discussion, it is worth mentioning that it followed similar trends to Tleaf.

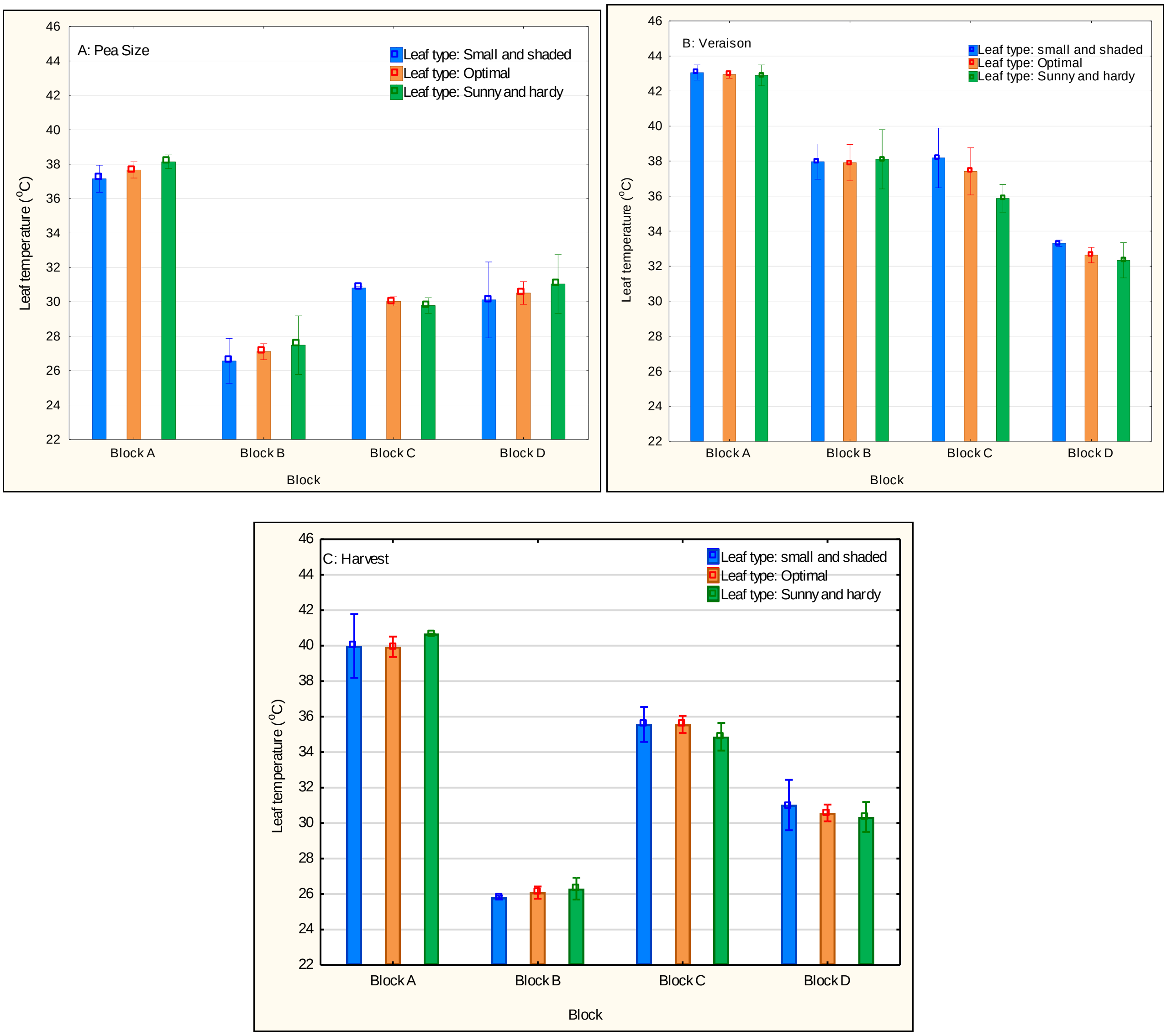

Figure 4.4: Leaf temperature (ºC) of the four experimental blocks at (A) pea size, (B) véraison and (C) harvest measured on different leaf types (small shaded, optimal & sunny hardy) for the 2013/14 season (means with +/- standard error shown).

Season 2014/15

Tleaf was highest at harvest compared to the other phenological stages. This might have been influenced by the higher temperature and radiation with a lower relative humidity noted at harvest (Table 4.2). The diurnal Tleaf cycle at pea size indicated that temperatures were the lowest early in the morning (Figure 4.5). There was a rapid increase in Tleaf reaching a peak at mid-morning in both blocks. The Tleaf of the optimal and lateral optimal leaves remained constant in both blocks between 10:00 and 14:00. Thereafter there was a slight decline in Tleaf in late afternoon. At harvest, Tleaf increased in all leaf types of both blocks, reaching a peak at 12:00 and 14:00 in Blocks B and D, respectively. At this stage, Block B and D’s sunny hardy leaves had a distinct peak of 38°C and 40°^{0}C, respectively. No significant differences were observed in leaf type Tleaf at the different stages, with the exception of pea size, where the Tleaf of Block B’s sunny hardy leaf was higher at 10:00.

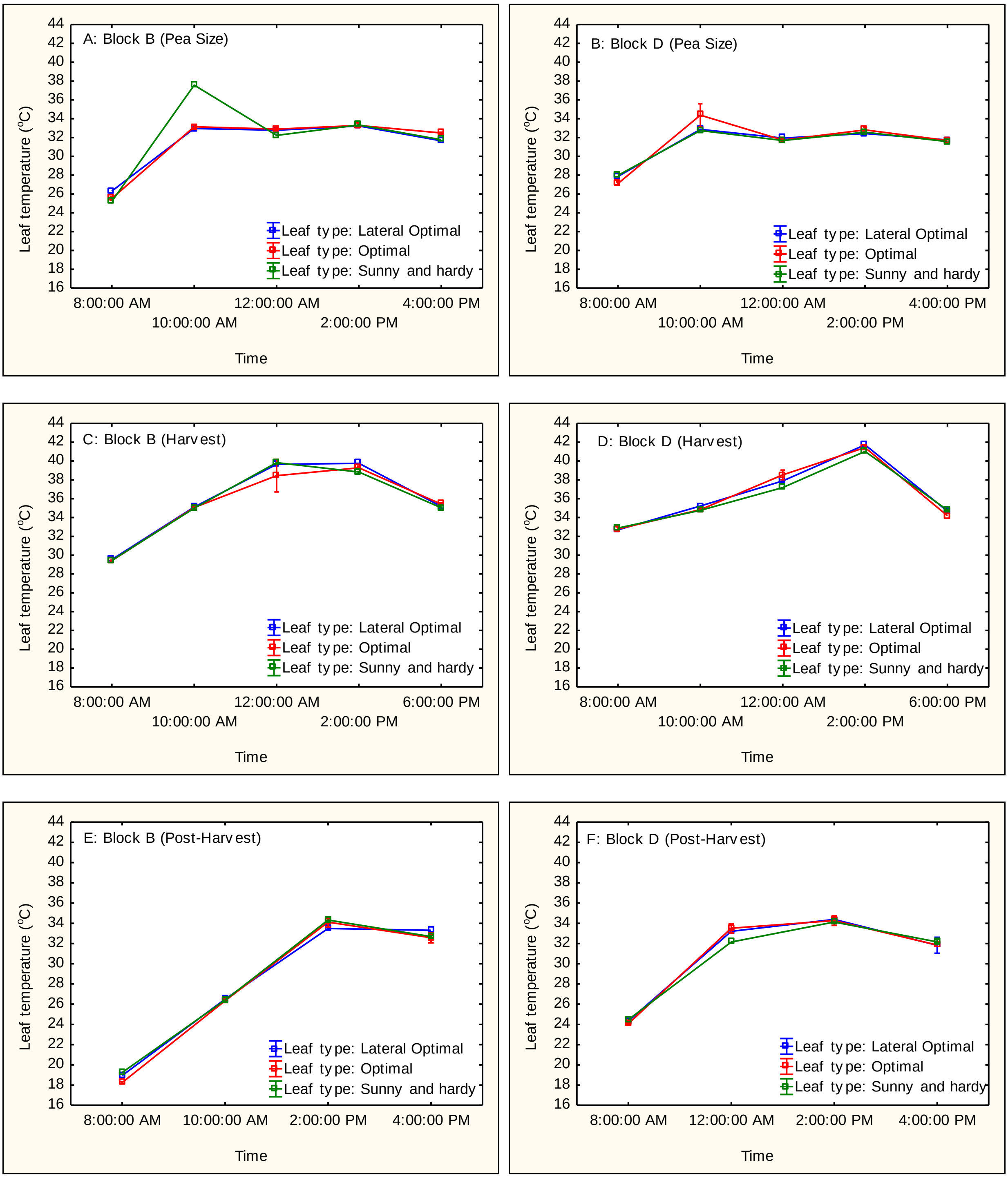

Figure 4.5: Diurnal progression of leaf temperature (ºC) of Blocks B and D at (A & B) pea size, (C & D) harvest and (E & F) post-harvest measured on different leaf types (optimal, lateral optimal and sunny hardy) for the 2014/15 season (means with +/- standard error shown).

The relationship between net carbon assimilation rate and Tleaf also revealed an inverse relationship, *i.e.* as leaf temperatures increased, there was a reduction in net carbon assimilation rates (Fig. 4.6). Additionally, the midday measurements also indicated a reduction in net carbon assimilation with peak temperatures. This is in agreement with other reported findings that indicated that there was a parabolic relationship between temperature and photosynthesis (Mullins *et al.*, 1992; Iland *et al.*, 2011).

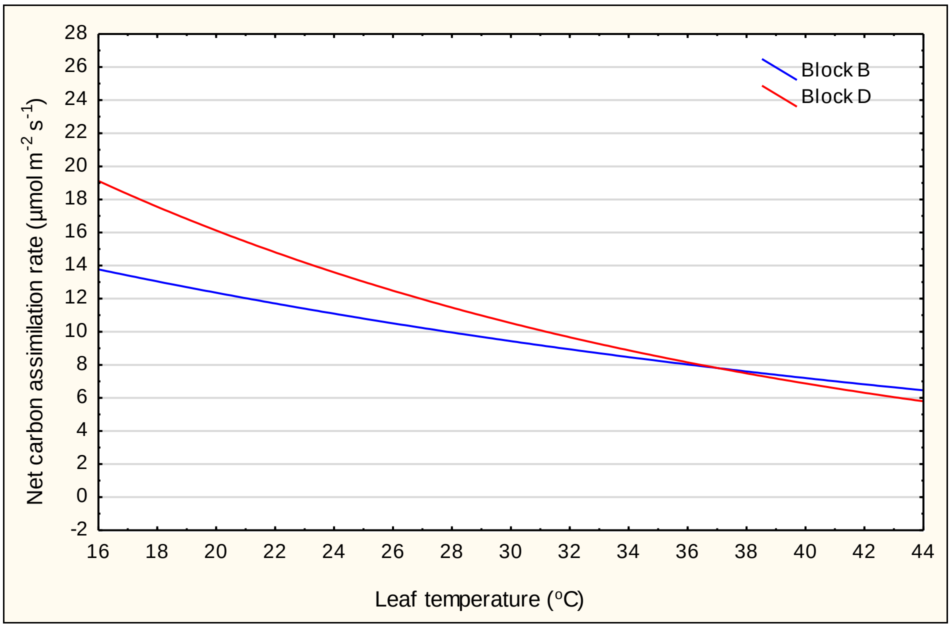

Figure 4.6: Relationship between net carbon assimilation rate (µmol m^{-2} s^{-1}) and leaf temperature (°C) of the two experimental blocks for the 2014/15 season. An exponential fit was drawn.

4.3.3 Light measurements

Season 2013/14

Light interception within grapevine canopies is mainly influenced by the trellis systems, canopy management, as well as grapevine vigour (Dokoozlian & Kliewer, 1995). Ceptometer light measurements in the 2013/14 season indicated apparent higher light interception in Block A at pea size and post-harvest at the higher canopy position (Fig. 4.7). This suggested that this particular block did not have a dense canopy and allowed more light interception. At véraison, Blocks B and D had a tendency towards higher light interception at the higher canopy position. This was probably because of the lateral shoot removal and shoot topping that took place in December and January (véraison). At this stage, Block D had the highest light interception of 72% PAR at the higher canopy position. This was due to the standardised topping of all shoots that grew over the last wire around véraison so that more light could be intercepted in the denser canopy. At harvest, there were no appreciable differences among Blocks A, C and D, though Block B had a higher light interception at the low and higher position probably due to a less dense canopy and leaf removal. Block A had a tendency towards higher light interception at the middle and higher canopy position at post-harvest. There were substantial variations of light interception observed in the different blocks at the different phenological stages, with the lowest and highest PAR % of 8 and 76% in Blocks C and A, respectively. Blocks A and B indicated slow growth throughout the season (Refer to Chapter 3) and was not dense allowing more light interception in their canopies compared to Blocks C and D. Results suggest that canopy position plays an important role in light interception, where measurements taken further away from the vine display more light interception compared to the lower position. The practice of leaf removal around the bunches in the bunch zone also contributed to “opening up” the canopy in this particular zone and allowed more light interception. No apparent differences were noted between the lower and middle canopy position at pea size, véraison and harvest in all the blocks. The differences in the PAR with respect to the different measurement positions was minimal in the post-harvest period. Therefore, it can be concluded that more shading occurred closer to the vine whereas more light interception took place further away from vines, particularly in the pre-harvest period. This finding was in agreement with Dokoozlian and Kliewer (1995) who reported that R:FR and sun fleck in vineyards reduces below the canopy with the lowest values near the fruit zone. It has previously been reported that for most C3 plants the rate of photosynthesis in vineyards is light saturated at ±800 $\mu E.m^{-2}\ s^{-1}$ and the light compensation point is at 15–30 $\mu E.m^{-2}\ s^{-1}$ (Strever, 2014). Therefore, despite the lower light interception percentages obtained in the current study, it would not be expected to limit photosynthesis.

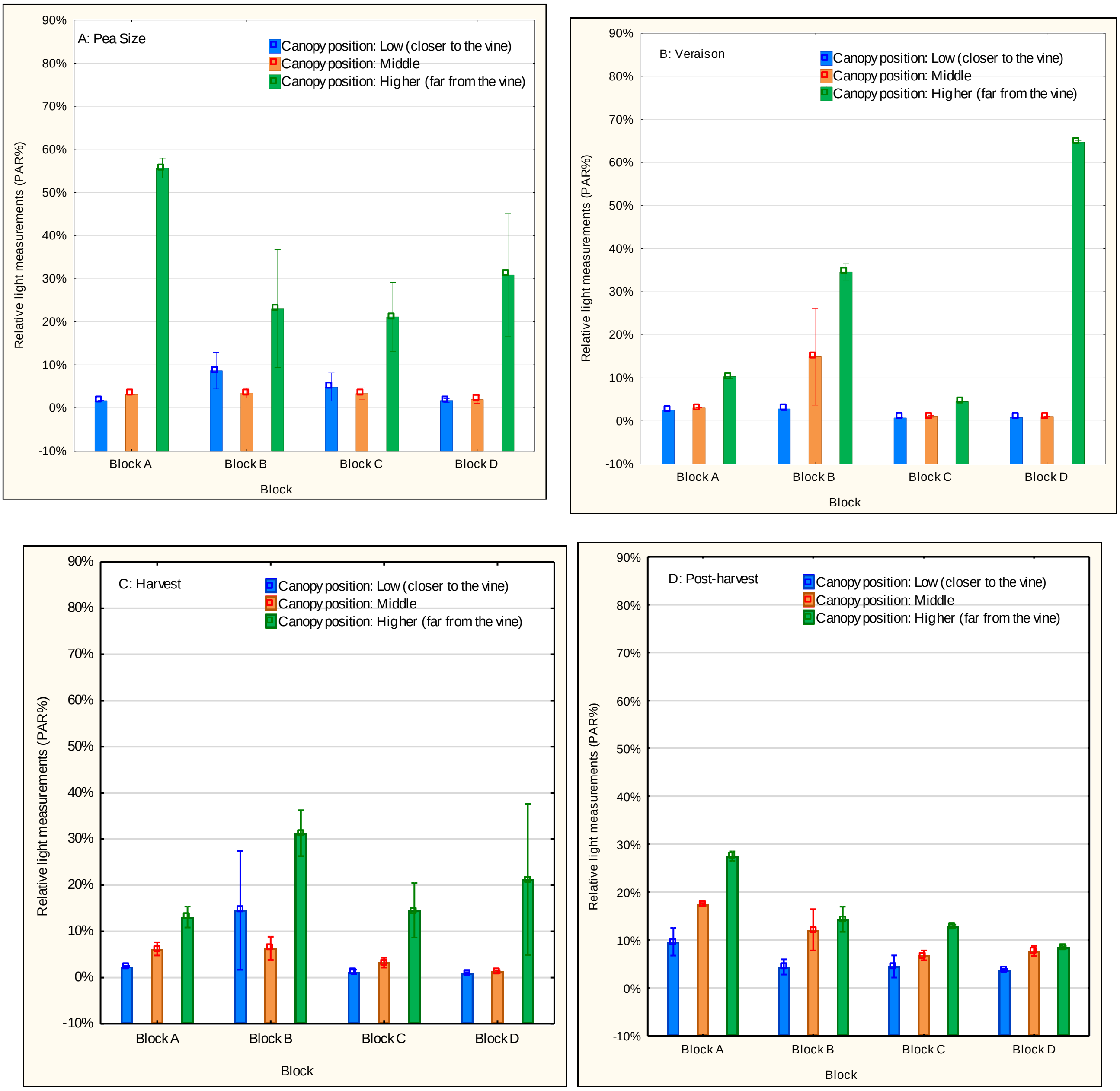

Figure 4.7: Relative light interception (PAR %) of the four experimental blocks at (A) pea size, (B) véraison, (C) harvest and (D) post-harvest measured at different canopy positions (low, middle & higher) for the 2013/14 season (means with +/- standard error shown).

Season 2014/15

During 2014/15 season, the red versus far-red radiation (R:FR) was measured around the gas exchange measured leaves in Blocks B and D. The areas around the sunny exposed leaves had a higher R:FR ratio compared to the partially shaded or not so exposed areas around the optimal and lateral optimal leaves as measured in this study at the different phenological stages (Figure 4.8). The diurnal cycles also indicated lower R:FR ratios around the optimal lateral leaves later in the season indicating that shaded leaves have lower radiations. This might have a detrimental effect on gs, as well as net carbon assimilations as noted in this study. At most of the measurement times, the R:FR of optimal and lateral leaves was below 1 throughout the day except at post-harvest where the optimal leaves had a slightly higher R:FR ratio early in the morning. At harvest and post-harvest, both blocks had a higher R:FR ratio in the early morning, decreasing to mid-morning and followed by a constant ratio to late afternoon. Dokoozlian and Kliewer (1995) reported the ratio of red to far-red light to be in the range of 1.1 to 1.2 in sunlight. Furthermore, in dense canopies the value can be below 0.1. Based on this, it can be concluded that both these blocks did not have very dense canopies. However, Block D had a tendency towards being denser and this was also confirmed by visual observations during the season. A slight reduction in R:FR ratios was noted between pea size and harvest, while a higher ratio was noted at post-harvest.

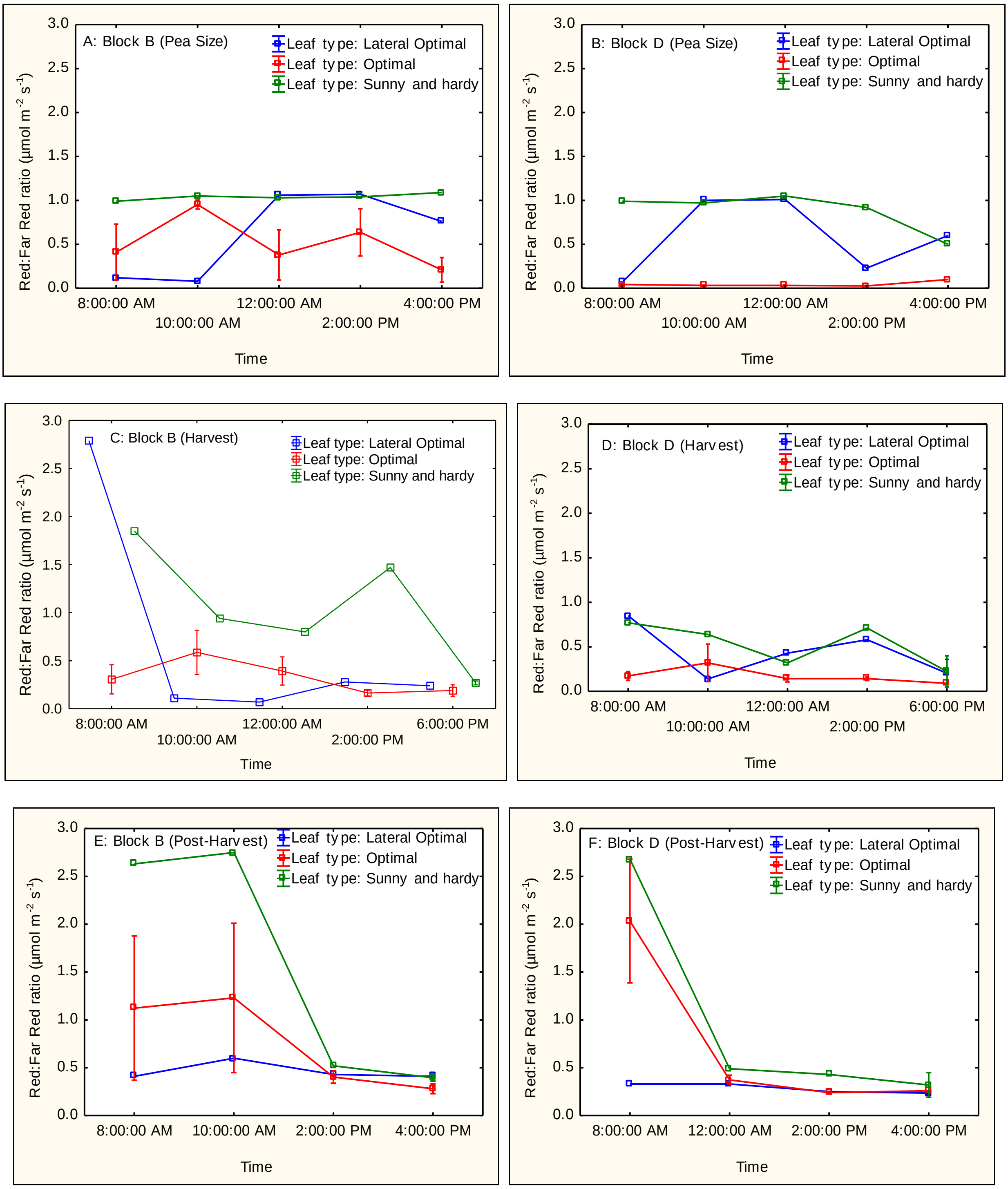

Figure 4.8: Diurnal course of red:far red ratio (µmol m^{-2} s^{-1}) of Block B and D at (A & B)pea size, (C & D) harvest and (E & F) post-harvest for the 2014/15 season (means with +/- standard error shown).

At pea size, midday ceptometer readings indicated that Block D had lower light interception at the different canopy positions compared to the other blocks (Fig. 4.9). Block D had vigorous shoot growth during the season leading to a denser canopy compared to the other blocks (Refer to Chapter 3). This was confirmed by the lower light interception at the different positions for the different phenological stages as shown by ceptometer and the R:FR ratio. Growth in Blocks A and B was slower during this season with a less dense canopy therefore allowing a higher light interception at the different stages. At harvest and post-harvest, Blocks A and B had higher light interception (Fig. 4.9). Over the progression of the season, higher light interception was measured at harvest in all blocks. This can be explained by the canopy opening from véraison to allow more light interception for berry colour development. Higher light interception tendencies were observed at middle and higher canopy position in Blocks A and B, while the opposite was seen in Blocks C and D. Radiation values recorded in this study were within the light compensation point of 15-30 $\mu E.m^{-2}\ s^{-1}$ (Strever, 2014). Similarly, Iland *et al.* (2011) stated that ambient PAR light intensity of exposed leaves under sunny conditions in most viticulture regions is above the saturation point of 700 to 1000 $\mu mol\ m^{-2}\ s^{-1}$ unless there are overcast conditions.

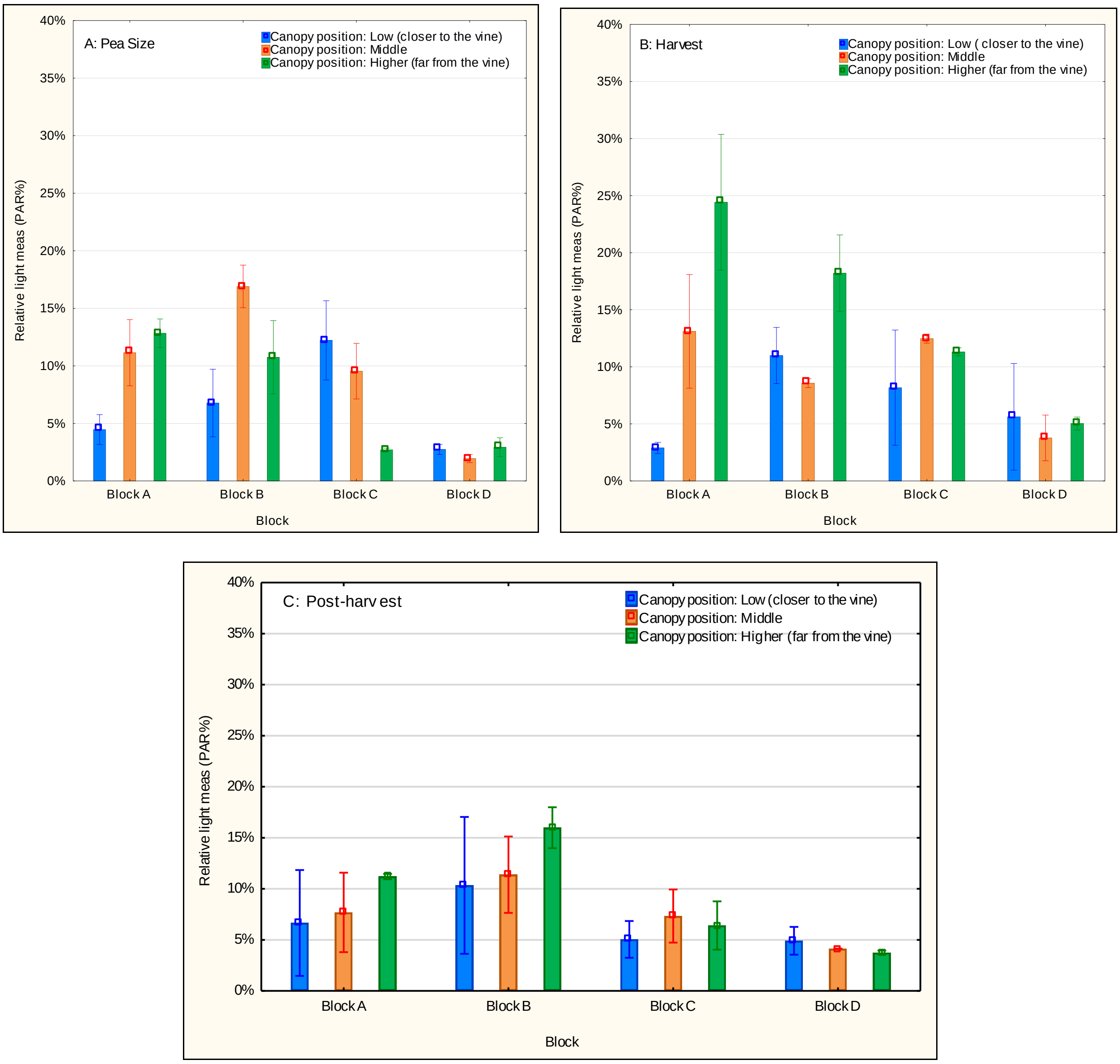

Figure 4.9: Relative light interception (PAR %) of the four experimental blocks at (A) pea size, (B) harvest and (C) post-harvest measured at different canopy positions (low, middle, higher) for the 2014/15 season (means with +/- standard error shown).

Both seasons indicated Block D to have a tendency towards lower light interception in most of the canopy positions at all stages, indicating vigorous growth and shading in this block as already indicated with the vegetative measurements (Refer to Chapter 3). This mean that this block's canopy had a variety of exposed and shaded leaves that can maximise photosynthetic activities, reduce transpiration in the shaded leaves leading to increased WUE. This is supported by Bacon (2004) who reported that fast leaf development increases WUE by increasing leaf area that will minimise evaporation and increase soil moisture for productive plant use. Additionally, the leaf morphological attributes as already discussed in Chapter 3, also indicated a tendency towards thicker leaves and a larger SLA in Block D's different leaf types, which is reported to be beneficial for photosynthesis and improved WUE.

4.3.4 Reproductive measurements

4.3.4.1 Yield and its components

Berry mass increased gradually as the season progressed from véraison to harvest in both seasons (Addendum, Figs. B.1 & B.2). Block A had lower berry mass and a smaller berry diameter during both seasons (Table 4.3). Berry mass and diameter was larger in the 2013/14 season compared to the 2014/15 season. The 2014/15 season had a faster accumulation of heat units, because of average higher temperatures at the beginning of the season compared to the 2013/14 season (Refer to Chapter 3). Berry mass in all blocks for both seasons were higher than the 4.76 g recommended minimum for export (Anon, 1994, Myburgh, 1996).

In the 2013/14 season, Block D's total yield per vine and class 1 yield per vine were higher compared to Blocks A, B and C (Table 4.3). This corresponded to the higher net carbon assimilation rate and gs measured in this block at the different phenological stages. Blocks B and C had similar yield in both seasons. An increase in yield was seen in the second season, with Block A yielding the lowest in both seasons. Yield of the 2014/15 season compares well to the findings of Links (2015) for the first season of his study. In contrast, the yield data of the 2013/14 season data was higher than his second season's data. A reduction in yield was noted in Block D in the 2014/15 season. This might have been due to stricter crop control in the second season in an effort to have fewer but higher quality bunches. Export quality grapes in Blocks A, B, C and D was 51%, 69%, 67% and 77%, respectively, during the 2013/14 season. During the 2014/15 season, Block A was harvested by the farm team before measurements could be done and therefore total kg yield per vine was determined from the producer's pack out records. During this season, Block B had higher yield than Blocks A and D. Export quality grapes in Blocks B, C and D were 75%, 86%, 97%, respectively. More export grapes were harvested during the 2014/15 season, which was drier and warmer compared to the 2013/14 season. This might be an indication that the drier and warmer climatic conditions exposed the grapevines to a certain degree of mild water stress during the growing season, hence reducing vegetative growth in favour of improved fruit quality (Myburgh, 1996; Costa *et al.*, 2007; Myburgh & Howell, 2007).

Maintaining vine balance is very important in table grape vineyards in order to improve WUE. One of the metrics used for assessing vine balance, is to compare yield to leaf area. Kliewer and Dokoozlian (2005) reported that 0.5-1.2 m^2 leaf area (LA) is necessary to ripen 1 kg of fruit, considering the different training systems. Based on the 2014/15 season total vine LA calculation at pea size, the LA to fruit ratio at harvest was 0.69 m^2/kg, 0.66 m^2/kg, 0.57 m^2/kg and 0.91 m^2/kg for Blocks A, B, C and D, respectively. Therefore, under the prevailing conditions in the different blocks it appeared that the LA: to fruit ratio was optimal for grape production. Even though all these blocks are on the same trellis system, Block D had a higher leaf area per fruit produced because of the vigorous growth and fewer fruit harvested in that block compared to the lower ratio obtained in Block C. These results are also in agreement with Williams *et al.* (1987) who reported 0.49–0.65 m^2/kg for defoliated treatments of Thompson Seedless grapevines. Araujo *et al.* (1995) reported a LA to fruit weight ratio of 0.9 m^2/kg for drip irrigated Thompson Seedless grapevines, which compares very well with Block D's ratio.

Table 4.3: Total mean yield (kg/vine), berry size and quality class classifications of the four experimental blocks for the 2013/14 and 2014/15 seasons.

Season 2013/14							
Block	Total (kg/vine)	Average berry mass (g)	Average berry diameter (cm)	Export: Class 1 (kg/vine)	Local: Class 2 (kg/vine)	Cull: Class 3 (kg/vine)	Export (%)
A	9.93 ± 3.36(1)	5.05 ± 0.18	16.61 ± 0.19	5.09 ± 1.78	3.88 ± 1.72	0.97 ± 0.22	51
B	12.66 ± 1.02	6.64 ± 0.21	18.06 ± 0.18	8.78 ±1.39	1.27 ± 0.36	2.60 ± 1.23	69
C	12.54 ± 1.91	6.92 ± 0.20	17.84 ± 0.12	8.36 ± 1.63	2.85 ± 0.60	1.33 ± 0.55	67
D	19.81 ± 2.72	6.71 ± 0.16	17.48 ± 0.13	15.30 ± 2.41	4.10 ± 0.71	0.41 ± 0.16	77
Season 2014/15							
A	9.72(2)	4.90 ± 0.22	16.94 ± 0.15	-	-	-	-
B	16.86 ± 1.83	5.37 ± 0.15	16.73 ± 0.14	12.67 ± 1.79	2.51 ± 0.35	1.68 ± 0.36	75
C	16.28 ± 2.36	5.90 ± 0.18	17.08 ± 0.13	14.01 ± 2.32	1.80 ± 0.49	0.64 ± 0.16	86
D	12.97 ± 1.99	5.99 0.14	17.27 ±0.20	12.57 ± 1.94		0.46 ± 0.10	97

(1) Values are means (n=10) ± standard errors of mean
(2) Season 2014/15 Block A total yield was calculated from farm's pack out due to early harvesting by the farm before yield of data vines could be measured.

4.3.4.2 Fruit ripening and quality

Grape composition at harvest for both seasons is given in Table 4.4. The TSS, TTA and pH were in the following ranges for both seasons: 17.05-18.45°B, 4.26-6.78 g/L and 3.49-3.69, respectively.

Block A had lower TSS during the 2013/14 season, whilst Block C had a lower TSS during the 2014/15 season. Block D had slightly higher TSS due to lower soil water content. A similar tendency was reported by Saayman and Lambrechts (1995) who reported that limited irrigation during grape maturation increased sugar concentration and reduced acidity without decreasing yield. At harvest, Block A had lower TTA during the 2013/14 season. Sonnekus (2015), reported an average TTA concentration of 5.15 g/L at 63 days after pea size (DAPS) for both seasons, which compares well with the current study's TTA concentration at harvest for both seasons. Berry TTA correlated with berry size, hence blocks with bigger berry sizes (C & D) had higher TTA content. Similar findings were reported by Sonnekus (2015). The TTA for Blocks A and B during the 2013/14 season was similar to what was reported by Links (2015). However, TTA for Blocks C and D for both seasons and Block A during the 2013/14 season was higher than that reported by Links (2015). The juice pH for both seasons in Blocks A and B during the 2013/14 season was similar to what was reported by Links (2015). Fruit composition analyses results from véraison to harvest during both seasons are presented in Addendum, Figs. B.3. to B.10. Block A had tendencies towards higher TSS (Addendum, Figs. B.3 & B.4), °B/TTA (Addendum, Figs. B.9 & B.10) and sugar loading (2014/15 season) (Addendum, Fig. B.8). While, TTA (Addendum, Figs. B.5 & B.6) and sugar loading (2013/14 season) (Addendum, Fig. B.7) was lower than the other blocks. Block D also had a tendency towards a higher TSS and sugar loading compared to Blocks B and C.

Table 4.4: Total soluble solids (TSS), total titratable acidity (TTA) and pH in juice of Crimson Seedless table grapes from four different blocks in the Hex River Valley at harvest in the 2013/14 and 2014/15 seasons

	Season 2013/14		
Block	TSS (°B)	TTA (g/L)	pH
A	17.42 ± 0.21[(1)]	4.26 ± 0.14	3.64 ± 0.02
B	18.47 ± 0.21	4.42 ± 0.08	3.59 ± 0.01
C	17.70 ± 0.37	5.00 ± 0.13	3.49 ± 0.02
D	18.45 ± 0.15	5.33 ± 0.10	3.60 ± 0.04
	Season 2014/15		
A	17.96 ± 0.37	5.78 ± 0.17	3.68 ± 0.02
B	17.85 ± 0.22	4.60 ± 0.09	3.69 ± 0.04
C	17.05 ± 0.58	5.11 ± 0.13	3.65 ± 0.03
D	18.22 ± 0.25	5.42 ± 0.14	3.59 ± 0.03

(1) Values are means (n=10) ± standard errors of mean

4.3.4.3 Anthocyanin analysis

Crimson Seedless is a red seedless cultivar and berry skin colour is an important quality parameter. However, this cultivar tends to have problems with poor berry colouring and some bunches are not harvested, hence causing economic losses (Brar *et al.*, 2008; Avenant, 2010). In this study poor berry colouring was also observed. Berry skin total anthocyanin accumulation occurs in three phases. It begins with a slow accumulation, followed by a rapid increase, and then become steady until it start declining at the end of ripening stage (Brar *et al.*, 2008). The same observation was made during the 2013/14 season (Fig. 4.10). Throughout berry ripening, anthocyanin accumulation of Blocks A and D was much lower compared to Blocks B and C. The low anthocyanin accumulation in Block D might have been caused by the heavy crop load and water stress observed in this particular block. In contrast, Block A anthocyanin accumulation was very low and remained constant throughout the ripening stage while a slight increase was noted by harvest (Figure 4.10). Anthocyanin accumulation was higher during the 2014/15 season (Fig. 4.11) compared to the 2013/14 season in all blocks. The optimal temperature range for anthocyanin production is between 15^0C and 35^0C (De Oliveira *et al.*, 2015). Season 2014/15 was warmer compared to season 2013/14 as already indicated in Chapter 3 Figure 3.2, hence the higher anthocyanin concentration measured in 2014/15. Sonnekus (2015) reported an average anthocyanin concentration of up to 0.60 mg/berry and 0.65 mg/berry during the 2011/12 and 2012/13 seasons, respectively. Both season's anthocyanin concentrations in that study was higher than the concentrations found in the current study for the 2013/14 season. Nevertheless, the current study's anthocyanin concentration during the 2014/15 season for Blocks B and C was slightly higher than Sonnekus (2015), while Block D compared well with both season's reported results. Links (2015) reported a total red pigments (A_{520}) of 1.40 and 1.17 for the 2011/12 and 2012/13 season which is higher than reported in the current study.

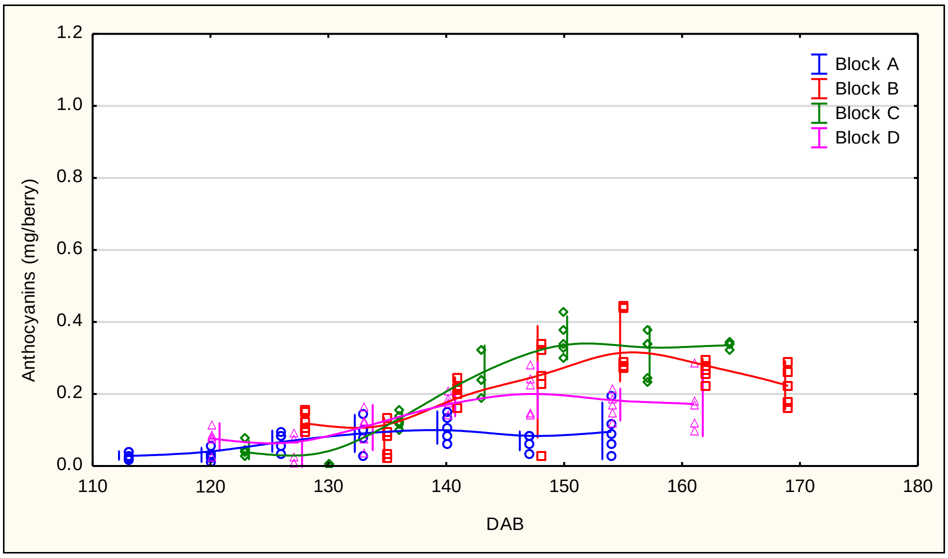

Figure 4.10: Total anthocyanins (mg/berry) relative to date after budburst (DAB) of the four experimental blocks for the 2013/14 season. A distance weighted least squares fit was drawn.

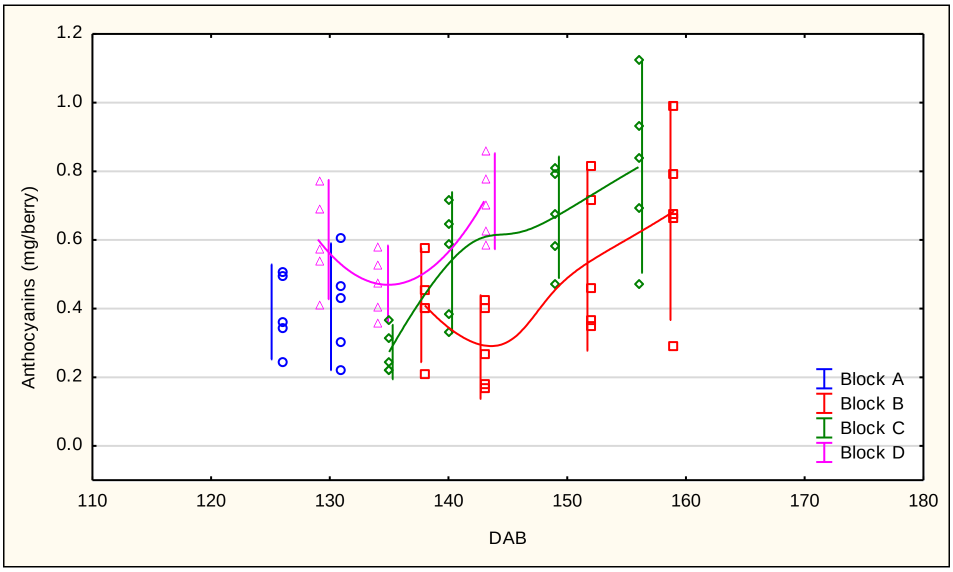

Figure 4.11: Total anthocyanins (mg/berry) relative to date after budburst (DAB) of the four experimental blocks for the 2014/15 season. A distance weighted least squares fit is drawn.

4.3.4.4 Ravaz Index (Yield: pruning mass ratio)

In order to determine the Ravaz index (yield: pruning mass ratio) (Howell, 2001a), the detailed measured Blocks (B and C) data vine pruning mass were used to determine its correlation to the average experimental unit pruning mass. A positive correlation was found between the two sets of data as seen in Figure 4.12 with an r= 0.91 and r^2 = 0.83. These results indicated that there was no difference in using the data vine pruning data or the average experimental unit pruning data. Therefore, the average experimental unit pruning mass was used to calculate the Ravaz index for all four blocks. Individual data vine yield as recorded at harvest were used for this calculation in both seasons. The specific data vine yield was divided by the average experimental unit pruning mass to determine the Ravaz index as shown in Table 4.5. The same trend observed for cane mass was seen with the Ravaz index, with Block D having the highest ratio of 7.58 and Block A having the lowest ratio of 4.02 for the 2013/14 season. The high yield to pruning mass ratio observed in Block D indicates that this block was highly productive; while Blocks B and C was average and Block A was the least productive. The Ravaz index calculated for Blocks B and C for both seasons and Block D for the 2013/14 season was higher than the Ravaz index of 4.1 reported for Festival Seedless (Avenant, 1998). Depending on the different cultivars, management and training systems, a Ravaz index of a range of 5 to 10 is considered optimal for *Vitis vinifera* (Skinkis, 2013). Ravaz index ratios below 5 are indications of low productivity (low yields & higher/more vegetative growth), while higher indexes indicate a higher productivity (more fruit & less vegetative growth). Henceforth, values towards end of the range can lead to unsustainable vine growth and production (Skinkis, 2013). The heavy crop load of the 2013/14 season and the low soil moisture content measured in Block D during the 2014/15 season could have influenced the low Ravaz index observed during this season. This is supported by Skinkis (2013) who reported that vines which are excessively vigorous often have poor bud fruitfulness, reduced fruit set, and lower yields. Block B had a higher Ravaz index of 9.19 in the second season and that signalled a risk factor in that block, since growth was lower with higher yield and decreased fruit quality.

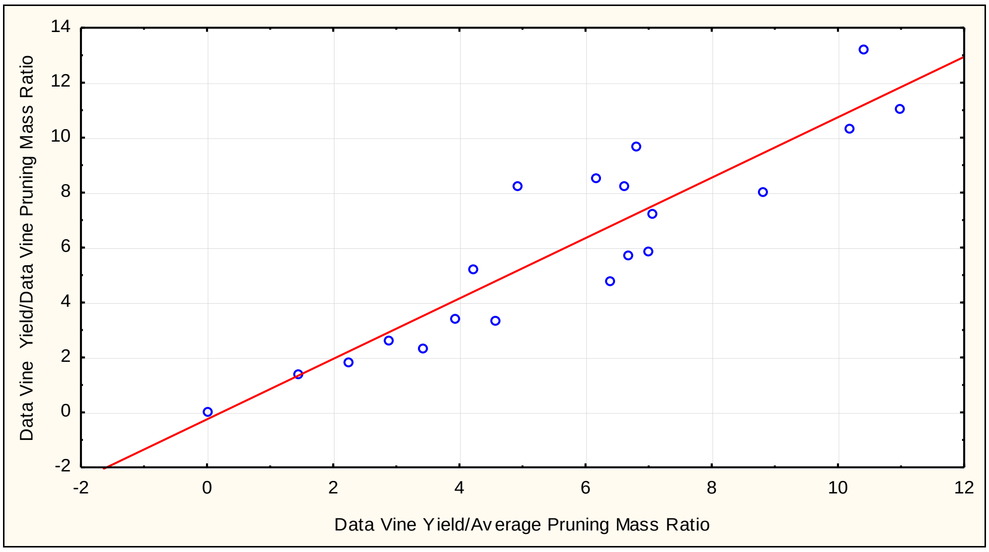

Figure 4.12: Relationship between the data vine yield divided by data vine pruning mass ratio and data vine yield divided by average experimental unit pruning mass of two experimental blocks for the 2013/14 season (r = 0.91, r^2=0.83).

Table 4.5: Ravaz Index of the four experimental blocks for 2013/14 and 2014/15 seasons.

Ravaz Index (Ratio of yield to cane mass)		
Block	Season 2013/14	Season 2014/15
A	4.02(1)	4.40(2)*
B	5.33	9.19
C	6.14	8.37
D	7.58	3.53

(1) Values are means (n=10)

*Block A, Ravaz index was calculated from the average yield determined from the farm's pack out records.

4.3.5 Yield water use efficiency

The WUEy and WUEirr are presented in Table 4.6 and Table 4.7. Block A had the lowest WUEy while block B had a tendency towards a higher WUEy for all the calculations (Table 4.6). The two blocks irrigated with a drip irrigation system (A & D) had lower WUEy for the 2014/15 season and this might have been due to the lower yields recorded in those blocks in that season. Block A had a WUEy of 5.44 kg/m^3, 3.57 kg/m^3 and 4.07 kg/m^3 with the WUEy(ETL), WUEy(ETM) and WUEy(ETFL) calculations, respectively. In contrast, Block B had a WUEy of 9.33 kg/m^3, 6.05 kg/m^3 and 6.59 kg/m^3 with the WUEy(ETL), WUEy(ETM) and WUEy(ETFL) calculations, respectively. Calculations from the lower ETWB(L) had a higher WUEy compared to the rest. The WUEirr of the 2013/14 and 2014/15 seasons indicated that Block D had a higher WUEirr with 5.74 kg/m^3 and 3.96 kg/m^3, respectively (Table 4.7). The WUEy was higher than the average of 3.7 kg/m^3 calculated from remote sensing data in the Winelands region of the Western Cape (Jarmain et al., 2007). Where

Sultanina grapevines were irrigated with flood irrigation on wide and narrow beds at an interval of 14 and 21 day cycles, WUE_y ranged from 1.9 to 3.3 kg/m^3 (Myburgh, 2003a). These values are comparably lower than what was measured in this study. This was to be expected because the lower values in that study were probably due to the higher volumes of water used for the flood irrigation compared to the drip and micro irrigation used in the current study. However, the 4.05 kg/m^3 recalculated from furrow irrigated Sultana in Australia was comparable to Block A's $WUE_{y(ETFL)}$(Yunusa et al. 1997b). The WUE_y data recalculated from a Thompson Seedless grapevine study using drip and furrow irrigation in California indicated an average of 5.50 kg/m^3 (Araujo *et al.*, 1995), which compared well to Block A (5.44 kg/m^3) $WUE_{y(ETL)}$ and Block D's (5.71 kg/m^3) $WUE_{y(ETM)}$. Yunusa et al. (1997a) reported a recalculated WUE_y of 4.27 kg/m^3 for own-rooted and 8.64 kg/m^3 for grafted Sultana grapevines using drip irrigation in Australia. The grafted Sultana grapevine WUE_y was in close range with the $WUE_{y(ETL)}$ reported for Blocks D but slightly lower than the sprinkler irrigated Blocks B and C. Even though Block C had a higher irrigated volume during both seasons, it had a lower WUE_{irr} compared to Block D, indicating that the irrigation scheduling might not be optimal in this block. Subsequently, more water could be saved by implementing a proper irrigation scheduling method. Block D had the lowest ET with all calculations, as well as a lower seasonal irrigation volume for the 2014/15 season, but still had a comparable WUE_y to Block's B and C, with a higher WUE_{irr}, indicating that this block was more productive and water use efficient.

Table 4.6: Yield water use efficiency (kg/m^3) determined from evapotranspiration (ET) values from December to April of the four experimental blocks for the 2014/15 season.

	Block A	Block B	Block C	Block D
Yield (kg/vine)	9.72	16.86	16.28	12.97
Yield (t/ha)	18.00	31.22	32.89	24.02
Yield (kg/ha)	18001	31225	32886	24020
ETWB (m^3)	6344	6747	6699	5264
$WUE_{y(ET)}$ (kg/m^3)	2.84	4.63	4.91	4.56
ET corrected with a Crop Factor				
$ETWB_{(L)}$ (m^3)	3306	3346	3385	2728
$WUE_{y(ETL)}$ (kg/m^3)	5.44	9.33	9.72	8.80
$ETWB_{(M)}$ (m^3)	5036	5161	5263	4208
$WUE_{y(ETM)}$ (kg/m^3)	3.57	6.05	6.25	5.71
$ETWB_{(FL)}$ (m^3)	4427	4741	5339	4716
$WUE_{y(ETFL)}$ (kg/m^3)	4.07	6.59	6.16	5.09

Table 4.7: Irrigation water use efficiency (kg/m^3) determined from seasonal irrigation volumes from September to April of the four experimental blocks for the 2013/14 and 2014/15 seasons.

	Block A		Block B		Block C		Block D	
Season	2013/14	2014/15	2013/14	2014/15	2013/14	2014/15	2013/14	2014/15
Yield (kg/vine)	9.93	9.72	12.66	16.86	12.54	16.28	19.81	12.97
Yield (t/ha)	18.39	18.00	23.45	31.22	25.33	32.89	36.69	24.02
Yield (kg/ha)	18390	18001	23446	31225	25331	32886	36688	24020
Irrigation (m^3) (Sep-April)	4550	7550	9630	9130	10510	9960	6390	6060
WUE_{irr} (kg/m^3)	4.04	2.38	2.43	3.42	2.41	3.30	5.74	3.96

4.4 Conclusions

Vegetative growth, yield and fruit quality is determined by the grapevine water status. Therefore, there should be a balance between vegetative and reproductive growth in order to increase productivity and improve water use efficiency. High leaf temperature and VPD, combined with low stem water potential reduced net carbon assimilation and stomatal conductance in Block A during the 2013/14 season. Higher values of net carbon assimilation rate and stomatal conductance corresponded with larger berry size and higher yield.

Block A had poor growth, lower yield, as well as poor fruit quality in both seasons. Soil water content was the highest in this block and there were also certain soil limitations that could have affected productivity and fruit quality. Despite the slower vegetative growth in Blocks B and C, these two blocks indicated an increase in yield and fruit quality from the first to the second season. Compared to the other blocks, Block D had the highest yield during the 2013/14 season, with the best quality in both seasons. Block D was more vigorous, with a denser canopy, which was confirmed by the lower light interception throughout the season. Furthermore, the heavy crop load observed for Block D in the first season had a negative effect on grape colour development and the percentage of export grapes. Therefore, in an effort to contribute to improved colour development and Export % in the next season, the producer applied stricter crop control, as well as more drastic canopy opening measures at véraison to improve light interception in this dense canopy leading to a reduced leaf area recorded at harvest.

More export grapes were harvested during the warmer, drier 2014/15 season. This might be an indication that prevailing drier and warmer climatic conditions exposed grapevines to a certain degree of water stress during the growing season, hence reducing vegetative growth in favour of improved fruit quality. The two sprinkler irrigated blocks (B and C) had a tendency towards a higher WUE_y in the 2014/15 seasons due to the higher ET and yield measured in these blocks. Yield water use efficiency measured in this study compared well with published results. Block D (drip irrigated) had a higher WUE_{irr} in both seasons, and also produced grapes of the best quality which means a certain stress level can be applied even when grapevines are cultivated for table grape production without forfeiting fruit quality and in the process, saving some water. Nonetheless, proper management with a proper irrigation and soil and plant water status monitoring is needed to be able to farm optimally and improve WUE_y and WUE_{irr}.

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Chapter 5

Research results

A case study on the practical application of FruitLook for improving water use efficiency in table grape production

CHAPTER V: A CASE STUDY ON THE PRACTICAL APPLICATION OF FRUITLOOK FOR IMPROVING WATER USE EFFICIENCY IN TABLE GRAPE PRODUCTION

5.1 Introduction

The availability of water is critical in almost all economic sectors. Of these sectors, agriculture is the most sensitive to water scarcity (Department of Water Affairs and Forestry, 2004). In South Africa, crops such as table grapes grown mostly in the warm and semi-arid areas of the Western Cape Province require irrigation. However, due to rising temperatures associated with global climate change, drier seasons are projected (Southey, 2017). In addition, the table grape growth cycle coincides with times in the year when high temperature, high evaporative demand and limited water resources prevail (Jones, 1990; Chaves *et al.*, 2007). These environmental conditions can have a negative impact on table grape production as well as on water resources if not well managed. To circumvent this, table grape producers have to maximise yield per unit of water used (Cifre *et al.*, 2005; Chaves *et al.*, 2007; Flexas *et al.*, 2010), a concept known as water use efficiency (WUE).

In order to fulfil the WUE concept, the objective of irrigation scheduling should be to provide enough water that will support normal plant growth without causing too much stress which could have a negative effect on production and fruit quality. Therefore, there is a need to know the required irrigation volume at the different phenological stages to optimise crop production and improve WUE. Currently most farmers are using either soil moisture content, standard irrigation hours per month or, in rare cases, plant water potential monitoring in irrigation scheduling. Unfortunately, these different methods have their own disadvantages such as soil variability in vineyards, inaccuracy of the sensor placing, distance from the roots and poor contact between the sensors and the soil. With variability in soil types and irrigation systems there is a need to accurately determine the crop water use to avoid over- or under supply. Unfortunately, there is a lack of information on exact crop water requirements, therefore tools that can aid in irrigation scheduling are needed to reduce unnecessary under- or over irrigation. Hence, tools that provide frequent information in time and space, such as satellite and aerial photography derived products, may be useful in irrigation scheduling and have potential to improve water use. A remote sensing satellite-based information service such as the FruitLook platform that provides plant growth, water and nutrient use information for vineyards in the Western Cape has the potential to be used as a water management tool in order to improve WUE (Jarmain *et al.*, 2014; Roux *et al.*, 2014). From survey feedback conducted on the FruitLook web portal usefulness, farmers indicated at least a 10-30% reduction in irrigation water use, suggesting that it has a potential to improve irrigation efficiency and can lead to increased WUE.

This chapter is presented as a case study and its aim is to compare FruitLook data to field measured data in order to (i) determine whether FruitLook satellite data reflects what is happening in the vineyard and (ii) whether FruitLook can add value in irrigation management and water footprint determination.

5.2 Materials and Methods

5.2.1 Study area

To evaluate the accuracy of FruitLook spatial data products available to table grape producers, four Crimson Seedless table grape blocks under different cultivation conditions, *i.e* soil types and irrigation systems in the Hex River Valley were selected and studied during the 2013/14 and 2014/15 growing seasons. Details on the respective blocks and conditions have been given in Chapter 3. The experimental units and data vines measured for field data measurements were representative of the whole block.

5.2.2 FruitLook

FruitLook is an open web portal funded by the Western Cape Department of Agriculture with eLeaf (eleaf.com) generating and providing the spatial data provided on www.fruitlook.co.za. On this portal, fruit and grape producers in the Western Cape have access to satellite-based information on plant growth, water use and nutrient status. FruitLook data is derived from a combination of satellite and field data and the ETLook algorithm is used (Bastiaanssen *et al.*, 2012; Pelgrum *et al.*, 2010). The ETLook uses the surface energy balance to estimate total evapotranspiration (ET) or the latent heat flux density (λE), biomass production, water deficit and biomass water use efficiency spatially. The simplified energy balance is given by the following equation:

$$\lambda E = Rn - G - H \qquad \text{(Eq. 4.1)}$$

where Rn is the net irradiance, G is the soil heat flux density and H is the sensible heat flux.

Land surface characteristics such as surface albedo, the normalised difference vegetation index and surface temperature are derived from satellite imagery. Meteorological data is taken from different weather stations in the same area and spatially extrapolated using an interpolation model called Daymet (Thornton *et al.*, 1997), that also takes into account land characteristics (like a DEM) during the interpolation of station measurements.

FruitLook data was extracted directly from their website using the block coordinates to define the corners of the blocks to make the polygon necessary for data extraction. Data was extracted for two seasons, namely the 2013/14 and 2014/15 seasons. FruitLook data is provided at a 20 m x 20 m spatial resolution and made available on a weekly basis for the main growing season (1 October to 30 April). The FruitLook data is categorised in three groups: growth, moisture and mineral parameters. Growth parameters include biomass production (kg) (total above & below ground dry matter), leaf area index (LAI) and the vegetation index. Moisture parameters in FruitLook consists of evapotranspiration deficit (mm), actual evapotranspiration (mm) and biomass water use efficiency (kg/m^3). The mineral parameters comprise of N (kg) present in the upper leaf layer as well as N in the total plant. Hence, the following FruitLook and field measurements datasets were compared as indicated in Table 5.1.

Table 5.1: A list of the FruitLook and field measurements datasets used to validate FruitLook for the four experimental blocks during the 2013/14 and 2014/15 seasons.

FruitLook datasets	Field measurements datasets
Biomass production Accumulated biomass production	Shoot growth
Actual evapotranspiration (ET_{FL})	Estimated ET from water balance equation (ETWB)
Evapotranspiration deficit (ETdef)	Stem water potential (SWP)
Biomass water use efficiency (BWUE)	Yield water use efficiency (WUE_y) Irrigation water use efficiency (WUE_{irr})

5.2.3 Shoot growth and biomass production

Shoot growth was measured as a growth indicator (Refer to Chapter 3). Shoot growth was compared to the weekly FruitLook biomass production and the accumulated biomass production.

5.2.4 Soil water balance calculations

For details regarding soil water content measurements and calculations needed for estimated evapotranspiration (ETWB) determination, refer to Chapter 3, Section 3.2.5.

5.2.5 Actual evapotranspiration and estimated evapotranspiration

FruitLook actual evapotranspiration (ET_{FL}) is a combination of evaporation from the land surface and grapevine transpiration as determined by ETLook algorithm. The ETWB was calculated by means of the water balance equation, using measured values of rain, irrigation and soil moisture change as already discussed in Chapter 3, Section 3.2.6. Estimated ETWB was calculated for the period from 8 December 2014 to 21 August 2015 on a bi-weekly interval. FruitLook data was, however, only available from the beginning of October 2014 to the end of April 2015 Therefore, for comparison purpose between ET_{FL} and ETWB, the period between December 2014 and April 2015 was used. Water Balance estimated ET (ETWB) was corrected with published crop factors (CF) from Lategan (1996) ($ETWB_{(L)}$), (Myburgh, 2003a) ($ETWB_{(M)}$) and FruitLook (fruitlook.co.za) ($ETWB_{(FL)}$) respectively, in order to estimate the actual plant water use.

5.2.6 Evapotranspiration deficit and stem water potential

Evapotranspiration deficit (ETdef) is the difference between the actual ET and the potential ET. This parameter is an indicator of total plant stress whether it is from water, heat, wind or salinity *etc.* Stem water potential (Ψ_S) was used to determine the effectiveness of ETdef as a possible plant stress indicator. Refer to Chapter 3 for details on Ψ_S measurements.

5.2.7 Yield water use efficiency and irrigation water use efficiency

Yield water use efficiency (WUE_y) was determined by dividing yield (kg/ha) by seasonal FruitLook accumulated actual ET (September-April). The following equation was used:

$WUE_y = Y/ ET$ (kg/mm or kg/m^3) (Eq. 4.2)

where Y is yield in kg/ha and ET is evapotranspiration in mm.

Irrigation water use efficiency (WUE_{irr}) was determined by dividing yield (kg/ha) by seasonal irrigation volumes according to the following equation: $WUE_{irr} = Y/I$ (Eq. 4.3)

FruitLook Biomass water use efficiency was compared to WUE_y and WUE_{irr}.

5.2.8 Statistical analysis and software

Statistical analysis was conducted using Statistica 10 ® software (Statsoft, Tulsa, UK). Pearson's regression was used for data presented in this chapter to determine the relationship between the different 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.

5.3 Results and Discussion

5.3.1 Shoot growth and biomass production

Details regarding the shoot growth responses of the four blocks were given in detail in Chapter 3. Results showed that Block D had more vigorous shoot growth in both seasons compared to the other three blocks (Fig. 5.1A & 5.2A), probably due to higher carbon percentage and clay content that might have stimulated growth. FruitLook Block A also indicated a slower shoot growth with an earlier cessation of shoot growth at about 85 DAB during the 2013/14 season (Fig. 5.1B). Biomass production according to FruitLook showed similar trends (Fig. 5.1B). During the 2014/15 season, Blocks B and C shoot growth were comparably lower than Block A and D throughout the season (Figure 5.2A). Similar patterns were observed in the FruitLook biomass production graphs (Figure 5.2B), also indicating that Block D had higher biomass production in this particular season. Field measurements showed that Block A had a slower growth with earlier shoot growth cessation compared to the rest of the blocks (Figs. 5.1A & 5.2A) and this trend was also evident on the weekly FruitLook biomass production graphs, particularly for the 2013/14 season.

Block A count ratios was high throughout the growing season indicating that this block was wet, which could have had a negative impact on growth. From the beginning of each season, there was an increase in shoot growth and biomass production in all blocks until shoot growth cessation at about 85 to 100 DAB and 90 to 105 DAB during the 2013/14 season and 2014/15 season, respectively (Figure 5.2). FruitLook weekly biomass production indicated a rapid increase in shoot growth between 60 to 100 DAB which corresponds with the fruit set to ripening stage. Harvest took place between 164 to 172 DAB and 136 to 146 DAB in the 2013/14 and 2014/15 seasons, respectively, and that is clearly indicated on the biomass production graph with a decline afterwards. From 100 DAB there is a decline in FruitLook biomass production which corresponds to the cessation of shoot growth. The FruitLook weekly biomass production does not reflect the total biomass of the crop, but the weekly gain in biomass. Therefore, it can be concluded that the weekly biomass production measurements capture the different growth patterns well at the different phenological stages based on the continued decline in biomass production between harvest (136-172 DAB) and post-harvest (173-240 DAB) period. There was a good correlation between weekly biomass production and shoot growth for both seasons, with the 2013/14 and 2014/15 seasons having an r^2 of 0.88 and 0.80, respectively (Figure 5.3).

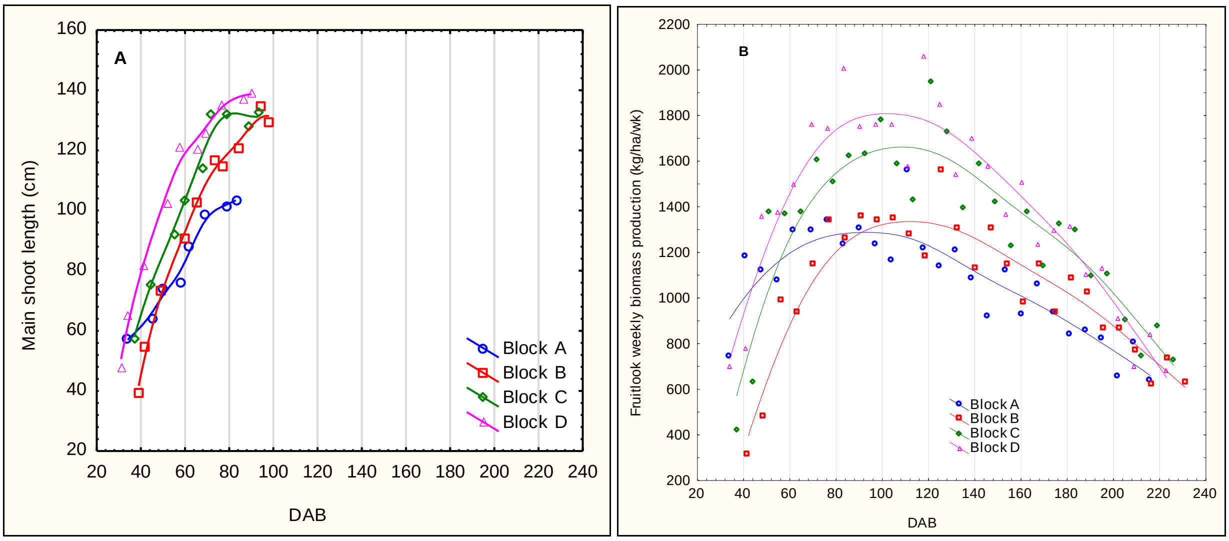

Figure 5.1: The (A) average main shoot length (cm) and (B) FruitLook weekly biomass production (kg/ha/week) relative to date after budburst (DAB) of the four experimental blocks for the 2013/14 season. A distance weighted least squares fit was drawn.

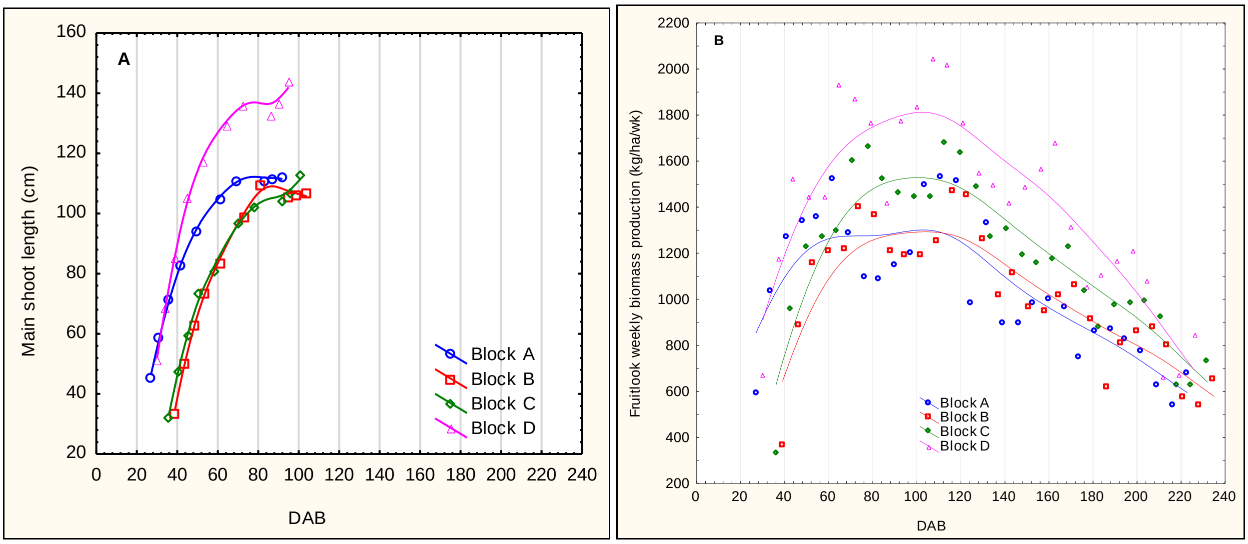

Figure 5.2: The (A) average main shoot length (cm) and (B) FruitLook weekly biomass production (kg/ha/week) relative to date after budburst (DAB) of the four experimental blocks for the 2014/15 season. A distance weighted least squares fit was drawn.

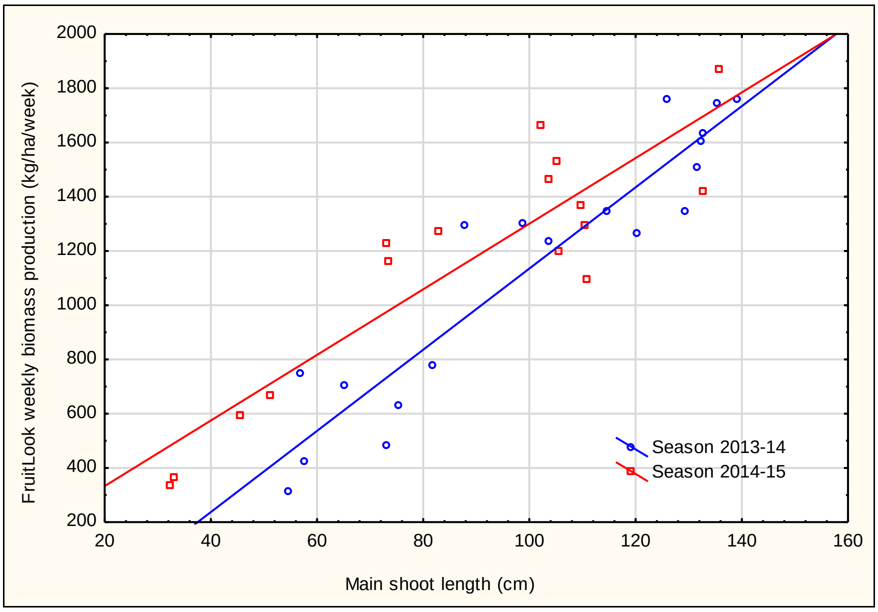

Figure 5.3: Relationship between FruitLook weekly biomass production and main shoot length measured for the 2013/14 and 2014/15 seasons. Regression results: Season 2013/14: r= 0.94; p= 0.00; r^2= 0.88; Season 2014/15: r= 0.90; p= 0.00; r^2= 0.80.

FruitLook accumulated biomass production for both seasons indicated that Block D had a higher biomass production with Block B showing lower values in both seasons (Figure 5.4). This agreed with the shoot growth and the canopy development observations in the vineyards, where Block D had more vigorous growth and a visually denser canopy. Blocks A and B had less dense canopies as indicated on the FruitLook accumulated biomass production (Figure 5.4). Distinct differences in accumulated biomass production between Blocks C and D were noted in the 2014/15 season whereas a smaller difference was noted during the 2013/14 season. Results were therefore similar to the field measurements, where Block C had more vigorous growth during the 2013/14 season compared to the 2014/15 season. Block C had a higher fraction of medium and course sand with low clay content and is sprinkler irrigated, with the second season also being drier and hotter, leading to more water loss through evapotranspiration hence causing a negative impact on growth. In general, shoot growth and biomass production was higher in the 2013/14 season compared to the 2014/15 season. This is due to the fact that the 2014/15 season was drier and hotter compared to the 2013/14 season. All these blocks had a uniform management practice and no green cover crops were grown, but natural grass was allowed to grow between the rows during the growing season and at pruning the pruning canes were left on the rows. No measurements were done between the working rows and the assumption was therefore included here that the conditions were similar in all blocks. The global (over seasons) comparison, supported an exponential fit (r = 0.88) between Fruitlook accumulated biomass production and main shoot length, which seemed to follow the vigorous growth very well. The seasonal comparison between Fruitlook accumulated biomass production and main shoot length is indicated on Figure 5.5.

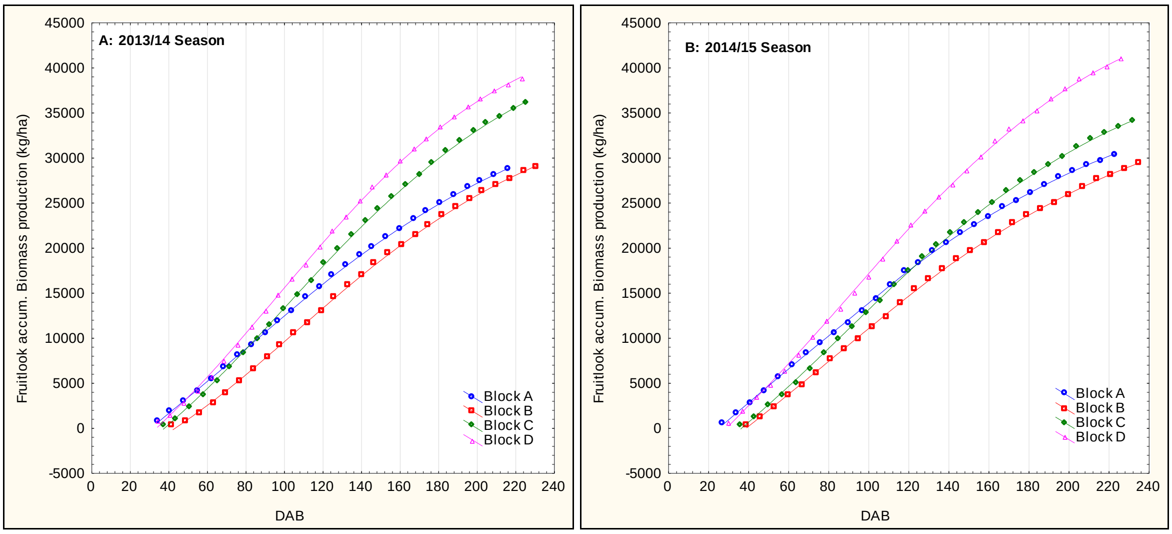

Figure 5.4: Accumulated biomass production (kg/ha) relative to date after budburst (DAB) of the four experimental blocks for the (A) 2013/14 and (B) 2014/15 seasons. A distance weighted least squares fit was drawn.

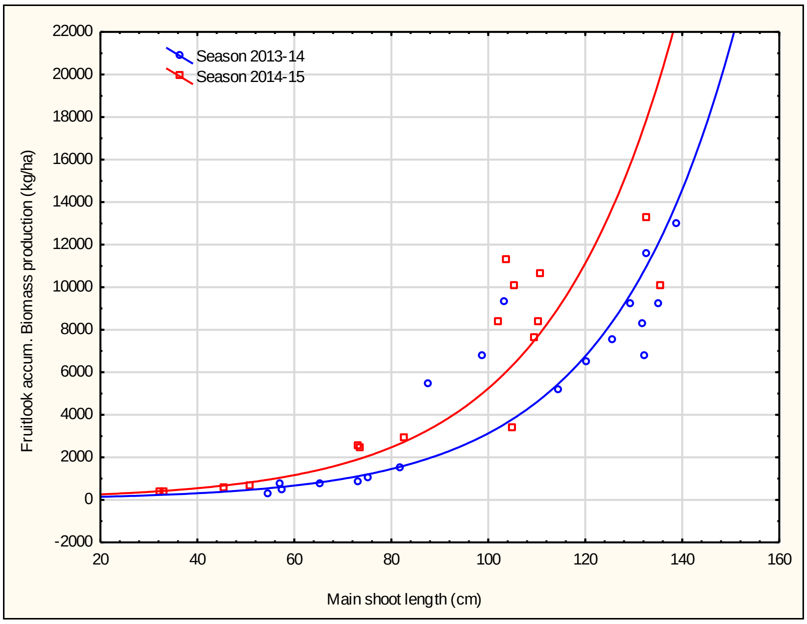

Figure 5.5: Exponential relationship between FruitLook accumulated biomass production and main shoot length measured for the four experimental blocks for the 2013/14 (r=0.91) and 2014/15 (r=0.89) seasons.

5.3.2 Evapotranspiration (ET)

Accumulated ET_{FL} and the accumulated ETWB, $ETWB_{(L)}$, $ETWB_{(M)}$ and $ETWB_{(FL)}$ is shown in Figure 5.6. The uncorrected water balance ET (ETWB) was the highest followed by $ET_{FL,}$ $ETWB_{(M)}$, $ETWB_{(FL)}$ and lastly the $ETWB_{(L)}$. FruitLook accumulated actual ET indicated higher ET in Block D and lower ET in Block B (Fig. 5.6A). In contrast, ETWB indicated lower ET in Block D (Fig. 5.6 B, C & D), except for $ETWB_{(FL)}$ that was corrected with the FruitLook CF derived from the higher ET_{FL} determined for that block. Accumulated ET values relative to date after budburst indicated a linear increase of ET over time up to 180 DAB (Fig 5. 6). This was followed by a depression point which was more evident in the corrected water balance ET estimations and corresponded with cessation of grapevine growth. This is also the stage where high climatic pressure with higher temperatures can increase evaporation. What is interesting to note is the uncorrected ETWB that seems to be accounting less for the high demand for evaporation. FruitLook ET and ETWB$_{(FL)}$ indicate a less drastic depression from 180 DAB compared to ETWB$_{(M)}$ and ETWB$_{(L)}$.

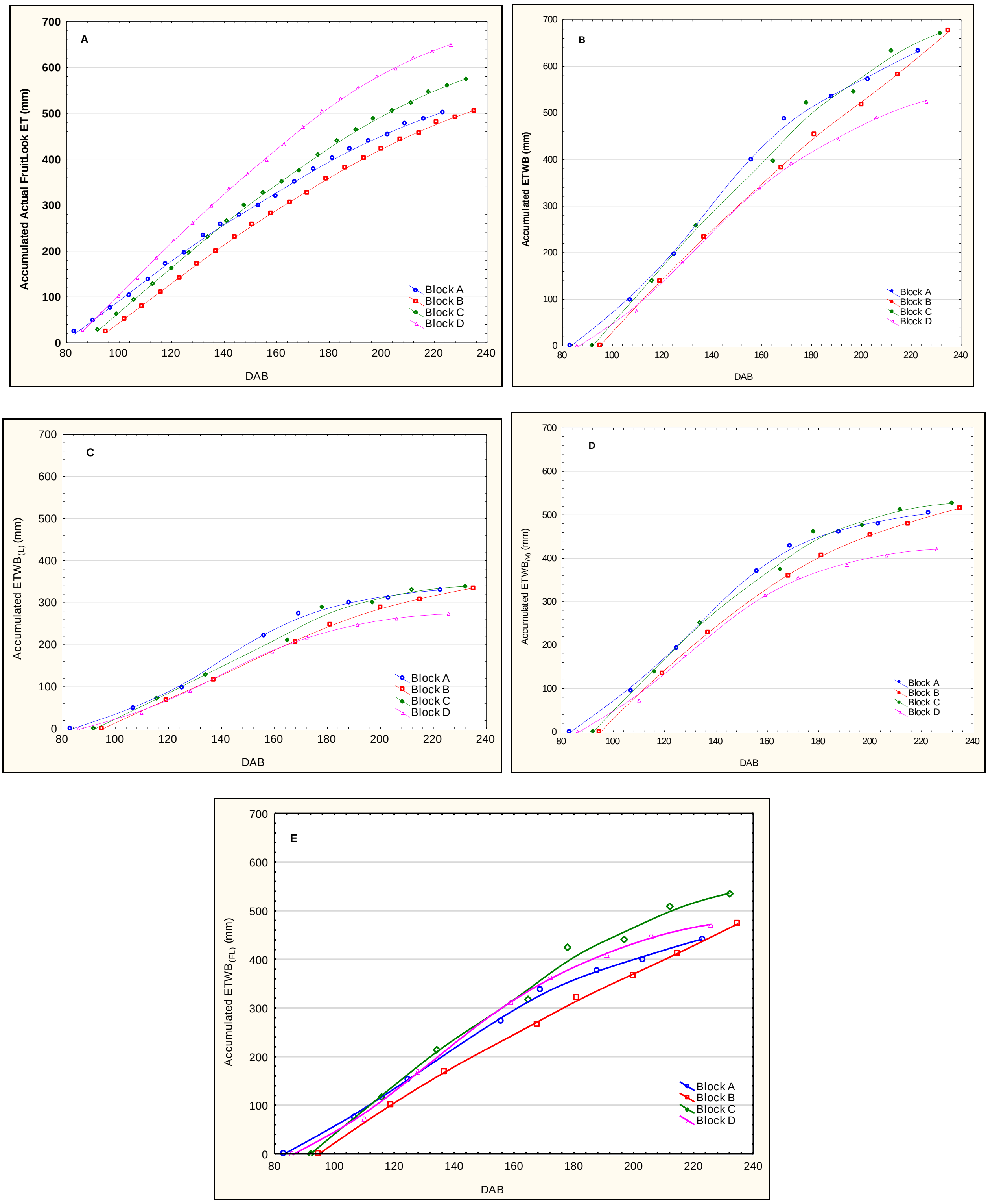

Figure 5.6: Accumulated (A) actual FruitLook ET, (B) ETWB, (C) ETWB$_{(L)}$, (D)ETWB$_{(M)}$ and (E)ETWB$_{(FL)}$ relative to date after budburst (DAB) of the four experimental blocks for the 2014/15 season. A distance weighted least squares fit was drawn.

Comparisons were made between the point-based evapotranspiration estimated from the ETWB and the spatially averaged ET_{FL} data from December to April 2015. There was a strong positive correlation between accumulated actual FruitLook ET (ET_{FL}) and the estimated accumulated water balance ET (ETWB, $ETWB_{(L)}$, $ETWB_{(M)}$ and $ETWB_{(FL)}$) as shown in Figure 5.7. to Figure 5.10. Remote sensing studies in different crops such as wine grapes (Campos *et al.*, 2012; Vanino *et al.*, 2015), apples trees (Odi-Lara *et al.*, 2016), citrus trees (Dzikiti *et al.*, 2009) and peach trees (Bellvert *et al.*, 2014) was reported to give a good estimation of crop water use with the technique. Similar patterns in ET were seen in Blocks A, B and C for all calculations, *i.e.* higher water balance ET compared to FruitLook ET. However, Block D water balance ET estimates were lower than the FruitLook ET. Block D had low soil moisture content throughout the growing season due to the high stone fraction that can reduce the count ratio (CR) significantly and that might have affected the water balance calculations. Additionally, the water balance equation did not account for drainage and it is possible that more water could have been lost in Block D that FruitLook could pick up. It was interesting to note that the relationship between ET_{FL} and $ETWB_{(FL)}$ indicated a similar relationship between the different blocks, hence making this crop factor suitable to be used in water balance equations.

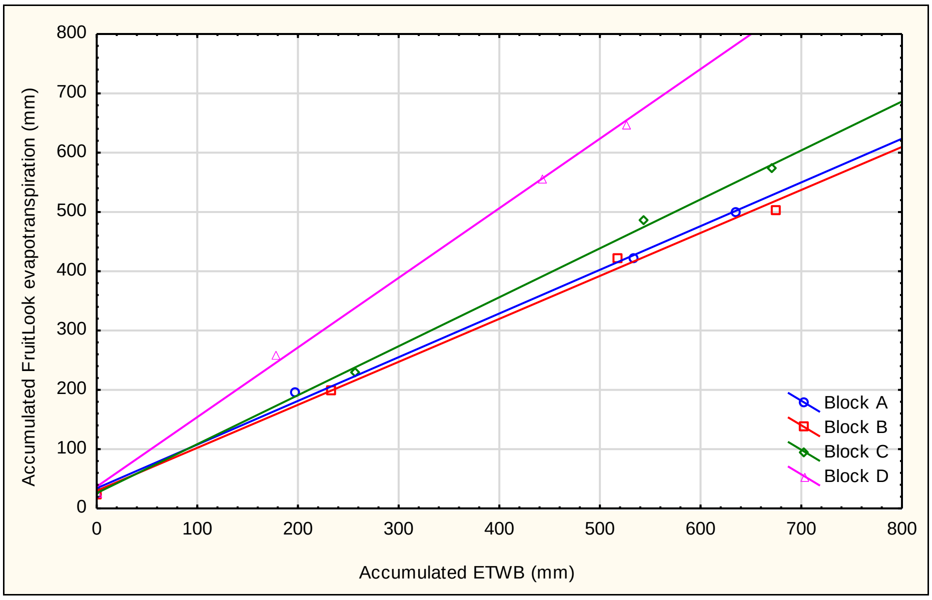

Figure 5.7: Relationship between FruitLook evapotranspiration and the estimated water balance evapotranspiration measured for the four experimental blocks for the 2014/15 seasons. Regression results: Block A: r = 1.00; p = 0.00; r^2 = 1.00; Block B: r = 1.00; p = 0.00; r^2 = 1.00; Block C: r = 1.00; p = 0.00; r^2 = 1.00; Block D: r = 1.00; p = 0.00; r^2 = 1.00.

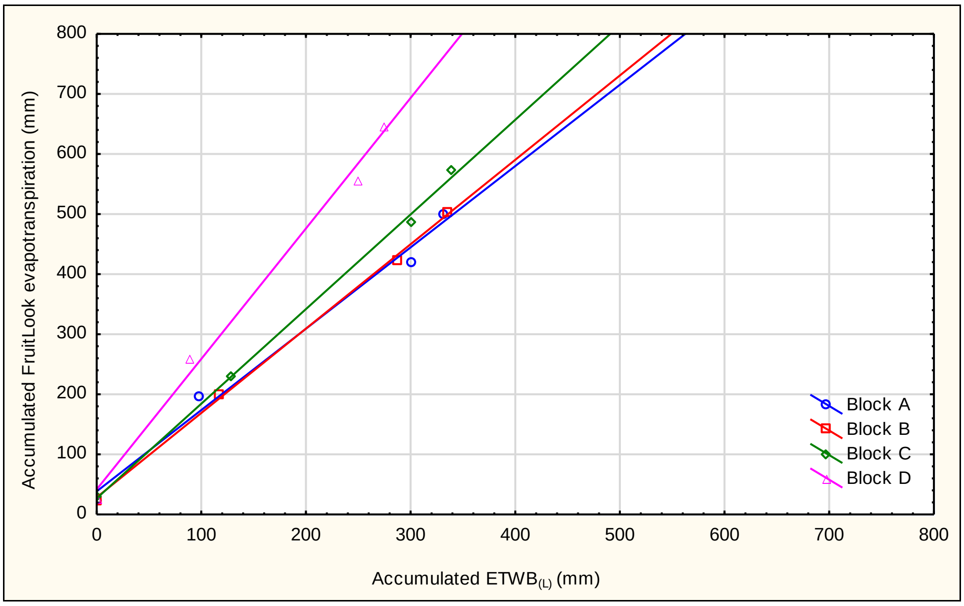

Figure 5.8: Relationship between FruitLook evapotranspiration and the estimated water balance evapotranspiration corrected with crop factors from Lategan (1996) measured for the four experimental blocks for the 2014/15 seasons. Regression results: Block A: r = 0.99; p = 0.01; r^2 = 0.99; Block B: r = 1.00; p = 0.00; r^2 = 1.00; Block C: r = 1.00; p = 0.00; r^2 = 1.00; Block D: r = 1.00; p = 0.00; r^2 = 0.99.

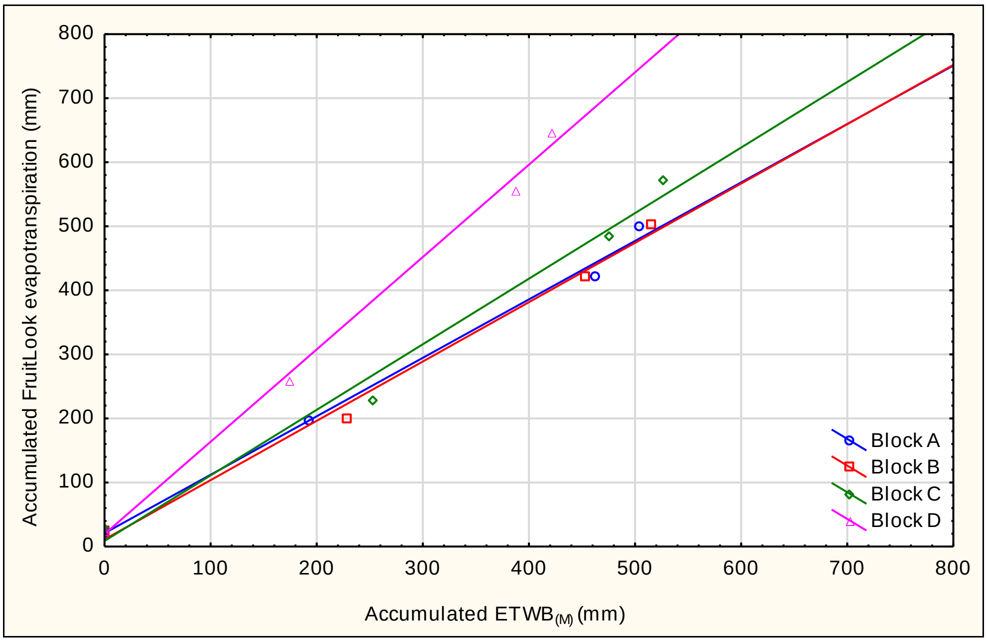

Figure 5.9: Relationship between FruitLook evapotranspiration and the estimated water balance evapotranspiration corrected with crop factors from Myburgh (2003a) measured for the four experimental blocks for the 2014/15 seasons. Regression results: Block A: r = 1.00; p = 0.00; r^2 = 0.99; Block B: r = 1.00; p = 0.00; r^2 = 0.99; Block C: r = 0.99; p = 0.01; r^2 = 0.99; Block D: r = 1.00; p = 0.00; r^2 = 1.00.

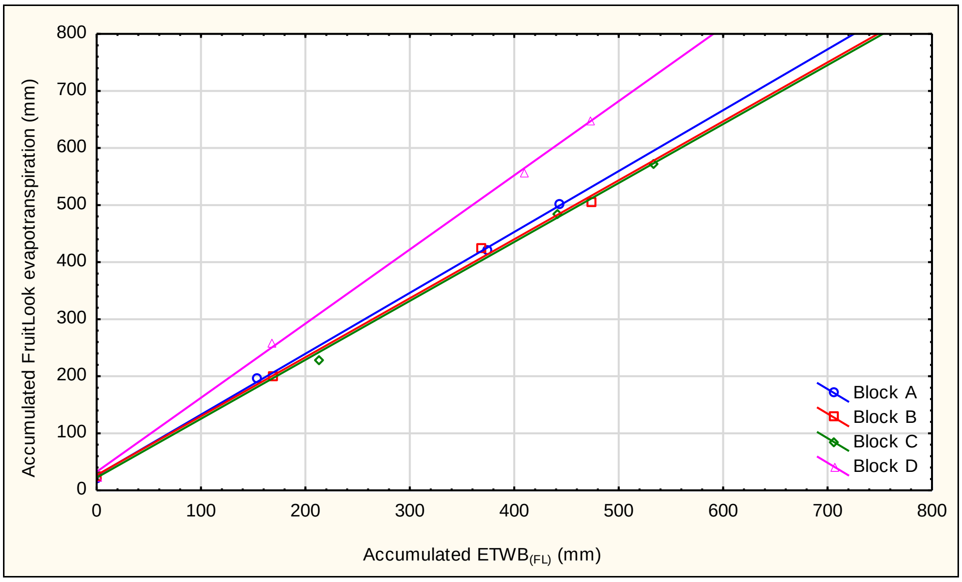

Figure 5.10: Relationship between FruitLook evapotranspiration and the estimated water balance evapotranspiration corrected with crop factors derived from FruitLook data measured for the four experimental blocks for the 2014/15 seasons. Regression results: Block A: r = 1.00; p = 0.00; r^2 = 1.00; Block B: r = 1.00; p = 0.00; r^2 = 1.00; Block C: r = 1.00; p = 0.00; r^2 = 1.00; Block D: r = 1.00; p = 0.00; r^2 = 1.00.

Irrigation volumes applied to each block were calculated for the same period as the ET determinations (Table 5..2). The water balance ET calculation that was not corrected with any CF is also included for comparison. It should be noted that it was 12% higher than ET_{FL}. Therefore, the focus of the following discussion will only be on the following: ET_{FL}, $ETWB_{(L)}$, $ETWB_{(M)}$ and $ETWB_{(FL)}$. Block C's $ETWB_{(FL)}$ and $ETWB_{(M)}$ was higher than all the other water balance estimated ET values, while the ET_{FL} was the highest in Blocks C and D (Table 5..2). The higher ET_{FL} in Blocks C and D was due to the more vigorous growth observed in those blocks. In contrast, the higher $ETWB_{(M)}$ was due to its crop factor that was determined from a full cover canopy in the Lower Orange River conditions. The $ETWB_{(L)}$ was the lowest of all the ET values for all blocks. The difference between irrigation volumes and ET_{FL} was 130 mm, 117 mm, 106 mm and -155 mm for Blocks A, B, C and D, respectively. The difference between the irrigation water applied and the highest $ETWB_{(M)}$ was 106 mm and 153 mm for Blocks B and C, respectively. Furthermore, the differences between the irrigation volumes applied and the highest $ETWB_{(FL)}$ was 148 mm and 145 mm for Blocks B and C, respectively. This suggested that the vineyard blocks were irrigated with more water than was necessary for optimal growth, *i.e.* they were over-irrigated. The only block that looked as if it had a better irrigation scheduling was Block D, where 493 mm of water was applied. It was evident that irrigation applications in Blocks A, B and C was very high and proper irrigation scheduling would reduce water use and improve WUE. Based on the block average comparison between the irrigation volumes and ET values, on over irrigation of 490 m^3, 2870 m^3, 1140 m^3 and 1250 m^3 was determined for ET_{FL}, $ETWB_{(L)}$, $ETWB_{(M)}$ and $ETWB_{(FL)}$ respectively. Therefore, in this case study, there could have been a water saving of about 1438 m^3 (average of the different ET types) if more stringent irrigation scheduling was adhered to.

Table 5.2: Irrigation, actual FruitLook evapotranspiration and estimated water balance evapotranspiration (mm) calculated for the four Crimson Seedless blocks from the second week of December 2014 to April 2015.

	Irrigation (mm)	FruitLook ET$_{FL}$ (mm)	Estimated ET$_{WB}$ (uncorrected) (mm)	Crop Factor Corrected ET$_{WB}$ (mm)		
Reference				Lategan, 1996 ETWB$_{(L)}$	Myburgh, 2003 ETWB$_{(M)}$	FruitLook ETWB$_{(FL)}$
Block A	630	500	634	331	504	443
Block B	622	505	675	335	516	474
Block C	679	573	670	338	526	534
Block D	493	648	526	273	421	472
Average	606	557	626	319	492	481

Accumulated actual FruitLook ET and irrigation volumes for the growing seasons (September to April) were compared for the 2013/14 and 2014/15 seasons (Table 5.3). The ET$_{FL}$ of the 2013/14 season was higher than the 2014/15 season and that also corresponded to the more vigorous growth observed in the 2013/14 season compared to the 2014/15 season which was drier and hotter. Block D had the highest ET$_{FL}$ while Block B had the lowest ET$_{FL}$ for both season (Table 5.3). As expected, the two drip irrigated blocks had lower irrigation volumes for both seasons. The difference between the irrigation volume and ET$_{FL}$ is presented in Table 5.3. Negative values indicate that the irrigation volumes for those specific blocks were below the ET$_{FL}$ values, indicating an under supply or a more conservative water use that might lead to increased WUE. Thus, Blocks A and D had a water saving of 3510 m3 and 3230 m3, respectively, for the 2013/14 season. Block D also indicated a further saving of 2830 m3 during the 2014/15 season. The micro-sprinkler irrigated blocks, *i.e.* Blocks B and C, had an average over-irrigation of approximately 1960 m^3 and 1620 m^3, respectively. Results confirmed the water balance ET calculation that indicated that Blocks A, B and C had higher ETWB compared to Block D that had the lowest ETWB.

Table 5.3: Seasonal irrigation (mm) and Actual FruitLook evapotranspiration (mm) (September–April) calculated for the four Crimson Seedless blocks for the 2013/14 and 2014/15 seasons.

Season	2013/14			2014/15		
Block	Irrigation (mm)	Accumulated ET_{FL} (mm)	Irrigation – ET_{FL} (mm)	Irrigation (mm)	Accumulated ET_{FL} (mm)	Irrigation – ET_{FL} (mm)
A	455	806	-351	755	710	45
B	963	784	179	913	700	213
C	1051	936	115	996	787	209
D	639	962	-323	606	889	-283

5.3.3 Evapotranspiration deficit and stem water potential

Moisture stress due to too little or too much water can have a negative impact on plant growth and productivity therefore it is important to monitor plant water status (Lakso, 1985; Jones, 1990; Flexas *et al.*, 1999; Medrano *et al.*, 2003; Bacon, 2004; Iland *et al.*, 2011). Plant water status as leaf or stem water potential is monitored mainly in research studies, but it is also monitored to a limited degree in commercial vineyards, (Choné *et al.*, 2001; Deloire *et al.*, 2004; Van Leeuwen *et al.*, 2009; Myburgh, 2011). Alternatively, ETdef can be used as a possible monitoring tool for plant stress. The ETdef gives an indication of the shortfall between the actual ET and the potential ET that might have a negative impact on growth. Weekly ETdef for the 2013/14 and 2014/15 seasons are presented in Figure 5.11. and Figure **5.12**. It is evident that the 2014/15 season had higher plant stress compared to the 2013/14 season. This was most likely due to the drier and hotter conditions in the 2014/15 season (Refer to Chapter 3 for further details). Season 2013/14 indicated higher ETdef early in the season with values between 0-6 mm/week (Figure 5.11). Blocks B and C indicated the highest plant stress early in the season, while Block A indicated stress throughout the season. In the 2014/15 season, higher ETdef were noted early in the season (Fig. 5.12)., This might have been aggravated by the higher temperatures recorded at that phenological stage (Refer to Chapter 3). Block D had a tendency towards lower plant stress from véraison to harvest, and then during the post-harvest stages. During the 2014/15 season, two ETdef peaks were noted at fruit ripening (76-125 DAB) and harvest (136-160 DAB) (Figure 5.12). The weekly ETdef was lowest in Block D and the highest in Block A in both seasons. This might have negatively affected biomass production, reduced shoot growth, yield and fruit quality in Block A. Furthermore, the soil water status monitoring during the 2014/15 season indicated that Block A was the wettest throughout the measuring period. Therefore, there might also be the possibility that roots were not functioning optimal hence affecting water uptake as well as growth.

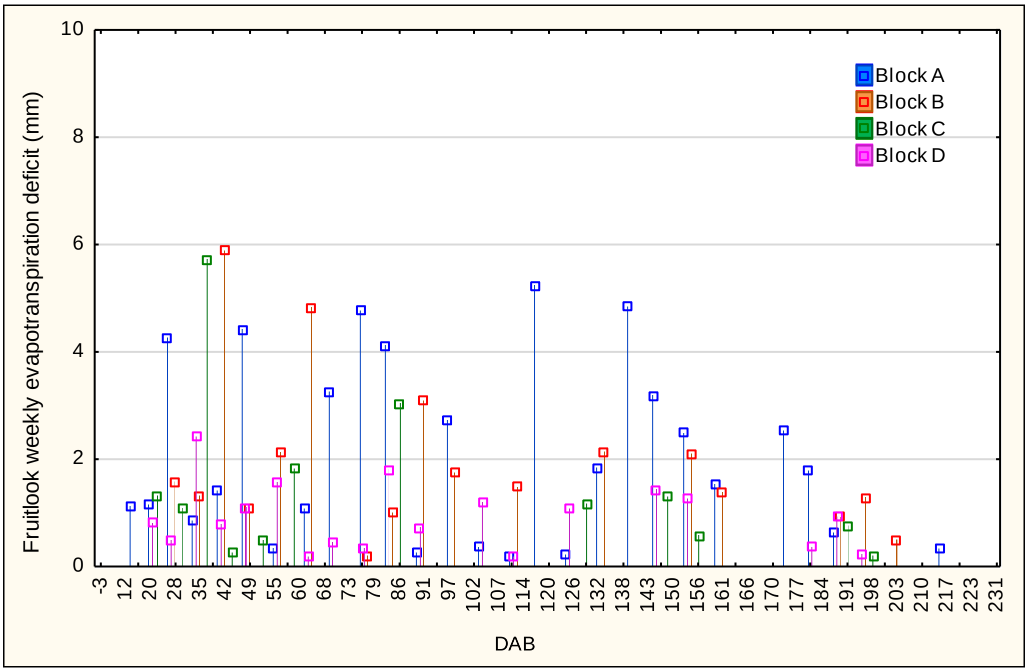

Figure 5.11: Fruitlook weekly evapotranspiration deficit (ETdef) in mm related to days after budbreak (DAB) of the four experimental blocks for the 2013/14 season.

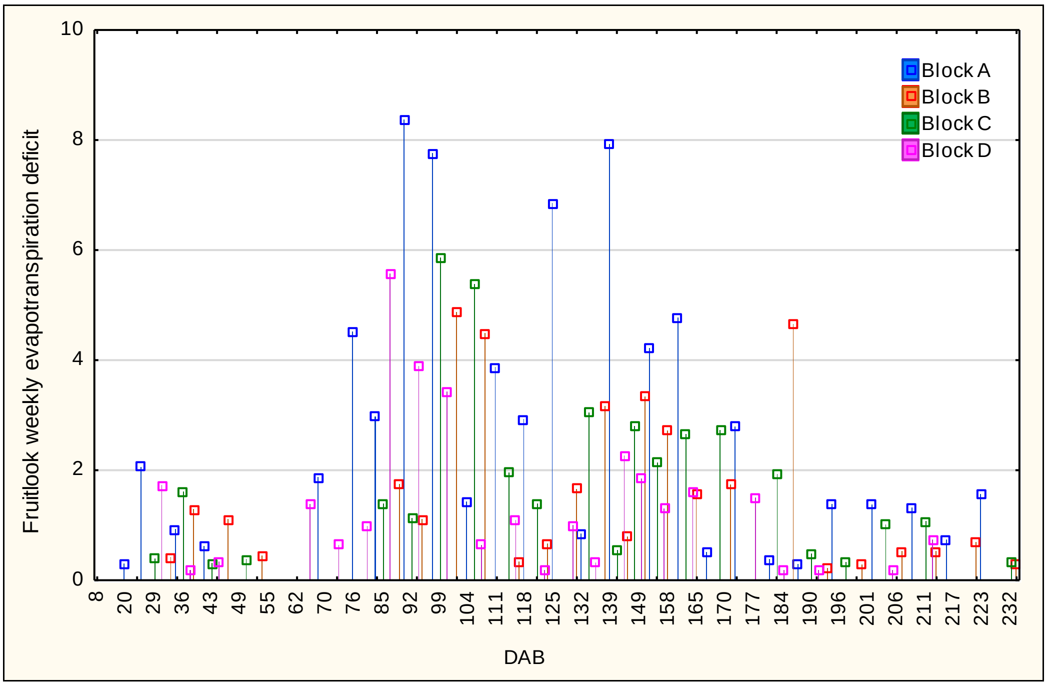

Figure 5.12: Fruitlook weekly evapotranspiration deficit (ETdef) in mm related to days after budbreak (DAB) of the four experimental blocks for the 2014/15 season.

Another recommended way of determining apparent stress experienced in the different blocks in percentage terms per season is to relate ETdef to accumulated Actual ET (ETdef/ET$_{FL}$). Block A had the highest perceived stress of 6.82% and 11.15% for the 2013/14 and 2014/15 season, respectively (Table 5.4). This corresponded with the slower shoot growth, lower yield and poorer fruit quality measured in that block. As discussed previously, Block A was the wettest throughout the measuring period and there might have been a possibility that the roots were not functioning optimal hence affecting water uptake as well as growth. Even though Block D had more vigorous growth in both seasons with a higher crop load in the 2013/14 season, it had the lowest apparent plant stress for both seasons. Blocks B and C seemed to have slower shoot growth and a higher crop load during the 2014/15 season that indicated higher plant stress.

Table 5.4: Accumulated FruitLook weekly evaporation deficit (ETdef) related to accumulated Actual evapotranspiration (ET) in order to determine stress experienced in the different blocks in percentage terms for the 2013/14 and 2014/15 seasons.

Block	2013/14 Season		2014/15 Season	
	Accumulated ETdef	$ETdef/ET_{FL}$ (%)	Accumulated ETdef	$ETdef/ET_{FL}$ (%)
A	54.94	6.82	79.15	11.15
B	32.71	4.17	38.66	5.52
C	17.76	1.90	49.01	6.23
D	17.37	1.81	31.16	3.51

Although there was a positive correlation between ETdef and Ψ_S in the 2013/14 season, there was no correlation between the two parameters in the 2014/15 season (Figure 5.13). No correlation relationship was found for the global analysis (r2=0.07). The reason for the poor relationship might be that the two parameters are not measuring the same thing. Stem water potential measures plant water status whereas ETdef is on indicator of total plant stress whether it be from water, heat, wind or salinity *etc*. Hence, higher ETdef values do not necessarily correspond to lower stem water potential values. Since FruitLook data is available on a weekly basis, sometimes stem water potential measurement times did not overlap with the FruitLook measurement time. Thus, data values measured at closer time/day were compared instead. Climatic conditions can influence both parameters making it hard for comparison, especially when measurements are not done at the same time. FruitLook also consider all vegetation in the vineyard, including weeds, to determine ET and ETdef thereby making a more global assessment compared to field measurements of stem water potential. Therefore, ETdef might not be a suitable tool to measure plant water stress and actual field measurements are necessary for optimal irrigation scheduling to improve WUE.

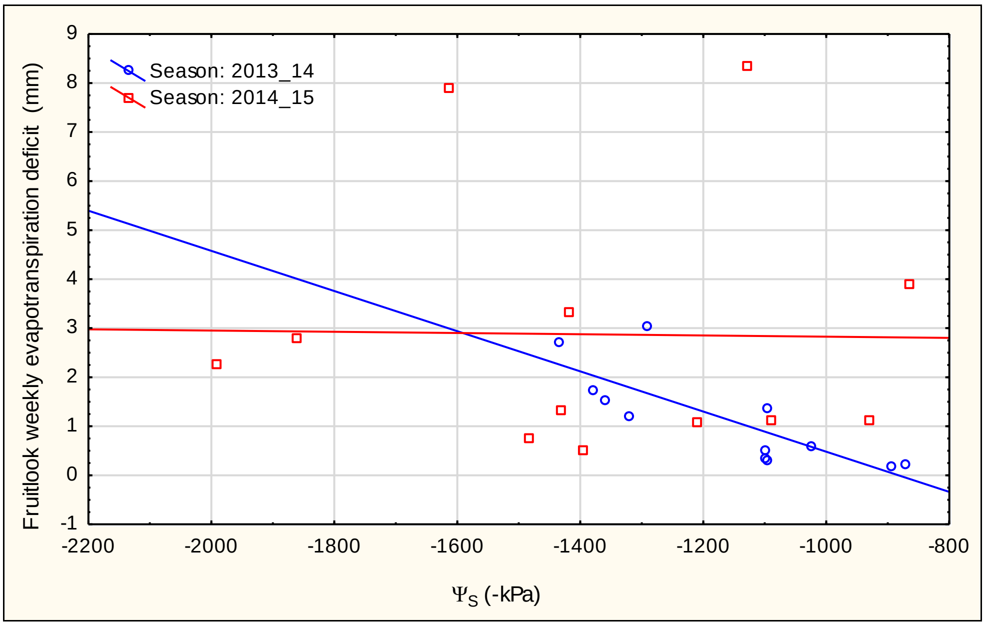

Figure 5.13: Relationship between FruitLook evapotranspiration deficit (ETdef) and stem water potential (Ψ_S) measured for the four experimental blocks for both seasons. Regression results: Season 2013/14: r= -0.80; p= 0.00; r^2= 0.63; Season 2014/15: r= -0.02; p= 0.96; r^2= 0.00.

5.3.4 Biomass water use efficiency and yield water use efficiency

The BWUE was higher than the WUE_y in both seasons, except for Block B during the 2014/15 season (data not shown). This was to be expected since FruitLook consider both above and below ground biomass while in the case study only yield was considered for WUE_y calculations. In the 2014/15 season, the WUE_y of Block B was 4.46 kg/m^3 compared to 4.25 kg/m^3 for BWUE. The BWUE of Block A (3.78 kg/m^3), B (3.73 kg/m^3) and C (3.86 kg/m^3) in the 2013/14 season was comparable to the 3.89 kg/m^3 reported for Crimson Seedless in the same area (Roux *et al*., 2014). However, the BWUE of Block D in the 2013/14 season and all the blocks in the 2014/15 season was higher than this reported value. There was a positive as well as a negative linear correlation between FruitLook BWUE and WUE_y for the different seasons (Fig. 5.14). The seasonal differences were likely due to different climatic conditions observed over these seasons. The 2013/14 season had a stronger positive relationship compared to the 2014/15 season. Similar observations were also noted for the correlation between BWUE and WUE_{irr}. In this instance, a weak relationship was found for the 2014/15 season (Figure 5.15). Since the correlation of WUE_{irr} with BWUE was more consistent than that of WUE_y, it appears that BWUE gives a better indication of WUE_{irr} rather than WUE_y. In this regard, the FruitLook BWUE parameter could be used in producers' management planning on grapevine growth and efficient water use to avoid unnecessary water wastage and improve WUE

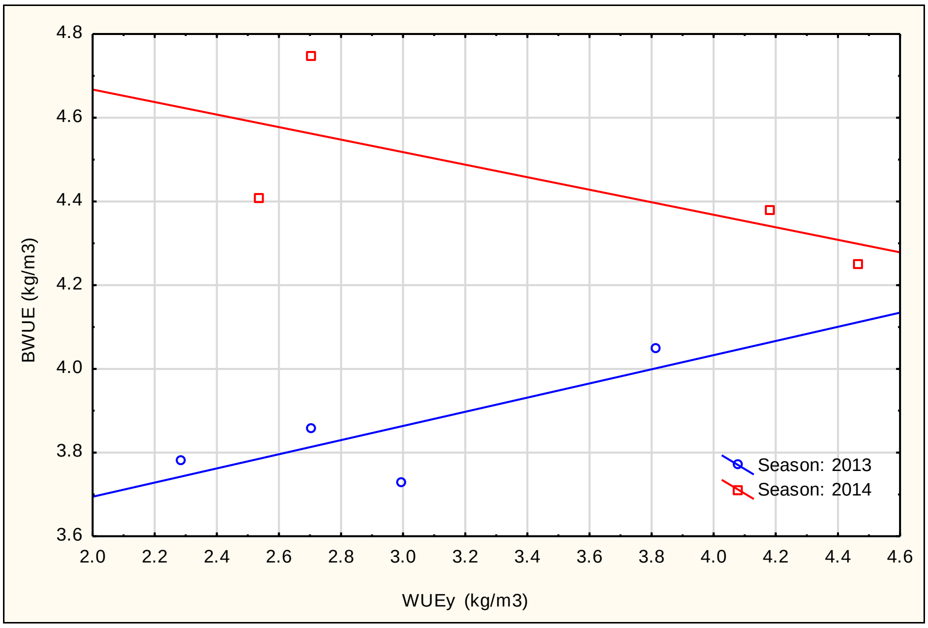

Figure 5.14: Relationship between FruitLook biomass water use efficiency (BWUE) and yield water use efficiency (WUEy) measured for the 2013/14 and 2014/15 seasons. Regression results: season 2013/14: r= 0.78; p= 0.22; r^2= 0.60; season 2014/15: r= -0.70; p= 0.30; r^2= 0.48.

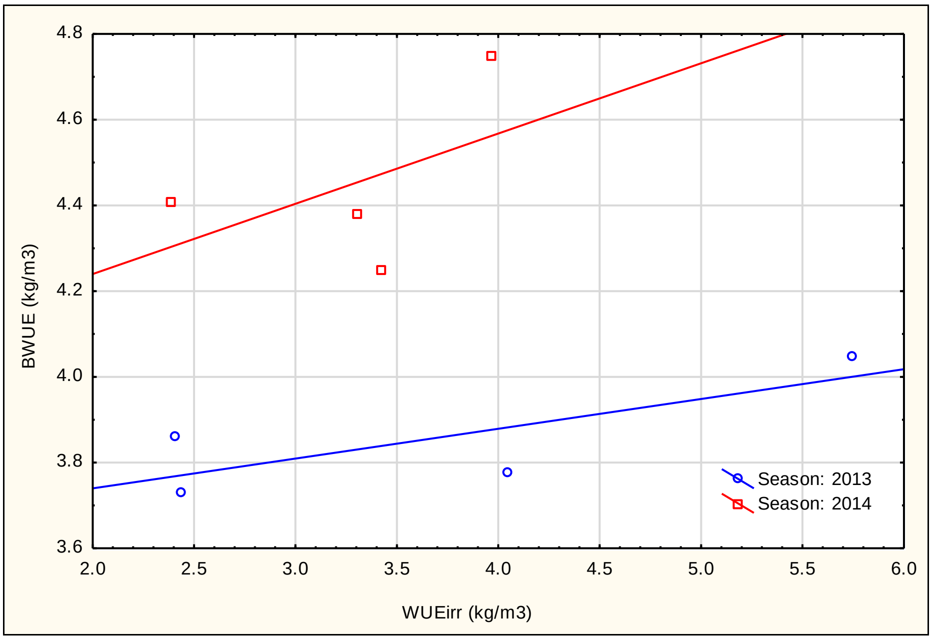

Figure 5.15: Relationship between FruitLook biomass water use efficiency (BWUE) and irrigation water use efficiency (WUE_{irr}) measured for 2013/14 and 2014/15 seasons. Regression results: season 2013/14: r= 0.78; p= 0.22; r^2= 0.61; season 2014/15: r= 0.50; p= 0.50; r^2= 0.25.

5.4 Conclusions

There was a positive correlation between weekly biomass production and shoot growth for both seasons, indicating the potential of using FruitLook to monitor grapevine vegetative growth. FruitLook determined higher biomass production for Block D; while slower shoot growth and an earlier shoot growth cessation was noted with the weekly FruitLook biomass production. This corresponded to the field measurements proving that there is a potential in using this data for improving productivity. Thus, FruitLook can be used to monitor vigorous and slow growth during the season and, where necessary, management practices can be applied to improve productivity. For example, if the biomass production of a particular block is not as expected on the Fruitlook data, the producer can go to the vineyard and investigate the cause to take the necessary steps to rectify the problem.

A positive correlation was found between FruitLook accumulated actual ET and the accumulated water balance ET. Consequently, FruitLook ET can give a good indication on water use and hence has potential to be used in irrigation scheduling. Although there was a positive correlation between stem water potential and evapotranspiration deficit for the 2013/14 season, there was no correlation between the two parameters in the 2014/15 season. Therefore, at this stage, it is unclear as to whether the evapotranspiration deficit will be a reliable indicator of plant water stress. Results also indicated that FruitLook does not really measure plant water stress, but instead measures an apparent deficit based on what should have been given to what is given relating to ET. Taking above-mentioned into consideration, producers still need to go to the vineyards to determine plant water stress rather than using the Fruitlook evapotranspiration deficit.

The comparison between seasonal irrigated volumes and ET_{FL} indicated on over supply of water in some of the blocks, therefore stringent irrigation scheduling is needed to reduce water use and probably improve WUE. Consequently, FruitLook offers the potential to indicate possible under and oversupply in the vineyards but for fine tuning irrigation scheduling, actual plant water stress measurements are still needed. There was a positive correlation between BWUE and WUE_y for the 2013/14 season and a negative correlation for the 2014/15 season. However, there was a positive correlation between BWUE and WUE_{irr} indicating the potential for BWUE to be used as a tool to improve water resource management and increase WUE. Thus, BWUE also allows the producer to monitor their vineyard’s performance and can aid in management decisions that will improve productivity and reduce water use.

Based on this study’s findings FruitLook can be used to make on estimation of irrigation requirements due to the positive water balance relationship. Water balance calculations are normally done using weather data and crop factor estimations and with FruitLook capturing that aspect well it will be a useful tool. Furthermore, FruitLook does not explain the differences observed with the satellite data and field data is still needed to be able to determine the causes. Therefore, an integrated approach between FruitLook data and actual field measurements is needed for improved irrigation scheduling and increased WUE_y.

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Chapter 6

Research results

An assessment of the blue water footprint and water use efficiency of Crimson Seedless table grapes

CHAPTER VI: AN ASSESSMENT OF THE BLUE WATER FOOTPRINT AND WATER USE EFFICIENCY OF CRIMSON SEEDLESS TABLE GRAPES

6.1 Introduction

Water footprint (WF) is the total quantity of water utilised for activities of a single social entity (Mekonnen & Hoekstra, 2010; Hoekstra *et al.*, 2011). Water footprint assessment has the potential to aid in decision making concerning sustainable, efficiency and equitable water distribution and water use efficiency determination (Pahlow *et al.*, 2015). About 75% of WF in South Africa is reported to come from crop production of which maize, fodder crops, sugarcane, wheat and sunflower seed contributes the highest proportion of about 83% (Pahlow *et al.*, 2015). Furthermore, based on the virtual water analysis it was revealed that South Africa's large amount of blue WF consumption is related to export (Pahlow *et al.*, 2015). Table grapes in South Africa is mostly grown under irrigation indicating the higher proportion of blue WF the table grape industry is using. The blue WF refers to the consumptive quantity of fresh surface or groundwater use (Hoekstra *et al.*, 2011). Thus, under irrigation it is the total volume of water used along the entire production chain of a particular crop (*e.g.* table grapes) and includes water used by the grapevine through evapotranspiration (ET) (which forms the bulk of the WF), as well as water used during spraying operations in the vineyard, water used in the pack store and evaporation of irrigation water stored in dams. Accurate information on the WF and water use efficiency (WUE) of table grapes can empower table grape producers, farm employees and staff at catchment areas to farm sustainably and efficiently under limited water resources. Water footprints also provide useful information on the water use of a specific area and strategies can be developed based on this information to improve WUE. When combined with crop yield data, it creates the basis for identifying existing levels of water use efficiency (so called 'crop per drop', for example kg/tonne of table grapes produced per m^3 of water used).

Several studies have evaluated irrigation practices and water use by horticultural crops (Seckler, 1996; Taylor & Gush, 2009; Annandale *et al.*, 2011). However, information on the impact of horticulture products on scarce freshwater resources is not sufficient. The WF approach is a concept introduced to aid in quantifying the impact different users have on a country's freshwater. The water use footprint category differs according to season and region. In winter rainfall areas, such as the Western Cape in South Africa, the green WF increases during winter due to high rainfall (Pegasys, 2010), while the blue WF is at its peak during summer, because of high crop demand due to high evapotranspiration (Pegasys, 2010). In arid and semi-arid countries such as South Africa, the blue WF is higher than the green WF, since most agricultural crops are under irrigation. Therefore, the main focus should be to minimize the blue water and optimize the green WF. Clothier *et al.* (2010) suggested that the green WF can be maximized by proper canopy management that will reduce transpiration and by using deficit irrigation that will reduce vegetative growth. Mekonnen and Hoekstra (2010) reported a global water footprint of 7404 billion m^3/yr for crop production estimated between 1996 to 2005. Based on global estimates, rainfed agriculture was reported to account for 5173 Gm^3/yr footprints and divided as follows: 91% green and 9% grey. In contrast, irrigated agriculture accounted for 2230 Gm^3/yr footprint and divided as follows: 48% green, 40% blue and 12% grey.

While some studies have determined the WUE of table grapes (Araujo *et al.*, 1995; Yunusa *et al.*, , 1997a; Yunusa *et al.*, , 1997b; Myburgh, 2003a or b), the total volume of water required throughout the entire production chain from field to consumption to produce a bunch of table grapes is not known. Apart from the WF analysis of the Breede Catchment (Pegasys, 2010) that focused on the economic impact of crop water use, there are few publications on the WF of table grapes in South Africa. Pahlow *et al.* (2015) also used the same data sets used for the global assessment by Mekonnen and Hoekstra (2010) to determine the South African national WF. Thus, the aim of this study is to determine the blue WF of Crimson Seedless table grapes for three regions in South Africa (winter & summer rainfall areas) along the production chain only.

6.2 Materials and Methods

6.2.1 Study area

Four farms in the Western Cape, five in the Lower Orange River and four in the Northern Province were selected for determining the blue WF of Crimson Seedless table grapes. Further information regarding the different blocks in the three different regions is given in Table 6.1. Since the three regions are characterised by different climatic conditions, surveys were conducted in each region to enable a comparison of the water use in the different regions. The Western Cape is a winter rainfall area, while the Orange River and Northern Province regions are summer rainfall areas. The application of irrigation on the different farms was aimed at optimal supply of water during each phenological stage. Fertilisation and pest/disease management practices were applied on the farms according to standard practices for the cultivar and region. Other viticultural practices were applied as recommended for the production of export quality Crimson Seedless table grapes (SATI, 2015).

6.2.2 Data collection

The four blocks in the Western Cape (Hex River Valley) were part of the main study (Refer to Chapters 3,4 & 5). In addition to the data collected in the main study, interviews and questionnaire surveys were conducted to obtain the relevant production information to determine the blue WF of the blocks included in the study. A "Water footprint questionnaire" was compiled and used for obtaining information from producers regarding crop water use and additional water use aspects that needed to be accounted for, such as irrigation quantities, water used during spraying operations in vineyards (for application of fertilizers, fungicides, pesticides, herbicides & PBRs), as well as water used in pack houses. Production data obtained through the questionnaire survey was used to determine the blue WF, yield water use efficiency (WUE_y) and economic water use efficiency (WUE_e) of these blocks.

6.2.3 Weather data

The Western Cape weather data for both seasons were obtained from Modderdrift automatic weather station (AWS), courtesy of iLeaf, Hortec (Pty Ltd). Weather data for the Lower Orange River and Northern Province regions were obtained from the AWS close to the blocks. For the Orange River region, the following weather stations were used: Kanoneiland, Augrabies and Raap en Skraap courtesy of iLeaf Hortec (Pty Ltd). Groblersdal and Marble Hall weather stations were used for the Northern Province, courtesy of ARC–ISCW, Pretoria. For the general seasonal graphs, weather data obtained from the ARC AWS at Hex River Valley experimental farm was used for Western Cape 2013/14 season while Modderdrift AWS was used for the 2014/15 season. Kanoneiland AWS data was used for both seasons for the Orange River region and Groblersdal AWS data was used for both seasons for the Northern Province region.

6.2.4 FruitLook Data

As already discussed in Chapter 5, Fruitlook is an open web portal funded by the Western Cape Department of Agriculture in collaboration with eLeaf (www.eleaf.com). On this portal, fruit and grape producers in the Western Cape have access to satellite based information on plant growth, water use and nutrient status. This made it possible for the ET values calculated from the AWS data to be compared to FruitLook data for the four farms in the Hex River Valley, Western Cape. The calculated ET from the AWS ET_o and the published crop factor was compared to actual FruitLook ET (ET_{FL}). Evapotranspiration values obtained from the different methods were compared to determine whether using a standard published K_c for determining ET_c is sufficient for different farms with different growth vigour.

6.2.5 Phenological stages

Phenological stages (Coombe. 1995) were recorded for the blocks in the different regions to be able to link water use to the growth stage.

6.2.6 Water use calculations

The amount of irrigation water applied was calculated based on irrigation data (spacing, emitter delivery rates & irrigated hours) supplied by the producers. Crop evapotranspiration (ETc) was estimated as the product of the reference crop evapotranspiration (ETo) and a crop coefficient (Kc), where:

ETc = Kc x ETo (Allen *et al.*, 1998). (Eq. 6.1)

Thus, atmospheric potential evapotranspiration (ETo) from the AWS nearest to the blocks and a published crop factor (Kc) (Lategan, 1996) values for the different regions were used. For the Western Cape region blocks, FruitLook Actual evapotranspiration (ET) (www.fruitlook.co.za) was also used to determine blue WF, WUE_y and WUE_e, respectively, for the period the data was available (October to April). The FruitLook data was included to make a comprising between the blue WF and WUE_y obtained from both methods to determine whether using a standard published Kc for determining ETc is sufficient for different blocks with different growth vigour. Additional water use aspects that were recorded for the 13 commercial farms (*via* completion of a "Water footprint questionnaire") included: water used during spraying operations in the vineyard, water used in the pack house and water used by workers. For the purpose of calculating the production blue WF, only seasonal ET and seasonal spray application volumes were considered. This was deemed sufficient since ET is reported to account for more than 90% of blue WF (Gush & Dzikiti, n.d.).

6.2.7 Blue water footprint, yield water use efficiency and economic water use efficiency

The blue WF was determined according to the method of Hoekstra *et al.* (2011) and the following formula was used:

$$\text{Blue WF} = \frac{Blue\ Crop\ W\ ater\ Use\ (m3/ha)}{Yield\ (\frac{ton}{ha})} = \text{m}^3\text{/ton} \qquad \text{(Eq. 6.2)}$$

of which blue crop water use only considered ET and total spray application volume.

The WUE_y was determined by using the following equation:

$$WUE_y = \frac{Yield\ (kg/ha)}{Blue\ Crop\ Water\ Use\ (\frac{m3}{ha})} = \text{kg/m}^3 \qquad \text{(Eq. 6.3)}$$

Economic water use efficiency (WUE_e) was determined by dividing selling price per kg export grapes by WUE_y using the following equation:

$$\text{WUEe} = \frac{ZAR\ (\frac{ZAR}{kg})}{WUEy\ (\frac{kg}{m3})} = \text{R/m}^3 \qquad \text{(Eq. 6.4)}$$

Price tracker records for 2016 were obtained from SATI and an average price of UK and Netherland wholesale as the main importers of South African Crimson Seedless grapes were determined, converted to ZAR by the conversion ratio (November 2017) and used for both seasons.

Table 6.1: Farm/block characteristic of the different farms used for water footprint determinations.

Region	**Sub region**	**Farm nr**	**Source of irrigation water**	**Planting year**	**Rootstock**	**Row orientation**	**Trellis system**	**Block size (ha)**	**Spacing (m × m)**	**Planting density (vines/ha)**	**Soil type**
Western Cape	Hex River Valley	1	Grootkloof River, Hex Valley Irrigation scheme	2001	Ramsey	NE-SW	Trentina	1.77	3.0 × 1.8	1852	Sandy clay loam
Western Cape	Hex River Valley	2	Grootkloof River, Hex Valley Irrigation scheme	2002	Ramsey	NE-SW	Trentina	1.30	3.0 × 1.8	1852	Sandy clay loam
Western Cape	Hex River Valley	3	Grootkloof River, Hex Valley Irrigation scheme	2000	Ramsey	NNW-SSE	Trentina	1.00	2.75 × 1.8	2020	Loamy fine sand
Western Cape	Hex River Valley	4	Grootkloof River, Hex Valley Irrigation scheme	2004	Ramsey	NNE-SSW	Trentina	1.50	3.0 × 1.8	1852	Sandy clay loam
Orange River	Kanoneiland	16	Orange River	2004	Ramsey	N-S	Pergola	3.98	3.0 × 2.5	1333	Loam
Orange River	Kakamas	17	Orange River	2007	Ramsey	N-S	Gable	1.52	2.0 × 3.3	1515	Loam
Orange River	Kakamas	18	Orange River	2007	Ramsey	N-S	Gable	0.92	3.3 × 2.0	1515	Loam
Orange River	Raap en Skraap	19	Orange River	2004	Ramsey	N-S	Pergola	4.70	3.3 × 2.5	1212	Sandy
Orange River	Kanoneiland	20	Orange River	2011	Ramsey	N-S	Pergola	5.13	3.0 × 2.5	1333	Loam
Northern Prov	Groblersdal	21	Loskopdam	2003	Ramsey	N-S	Gable	5.00	3.0 × 1.8	1852	Sandy loam
Northern Prov	Groblersdal	22	Loskopdam	2003	Ramsey	N-S	Gable	3.92	3.5 × 1.8	1587	Sandy loam
Northern Prov	Groblersdal	23	Loskopdam	2002	Ramsey	N-S	Gable	5.00	3.0 × 2.0	1667	sandy with high stone %
Northern Prov	Marble Hall	24	Loskopdam	2004	R110	N-S	Gable	13.00	3.0 × 2.0	1667	loam 25% clay

6.3 Results and Discussion

6.3.1 Climatic conditions

Figure 6.1 and Figure **6.2** show the average monthly minimum and maximum temperatures, as well as the monthly rainfall for the Western Cape, Lower Orange River and the Northern Province regions during the 2013/14 and 2014/15 seasons. The two graphs indicate that the Western Cape is a winter rainfall area, while the other two regions are summer rainfall areas, based on peak periods of rainfall occurrence in those regions. Average annual minimum temperature (September to August) for the Western Cape, Lower Orange River and Northern Province region was 10.05ºC, 6.95ºC and 11.45ºC respectively during the 2013/14 season, while for the same season the average maximum temperatures were 25.43ºC, 34.77ºC and 28.71ºC for the Western Cape, Lower Orange River and Northern Province region, respectively. Regarding temperature, similar patterns were noted during the following season with the Lower Orange River region having the lowest and highest average temperature of 7.33ºC and 34.97ºC, respectively, compared to the other two regions. Accumulated annual rainfall recorded during the 2013/14 season for the Western Cape, Lower Orange River and Northern Province regions was 1114 mm, 232 mm and 871 mm, respectively. In the 2014/15 season, the accumulated rainfall was 792 mm, 143 and 470 mm for the Western Cape, Lower Orange River and Northern Province regions, respectively. During both seasons, the Lower Orange River region had the lowest rainfall and highest temperatures while the Western Cape had higher rainfall during the winter months and an average lower maximum temperature.

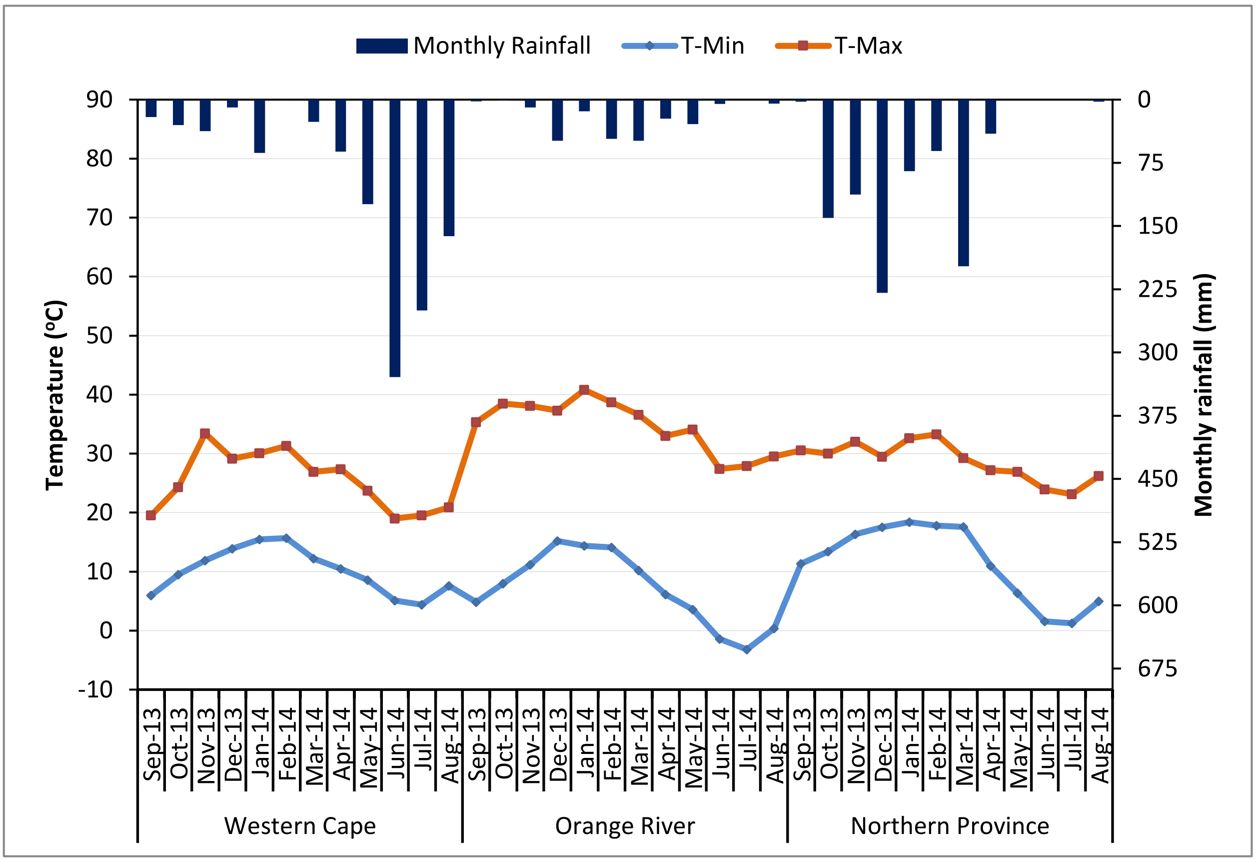


Figure 6.1: Monthly values of minimum and maximum temperature and rainfall recorded in the Western Cape, Orange River and Northern Province regions between September 2013 and August 2014.

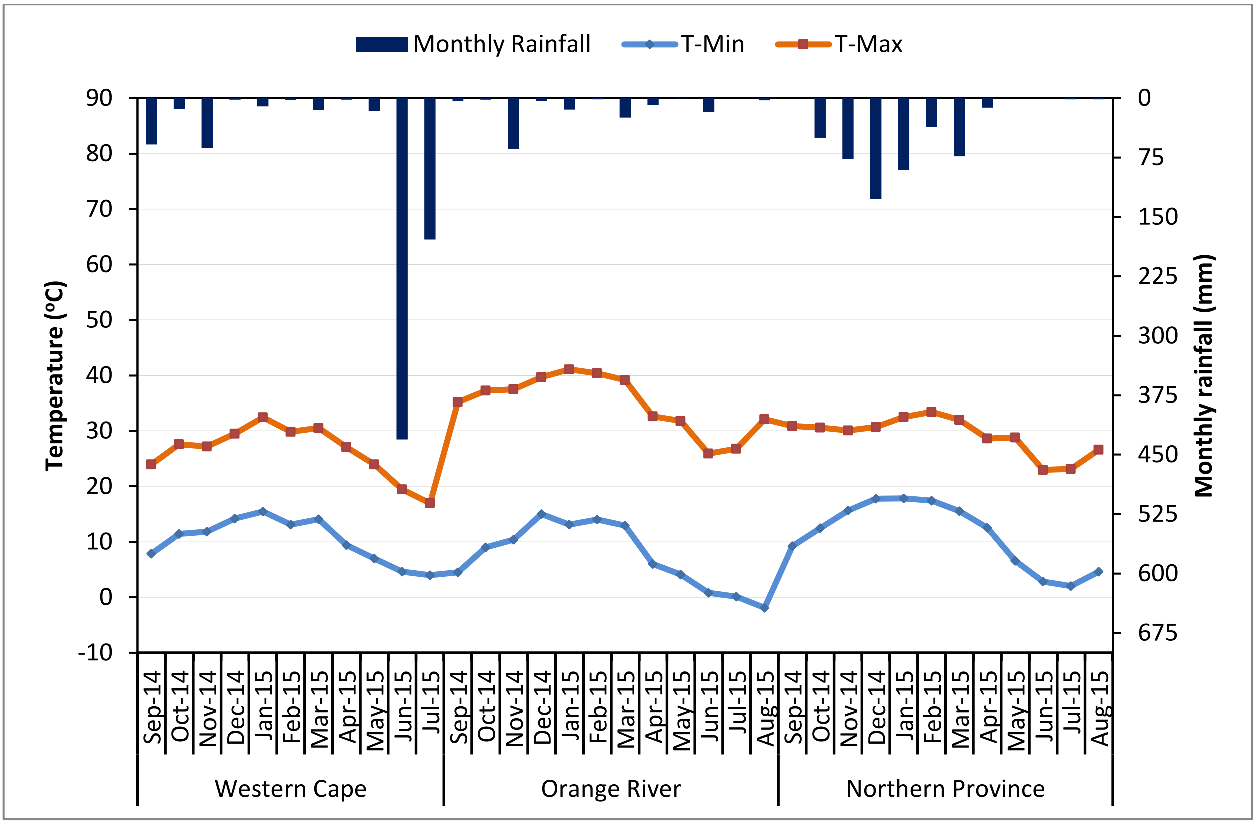


Figure 6.2: Monthly values of minimum and maximum temperature and rainfall recorded in the Western Cape, Orange River and Northern Province regions between September 2014 and August 2015.

6.3.2 Phenological stages

Important phenological stages for the three regions are presented in Table 6.2. Based on the information provided by producers in their questionnaires, it appeared that bud break was earlier in the Northern Province compared to the other two regions. Therefore, harvesting also started earlier in this region. This could be ascribed to the higher temperatures and thus also higher and faster heat unit accumulation. Comparing the Western Cape and Lower Orange River regions, bud break dates were in the same range even though harvesting started a bit earlier in the Lower Orange River region. This might be due to the higher temperatures observed in that particular region which likely increased rate of grape development and ripening.

Table 6.2: Phenological stages as recorded per farm in the different regions per season.

Region	Sub region	Farm nr.	Season	Phenological stages			
				Bud break	Flowering	Véraison	Harvest (beginning)
Western Cape	Hex River Valley	1	2013/14	25/9	28/10	25/12	12/2
			2014/15	17/9	23/10	20/12	6/2
Western Cape	Hex River Valley	2	2013/14	10/9	2/11	17/12	13/2
			2014/15	5/9	27/10	26/12	8/2
Western Cape	Hex River Valley	3	2013/14	15/9	7/11	22/12	18/2
			2014/15	8/9	30/10	29/12	11/2
Western Cape	Hex River Valley	4	2013/14	18/9	25/10	20/12	5/2
			2014/15	14/9	20/10	15/12	28/1
Orange River	Kanoneiland	16	2013/14	20/9	24/10	21/12	27/1
			2014/15	12/9	20/10	8/12	19/1
Orange River	Kakamas	17	2013/14	23/9	26/10	28/12	24/1
			2014/15	19/9	20/10	18/12	20/1
Orange River	Kakamas	18	2013/14	23/9	26/10	28/12	24/1
			2014/15	19/9	20/10	18/12	14/1
Orange River	Raap en Skraap	19	2013/14	9/9	16/10	4/12	9/1
			2014/15	28/8	-(1)	-(1)	-(1)
Orange River	Kanoneiland	20	2013/14	16/9	15/10	18/11	29/1
			2014/15	15/9	13/10	8/12	23/1
Northern Province	Groblersdal	21	2013/14	28/8	6/10	1/12	4/1
Northern Province	Groblersdal	21	2014/15	22/8	6/10	4/12	6/1
Northern Province	Groblersdal	21	2013/14	25/8	6/10	3/12	5/1
Northern Province	Groblersdal	22	2013/14&14/15	22/8	30/10	20/12	3/1
Northern Province	Groblersdal	23	2013/14&14/15	5/9	25/9	12/12	5/1
Northern Province	Marble Hall	24	2014/15	30/8	31/10	24/12	21/1

(1) Hail damage occurred shortly after bud break, destroying shoots before flowering occurred – no inflorescences and bunches available and therefore no recording of flowering, véraison and harvest dates

6.3.3 Water use calculations

6.3.3.1 Irrigation and other water use

Water use calculations (irrigation and other aspects of water use) for the four experimental blocks in the Western Cape, five commercial blocks in the Lower Orange River region and four commercial blocks in the Northern Provinces are presented in Tables 6.3 and 6.4. Total water use for irrigation (per ha per season) varies from 4 550 m^3 to 10 510 m^3 in the Western Cape, 12 760 m^3 to 24 531 m^3 in the Lower Orange River region and 4 710 m^3 to 8 972 m^3 in the Northern Provinces. The irrigation water use was the highest in the Lower Orange River region, which can be attributed to the high evaporative demand due to higher temperatures, lower relative humidity (RH) and higher vapour pressure deficit (VPD); the longer growing season compared to the other regions and micro sprinkler irrigation systems instead of drip. This is in agreement with Myburgh (2012), who reported a higher ET in Thompson Seedless table grapes irrigated with micro sprinkler irrigation system compared to drip irrigation in the Lower Orange River region. The Northern Province had the highest water use for spraying (Table 6.4) due to the long summer rainfall period, as well as the long growing season compared to the Hex River Valley region in the winter rainfall region. Hence, more sprays for protection of vineyards against fungal diseases are needed. Due to uneven bud break and flowering, more PBRs sprays (*e.g.* hydrogen cyanamide for rest breaking & GA for thinning & berry sizing) are required. “Pack house water use” refers to water used for cleaning of crates and work surfaces, as well as in pre-cooling systems. Only one farm (2 blocks) supplied values measured by means of a water meter in the pack house. All other values were obtained as calculations or estimates by the producers. There is vast variation, due to amongst others: no pre-cooling done in the Western Cape, while pre-cooling is applied in the Lower Orange River and Northern Provinces. The difference in pack house water use between the Lower Orange River and the Northern Provinces is that in the latter area, closed systems are used for pre-cooling and less water is used. Regarding estimated water use by farm workers: producers suggested that 11 L per worker per day is a realistic value (1 L drinking water & 10 L use for personal hygiene and toilet).

Table 6.3: Irrigation water uses for Crimson Seedless: Summary of information obtained from producers *via* ‘Water Footprint questionnaires”.

Region	Sub region	Farm number	Season	Irrigation season		Irrigation system	Seasonal Irrigation applied
				Start	End		m^3/ha
Western Cape	Hex River Valley	1	2013/14	1/10	9/5	Drip	4550
			2014/15	22/9	8/5	Drip	7550
Western Cape	Hex River Valley	2	2013/14	1/9	31/5	Micro	9630
			2014/15	15/9	31/5	Micro	9130
Western Cape	Hex River Valley	3	2013/14	1/9	31/5	Micro	10510
			2014/15	15/9	31/5	Micro	9960
Western Cape	Hex River Valley	4	2013/14	1/10	23/5	Drip	6390
			2014/15	1/10	29/5	Drip	6060
Orange River	Kanoneiland	16	2013/14	1/8	31/7	Micro	18209
			2014/15	1/8	31/7	Micro	18358
Orange River	Kakamas	17	2013/14	1/8	31/7	Micro	13140
			2014/15	1/8	31/7	Micro	12760
Orange River	Kakamas	18	2013/14	1/8	31/7	Micro	14580
			2014/15	1/8	31/7	Micro	13450
Orange River	Raap en Skraap	19	2013/14	1/8	31/7	Micro	24531
			2014/15	1/8	31/7	Micro	16617
Orange River	Kanoneiland	20	2013/14	1/8	31/7	Micro	18198
			2014/15	1/8	31/7	Micro	18634
Northern Prov	Groblersdal	21	2013/14 actual	1/8	31/7	Drip	6719
Northern Prov	Groblersdal	21	2014/15 actual	1/8	31/7	Drip	6719
Northern Prov	Groblersdal	21	2013/14&14/15	1/8	31/7	Drip	7848
Northern Prov	Groblersdal	22	2013/14&14/15	1/8	31/7	Drip	4710
Northern Prov	Groblersdal	23	2013/14&14/15	1/8	31/7	Drip	8402
Northern Prov	Marble Hall	24	2014/15	1/8	31/7	Drip	8972

Table 6.4: Other water uses for Crimson Seedless: Summary of information obtained from producers *via* ‘Water Footprint questionnaires”

Region	**Sub region**	**Farm**	**Season**	**Irrigation applied**	**Spray applications (for total season)**				**Spray application**	**Pack house**	**Worker water use**
		nr		**Total Irrigation**	**Plant protection**	**Nutrition**	**PBRs**	**Herbicides**	**Total**	**Total**	**Total**
					(Pest/Diseases)	**(Foliar sprays)**					
				m^3/ha	**m^3/ha**	**m^3/ha**	**m^3/ha**	**m^3/ha**	**m^3/ha**	**m^3/ha**	**m^3/ha**
Western Cape	Hex River Valley	1	2013/14	4550	9.0	1.0	1.0	1.5	12.5	0.6	5.1
			2014/15	7550	15.0	0.0	0.5	1.5	17.0	0.6	5.1
Western Cape	Hex River Valley	2	2013/14	9630	9.0	3.0	2.4	1.5	15.9	0.5	5.1
			2014/15	9130	9.0	3.0	2.4	1.5	15.9	0.5	5.1
Western Cape	Hex River Valley	3	2013/14	10510	9.0	3.0	2.4	1.5	15.9	0.5	5.1
			2014/15	9960	9.0	3.0	2.4	1.5	15.9	0.5	5.1
Western Cape	Hex River Valley	4	2013/14	6390	11.5	1.0	1.5	1.5	15.5	0.6	5.1
			2014/15	6060	16.0	0.0	0.5	1.5	18.0	0.6	5.1
Orange River	Kanoneiland	16	2013/14	18209	17.0	2.0	1.3	0.35	20.7	11.3	6.3
			2014/15	18358	18.0	2.0	1.4	0.35	21.7	11.3	6.3
Orange River	Kakamas	17	2013/14	13140	17.0	2.0	1.3	0.35	20.7	11.3	6.3
			2014/15	12760	18.0	2.0	1.4	0.35	21.8	11.3	6.3
Orange River	Kakamas	18	2013/14	14580	17.0	2.0	1.3	0.35	20.7	11.3	6.3
			2014/15	13450	18.0	2.0	1.4	0.35	21.8	11.3	6.3
Orange River	Raap en Skraap	19	2013/14	24531	17.0	2.0	1.3	0.35	20.7	11.3	6.3
			2014/15	16617	18.0	2.0	1.4	0.35	21.8	11.3	6.3
Orange River	Kanoneiland	20	2013/14	18198	17.0	2.0	1.3	0.35	20.7	11.3	6.3
			2014/15	18634	18.0	2.0	1.4	0.35	21.8	11.3	6.3
Northern Prov	Groblersdal	21	2013/14 actual	6719	14.3	7.0	3.2	0.2	24.7	4.2	5.1
Northern Prov	Groblersdal		2014/15 actual	6719	14.3	7.0	3.2	0.2	24.7	4.2	5.1
Northern Prov	Groblersdal		2013/14&14/15	7848	14.3	7.0	3.2	0.2	24.7	4.2	5.1
Northern Prov	Groblersdal	22	2013/14&14/15	4710	12.5	8.8	6.2	2.7	30.1	no info	5.1
Northern Prov	Groblersdal	23	2013/14&14/15	8402	14.3	7.0	7.2	2.7	31.1	1.0	5.1
Northern Prov	Marble Hall	24	2014/15	8972	12.5	8.8	6.2	2.7	30.1	no info	5.1

6.3.4 Blue water footprint, yield water use efficiency and economic water use efficiency

Water footprint calculations could be grouped according to production, water use or ET, region (climatic conditions) or length of the growing season. Blue WF, WUE_y and WUE_e for the 2013/14 and 2014/15 seasons are presented in Table 6.5. The results of the different regions were grouped together in the tables (the regions were also indicated in the relevant tables and a description of the rainfall season and quantity, as well as temperature conditions and the length of the growing season of each of the regions were briefly described in the text).

Seasonal ET for both seasons varies from 3483 m^3/ha to 5456 m^3/ha in the Western Cape, 6564 m^3/ha to 7132 m^3/ha in the Lower Orange River region and 4853 m^3/ha to 5033 m^3/ha in the Northern Provinces. Seasonal table grape ETc has been reported to range between 687 mm and 1350 mm, depending on climate (Suvočarev *et al.*, 2013). Myburgh and Howell (2007) reported a mean annual ETc of 1358 mm for micro sprinkler irrigated table grapes at 40% PAW depletion to a depth of 1.2 m in the Hex River Valley. Myburgh (2003b) reported a mean annual ETc for micro sprinkler irrigated Sultanina in the Lower Orange River region ranging from 989 mm to 1374 mm, depending on level of soil water depletion before application of irrigation. Measured ET in the current study was lower than the reported values, probably due to the lower Kc used compared to the actual calculated Kc. Since ET accounted for almost 99% of blue water use, the blocks with the higher ET had a higher blue water use as well. Despite the higher total spray application volumes in the Northern Province, this region's water use was lower than in the Western Cape and Orange River Region during the 2014/15 season, while higher water use was recorded in the Lower Orange River region. This can be explained by the higher temperatures and lower rainfall during both growing season as indicated by the weather graphs (Figure 6.1 and Figure **6.2**).

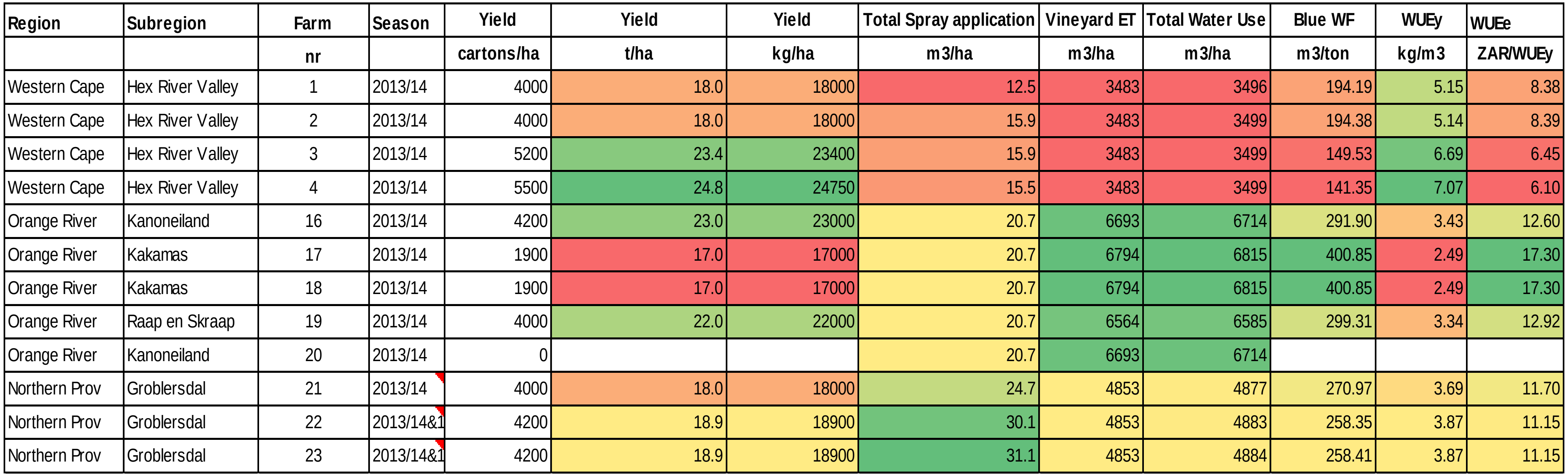
Among the 11 farms measured in the study during the 2013/14 season, approximately 36.4% had a blue WF that varied from 141.35 m^3/ton to 194.38 m^3/ton, hence having a higher WUE_y and WUE_e (Table 6.5). All these farms were from the Western Cape region. About 45.5% farms (two from the Orange River region and all Northern Province farms) had a higher blue WF that varied between 258.41 m^3/ton to 299.31 m^3/ton. The other two farms in the Orange River region (Farms 17 & 18) had the highest blue WF of about 400.85 m^3/ton due to the lower yield and higher water use recorded in those blocks. Similarly, Multsch *et al.* (2013) reported that WF decreases with higher crop yield. The higher the blue WF, the lower the WUE_y and consequently, more money is needed for production. Farm 20 in the Lower Orange River was a young block still in its establishment phase, therefore the 6714m^3/ha total water use was used for development and growth. During the 2014/15 season, Farms 2, 3 and 4 in the Western Cape had a lower blue WF of 253.33 m^3/ton, 243.20 m^3/ton and 202.74 m^3/ton respectively (Table 6.6.6). In the Lower Orange River region, higher blue WF was calculated for Farms 16, 17, 18 and 20 with the following values, namely 328.27 m^3/ton, 325.18 m^3/ton, 325.18 m^3/ton and 765.97 m^3/ton, respectively. The yield for Farm 20 was only 9.0 t/ha during the 2014/15 season, therefore a higher blue WF and a lower WUE_y and WUE_e was obtained. Farm 19 was affected by hail damage and no yield was recorded during the 2014/15 season. Taking in account the regional averages for both seasons, the blue WF of Crimson Seedless table grape production in the Western Cape, Lower Orange River region and the Northern Province was 210.35 m^3/ton, 392.19 m^3/ton and 272.42 m^3/ton, respectively. It should be noted that the no yield recorded for Farm 19 and the lower yield recorded for Farm 20 during the 2014/15 season contributed to the higher average blue WF of the Lower Orange River region. Excluding these two farms from the calculation reduced the blue WF of the Lower Orange River region to 337.22 m^3/ton. Average WUE_y for both seasons was 5.04 kg/m^3, 3.00 kg/m^3 and 3.68kg/m^3 for Western Cape, Lower Orange River region and Northern Province region respectively.

In general, the 2013/14 season had a lower blue WF and a higher WUE_y compared to the 2014/15 season except for Farms 17, 18 and 21. During the 2013/14 season, Farms 16, 19, 21, 22 and 23 had a WUE_y in the range of 3.34 kg/m^3 to 3.87 kg/m^3. This was closer to the 4.05 kg/m^3 recalculated from the furrow irrigated Sultana by Yunusa *et al.*, 1997b. The WUE_y data recalculated from a Thompson Seedless grapevine study using drip and furrow irrigation in California indicated an average of 5.5 kg/m^3 (Araujo *et al.*, 1995), which compared well to WUE_y of Farms 1 and 2 during the 2013/14 season., Farms 3 (6.69 kg/m^3) and 4 (7.07 kg/m^3) had the highest WUE_y during the 2013/14 season and was higher than all the above-mentioned studies but slightly lower than the reported value of 8.64 kg/m^3 for grafted Sultana grapevines using drip irrigation in Australia (1997a). Most of the farms' WUE_y during the 2014/15 season was in the range of 1.31 kg/m^3 to 3.95 kg/m^3. This findings compares well with Myburgh (2003a), who reported WUE_y in the range of 1.9 kg/m^3 to 3.3 kg/m^3 in a Sultanina study irrigated with flood irrigation on wide and narrow bed at on interval of 14 and 21 day cycles.

Blue WF reported for the two seasons in this study were in the ranges of 141.35 m^3/ton to 400.85 m^3/ton and 202.74 m^3/ton to 765.97 m^3/ton for the 2013/14 and 2014/15 season, respectively. The higher blue WF range reported during the 2014/15 season was caused by Farm 20 where there was lower yield (9 t/ha) with a higher total water use (6894 m^3). If that particular farm is excluded from the calculation, then the blue WF range for the 2014/15 season ranges from 202.74 m^3/ton to 325 m^3/ton. Mekonnen and Hoekstra (2010) and Pahlow *et al.* (2015) reported a blue WF for grapes of 97 m^3/ton (global) and 157 m^3/ton (South Africa). The blue WF determined by Pahlow *et al.* (2015) was based on a yield of 13.8 t/ha. The blue WF reported in both this study was lower than the blue WF calculated in the current study. Multsch *et al.* (2013) used a spatial system SPARE: WATER to calculate WF and a comparison was made to the global average as well as the country specific average calculated according to the Hoekstra *et al.* (2011) method. They reported a blue WF for grapes of 1448 m^3/ton and 754 m^3/ton for the SPARE: WATER and national average. Both these values were higher than the current study's blue WF for both seasons except for the 765.97 m^3/ton of Farm 20 during the 2014/15 season that compared well with the 754 m^3/ton. One possible explanation for the lower global WF values might be that smaller production units were included that might have impacted on the average global yield value obtained (resulting in a lower value compared to if the majority of units included were commercial units with quit high yield).

In a study conducted by Gush *et al.* (2017) on "Cripps" Pink apple trees and Navel oranges in the Olifant/ Doorn WMA they reported on average of 149 m^3/ton and 145.3 m^3/ton for blue WF of apples and oranges, respectively. Their study also indicated a water productivity of 4.40 kg/m^3 for apples and 4.77 kg.m^3 for oranges. Therefore, the blue WF values determined in this study for table grapes was higher than values reported for apples and oranges. The WUE_y calculated for the Western Cape region during the 2013/14 season was also higher than values reported by Gush *et al.* (2017). However, WUE_y in the same region for the 2014/15 season was comparable to their reported results. Nevertheless, the Lower Orange River region and Northern Province regions had a lower WUE compared to Gush *et al.* (2017).

Table 6.5: Production blue water footprint (WF), crop water use efficiency (WUE_y) and economic water use efficiency (WUE_e) for the different farms in the Western Cape, Orange River and Northern Province regions during the 2013/14 season.



Region	Subregion	Farm	Season	Yield	Yield	Yield	Total Spray application	Vineyard ET	Total Water Use	Blue WF	WUEy	WUEe
		nr		cartons/ha	t/ha	kg/ha	m3/ha	m3/ha	m3/ha	m3/ton	kg/m3	ZAR/WUEy
Western Cape	Hex River Valley	1	2013/14	4000	18.0	18000	12.5	3483	3496	194.19	5.15	8.38
Western Cape	Hex River Valley	2	2013/14	4000	18.0	18000	15.9	3483	3499	194.38	5.14	8.39
Western Cape	Hex River Valley	3	2013/14	5200	23.4	23400	15.9	3483	3499	149.53	6.69	6.45
Western Cape	Hex River Valley	4	2013/14	5500	24.8	24750	15.5	3483	3499	141.35	7.07	6.10
Orange River	Kanoneiland	16	2013/14	4200	23.0	23000	20.7	6693	6714	291.90	3.43	12.60
Orange River	Kakamas	17	2013/14	1900	17.0	17000	20.7	6794	6815	400.85	2.49	17.30
Orange River	Kakamas	18	2013/14	1900	17.0	17000	20.7	6794	6815	400.85	2.49	17.30
Orange River	Raap en Skraap	19	2013/14	4000	22.0	22000	20.7	6564	6585	299.31	3.34	12.92
Orange River	Kanoneiland	20	2013/14	0			20.7	6693	6714			
Northern Prov	Groblersdal	21	2013/14	4000	18.0	18000	24.7	4853	4877	270.97	3.69	11.70
Northern Prov	Groblersdal	22	2013/14&1	4200	18.9	18900	30.1	4853	4883	258.35	3.87	11.15
Northern Prov	Groblersdal	23	2013/14&1	4200	18.9	18900	31.1	4853	4884	258.41	3.87	11.15

Table 6.6: Production blue water footprint (WF), crop water use efficiency (WUE_y) and economic water use efficiency (WUE_e) for the different farms in the Western Cape, Orange River and Northern Province regions during the 2014/15 season.

Region	Subregion	Farm	Season	Yield	Yield	Yield	Total Spray application	Vineyard ET	Total Water Use	Blue WF	WUEy	WUEe
		nr		cartons/ha	t/ha	kg/ha	m3/ha	m3/ha	m3/ha	m3/ton	kg/m3	ZAR/WUEy
Western Cape	Hex River Valley	1	2014/15	4000	18.0	18000	17.0	5456	5473	304.06	3.29	13.12
Western Cape	Hex River Valley	2	2014/15	4800	21.6	21600	15.9	5456	5472	253.33	3.95	10.93
Western Cape	Hex River Valley	3	2014/15	5000	22.5	22500	15.9	5456	5472	243.20	4.11	10.50
Western Cape	Hex River Valley	4	2014/15	6000	27.0	27000	18.0	5456	5474	202.74	4.93	8.75
Orange River	Kanoneiland	16	2014/15	3900	21.0	21000	21.7	6872	6894	328.27	3.05	14.17
Orange River	Kakamas	17	2014/15	2411	22.0	22000	21.8	7132	7154	325.18	3.08	14.03
Orange River	Kakamas	18	2014/15	2411	22.0	22000	21.8	7132	7154	325.18	3.08	14.03
Orange River	Raap en Skraap	19	2014/15	0			21.8	7011	7033			
Orange River	Kanoneiland	20	2014/15	1650	9.0	9000	21.8	6872	6894	765.97	1.31	33.06
Northern Prov	Groblersdal	21	2014/15	4100	18.5	18450	24.7	4928	4953	268.44	3.73	11.59
Northern Prov	Marble Hall	24	2014/15	3800	17.1	17100	30.1	5033	5063	296.09	3.38	12.78

6.3.5 Comparison of FruitLook and automatic weather station data

Blue WF, WUE_y and WUE_e for both seasons calculated using the ET_{FL} is presented in Table 6.7. The ET_{FL} was higher than the ET derived from published crop factors and each farm had a different ET values according to its biomass production and water use according to the satellite information per farm. Blue WF determined from ET_{FL} was higher than the ones determined from the atmospheric ET_o and a published K_c. This was due to the fact that ET_{FL} was significantly higher than the estimated ET_c. Farms 3 (936.26 m^3/ha) and 4 (962.12 m^3/ha) had the highest ET_{FL} during the 2013/14 season, while Farm 4 (889.25 m^3/ha) remained higher during the 2014/15 season. For the published crop factor, ET calculations for the 2013/14 season had a lower ET of 3483 m^3/ha compared to 5456 m^3/ha for the 2014/15 season. Farm 3 during the 2014/15 season and Farm 4 during both seasons had a lower blue WF, therefore a higher WUE_y and WUE_e. In contrast, Farm 1 in both season and Farm 2 during the 2013/14 season had a higher blue WF and a lower WUE_y and WUE_e. The average blue WF for Farms 1, 2, 3 and 4 was 421.84 m^3/ton, 380.44 m^3/ton, 375.66 m^3/ton and 359.69 m^3/ton, respectively. There were no substantial differences in the WUE_y, even though Farm 4 had a tendency towards a higher WUE_y. Comparing WF, WUE_y and WUE_e based on the two methods (ET_{FL} & ET_C), a similar observation was seen with Farm 1 having the highest blue WF and lowest efficiency and Farm 4 having a lower WF and a higher WUE_y and $WUE_{e.}$ While, Farms 2 and 3 were intermediary. Even though the use of published crop factors is accepted as a norm in the viticulture sector, using the same crop factor for all farms despite the growth vigour might be a bit biased and inaccurate. Therefore, crop factors should be adjusted according to grapevine growth vigour, when determining the WUE_y.

Table 6.7: Production blue water footprint (WF), crop water use efficiency (WUE_y) and economic water use efficiency (WUE_e) determined from FruitLook evapotranspiration (ET) data for the different farms in the Western Cape for the 2013/14 and 2014/15 seasons.

Farm	**Season**	**Yield**	**Yield**	**Yield**	**Total spray application**	**FruitLook ET**	**Total water use**	**Blue WF**	**WUE_y**	**WUE_e**
		Cartons[1]/ha	**t/ha**	**kg/ha**	**m^3/ha**	**m^3/ha**	**m^3/ha**	**m^3/ton**	**kg/m^3**	**ZAR/WUE_y**
1	2013/14	4000	18.0	18000	12.5	8059	8071.00	448.39	2.23	19.35
	2014/15	4000	18.0	18000	17.0	7098	7115.20	395.29	2.53	17.06
Average			*18.0*	*18000*	*14.8*	*7578*	*7593.10*	*421.84*	*2.38*	*18.21*
2	2013/14	4000	18.0	18000	15.9	7836	7851.60	436.20	2.29	18.83
	2014/15	4800	21.6	21600	15.9	6997	7013.30	324.69	3.08	14.01
Average			*19.8*	*19800*	*15.9*	*7417*	*7432.45*	*380.44*	*2.69*	*16.42*
3	2013/14	5200	23.4	23400	15.9	9363	9378.50	400.79	2.50	17.30
	2014/15	5000	22.5	22500	15.9	7871	7886.80	350.52	2.85	15.13
Average			*23.0*	*22950*	*15.9*	*8617*	*8632.65*	*375.66*	*2.67*	*16.21*
4	2013/14	5500	24.8	24750	15.5	9621	9636.70	389.36	2.57	16.80
	2014/15	6000	27.0	27000	18.0	8893	8910.50	330.02	3.03	14.24
Average			*25.9*	*25875*	*16.8*	*9257*	*9273.60*	*359.69*	*2.80*	*15.52*

(1) 4.5 kg export carton

6.4 Conclusions

Irrigation volume was highest in the Lower Orange River region due to higher evaporative demand; longer growing season and the use of micro-sprinkler irrigation systems. Since ET accounted for almost 99% of blue water use, the Lower Orange River region had a higher blue water use as well.

In general, the 2013/14 season had a lower blue WF and a higher WUE_y compared to the 2014/15 season. This might be due to difference in prevailing weather conditions experienced during the two seasons. The higher the blue WF, the lower the WUE_y and the more money required for production. During the 2014/15 season, higher blue WF was calculated for the Lower Orange River region. The regional average blue WF for both seasons was 210.35 m^3/ton, 392.19 m^3/ton and 272.42 m^3/ton for the Western Cape, Lower Orange River region and the Northern Province, respectively. The regional average WUE_y for both seasons was 5.04kg/m^3, 3.00 kg/m^3 and 3.68kg/m^3 for the Western Cape, Lower Orange River and Northern Province region, respectively. Results showed that the average WUE for Crimson Seedless table grapes in the Western Cape was higher than the water productivity values reported for apples and oranges in the same region. Both ET derived from published crop factors and ET_{FL} indicated that Farm 1 had the highest blue WF and lowest WUE_y while Farm 4 had a lower WF with a higher WUE_y. With regard to different climatic regions, the study showed that table grape WUE was higher in the winter rainfall region and lower in the summer rainfall regions.

The average blue WF values determined for table grapes was higher than those of apples and oranges. In this regard, table grape producers need to use their water resources more judiciously so as to lower their WF and become more competitive with other crops. The WF and WUE analyses can aid in decision making as to which crop can be grown, especially in semi-arid areas where water is a scarce natural resource. A more water use efficient crop with a lower WF that can contribute to the economy of the particular region can be considered instead.

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Chapter 7

General discussion and conclusions

CHAPTER VII: GENERAL DISCUSSION AND CONCLUSIONS

7.1 Brief overview

The study aimed to provide new insights into the subject of water footprint (WF) analysis and ways of improving water use efficiency (WUE) of *Vitis vinifera* L. *cv*. Crimson Seedless table grapes. In this study, grapevine performance as affected by differing cultivation conditions, *i.e.* soil types, irrigation systems and cultivation practices, were compared during critical phenological stages through direct plant-based measurements in terms of plant growth (vegetative and reproductive), plant physiology, WUE, as well as environmental effects (climatic, soil conditions and soil water content). FruitLook datasets were also validated against field measurements to determine if FruitLook satellite data reflect what the actual situation in the field is, and whether it can add value in irrigation management and water footprint determination. Finally, blue WF along the production chain only, were determined for three regions in South Africa (one winter and two summer rainfall areas).

7.2 General discussion of findings according to original objectives

7.2.1 Objective I: To determine the effects of differing cultivation conditions on table grape *(Vitis vinifera* L. *cv.* Crimson Seedless) phenology, vegetative growth, WUE, yield, fruit quality and physiology.

The four selected blocks showed great variability in terms of their soil characteristics and vegetative growth responses. Block D had vigorous vegetative growth in both seasons. Higher clay and carbon contents, combined with good management practices, probably contributed to the higher vegetative growth. In contrast, Block A had poor vegetative growth, lower yield, as well as poor fruit quality in both seasons. The wetness of the soil, as well as saline soil conditions probably contributed to the poor growth. It appeared as if irrigation system had an effect on vegetative growth. In this regard, grapevine growth rate in Blocks B and C, which were irrigated with micro-sprinkler irrigation systems, was slower in the 2014/15 season, which was drier and warmer compared to the 2013/14 season. Block D had the highest yield during the 2013/14 season, with the best quality in both seasons. Block D was more vigorous, with a denser canopy, which was linked to lower light interception throughout the season. The heavy crop load observed for Block D in the first season had a negative effect on grape colour development and the percentage of export grapes. In addition, the high yield to pruning mass ratio observed in Block D indicates that this block was highly productive; while Blocks B and C were average and Block A was the least productive.

Stem water potential (Ψ_S) was highest at pea size and lowest at harvest, with Blocks A and B showing the lowest Ψ_S at most of the measured phenological stages during both seasons. However, midday Ψ_S at harvest was lower in Blocks C and D during the 2014/15 season. Diurnal cycle results showed that Ψ_S was highest in the early morning, followed by a steady decline until 14:00 and partial recovery for the remainder of the day. Blocks B and D had higher specific leaf area (SLA). Blocks A and B had a tendency towards thinner leaves that could have been linked to the lower Ψ_S measured in those blocks at the different phenological stages.

Higher values of net carbon assimilation rate and stomatal conductance corresponded with larger berry size and higher yield. High leaf temperature (Tleaf) and vapour pressure deficit (VPD), combined with low Ψ_S reduced net carbon assimilation and stomatal conductance in Block A during the 2013/14 season. The relationship between net carbon assimilation rate and Tleaf also revealed an inverse relationship, *i.e.* as leaf temperatures increased, there was a reduction in net carbon assimilation rates. Considering the response of the different types of leaves to net carbon assimilation rate over the progression of the season, it was clear that there were differences amongst the different leaf types' performance at pea size and harvest. However, at post-harvest all leaves had similar net carbon assimilation rate, because by then leaves had aged and were similar with respect to functionality.

Both seasons' data indicated Block D to have a tendency towards lower light interception in most of the canopy positions at all stages, indicating vigorous growth and shading. This means that this block's canopy had a variety of exposed and shaded leaves that could maximise photosynthetic activity, reduce transpiration in the shaded leaves and contribute to increased WUE. Additionally, the leaf morphological attributes also indicated a tendency towards thicker leaves and a larger SLA in Block D's different leaf types, which is reported to be beneficial for photosynthesis and improved WUE, hence the higher productivity observed in this block. However, the denser canopy in this block also contributed to a lower dry mass (DM), specific leaf mass (SLM) and leaf density in all leaf types.

More export grapes were harvested during the warmer, drier 2014/15 season. This may be an indication that prevailing drier and warmer climatic conditions exposed grapevines to a certain degree of water stress during the growing season, hence reducing vegetative growth in favour of improved fruit quality. The two micro-sprinkler irrigated blocks had a tendency towards a higher WUE_y in the 2014/15 season, due to the higher evapotranspiration (ET) and yield measured in these blocks. The drip irrigated Block D had a higher WUE_{irr} in both seasons and also produced grapes of the best quality, which means a certain stress level can be applied even when grapevines are cultivated for table grape production, without forfeiting fruit quality. Thus, using a drip irrigation system and irrigation applications as applied for Block D and under similar conditions to that in this study, could reduce the volume of irrigation water used and contribute to saving water.

7.2.2 Objective II: To conduct a blue water footprint analysis for the production of table grapes in the Hex River Valley and South Africa.

Seasonal ET for both seasons ranged from 3483 m^3/ha to 5456 m^3/ha in the Western Cape, 6564 m^3/ha to 7132 m^3/ha in the Lower Orange River region and 4853 m^3/ha to 5033 m^3/ha in the Northern Province. Data obtained from the Lower Orange River region indicated the highest irrigation volume, ET and blue WF, due to the higher evaporative demand; the longer growing season and use of micro-sprinkler irrigation systems. In general, the 2013/14 season had a lower blue WF and a higher WUE_y compared to the 2014/15 season, which may have been due to differences in prevailing weather conditions experienced during the two seasons. The regional average blue WF for both seasons was 210.35 m^3/ton, 392.19 m^3/ton and 272.42 m^3/ton for the Western Cape, Lower Orange River region and the Northern Province, respectively. The regional average WUE_y for both seasons was 5.04kg/m^3, 3.00 kg/m^3 and 3.68kg/m^3 for the Western Cape, Lower Orange River region and Northern Province, respectively. Results showed that the Western Cape had a lower WF with a higher WUE_y, followed by the Northern Province and, lastly, the Lower Orange River region. The average blue WF values determined for table grapes were higher than those of apples and oranges. However, the average WUE_y values determined for table grapes in the Western Cape were higher than the water productivity values reported for apples and oranges in the same region.

The FruitLook evapotranspiration (ET_{FL}) values were higher than the ET derived from published crop factors and each farm had different ET values according to its biomass production and water use according to the satellite information per farm. Thus, blue WF values determined from ET_{FL} were higher than that determined from the atmospheric ET_o and published K_c values. Even though the use of published crop factors is accepted as a norm in the viticulture sector, using the same crop factor for all farms despite the vigour and canopy characteristics may be biased and inaccurate. Therefore, crop factors should be adjusted according to grapevine vigour and canopy characteristics when determining the WUE_y. Since a positive correlation was obtained between ET_{FL} values and water balance ET estimations in this study, FruitLook data also has a potential to be used in crop factor determinations or in irrigation management planning. Despite the differences in ET and blue WF between the different methods, they both indicated that Farm 1 had the highest blue WF and lowest WUE_y, while Farm 4 had a lower blue WF with a higher WUE_y.

7.2.3 Objective III: Setting guidelines for improved water resource management in table grape production.

This study indicated that average blue WF values determined for table grapes were higher than those of apples and oranges reported by Gush *et al.* (2017). The table grape WUE_y values were also higher in the winter rainfall region, but lower in the summer rainfall regions. Furthermore, Pegasys (2010) also reported that table grapes had a higher WUE_y, generates a higher gross income per m^3 and also resulted in the highest number of jobs created per volume of water used in the production process compared to other deciduous fruit types in the Breede River Catchment Area. This type of information can unlock discussion as to which crop is more efficient to be grown in an area or in a specific region considering all factors affecting WUE and with the pressure on scarce water resources. Water use efficiency and WF information are very important for the industry/producer in decision making regarding crop selection, when expanding/ or replacing vineyards or orchards, especially in the current drought conditions, as well as when considering the impact of climate change with possible lower rainfall.

FruitLook data validation also showed a potential to be used in irrigation management decisions that could contribute to improved WUE. A positive correlation was found between shoot growth and FruitLook biomass production, as well as with ET_{FL} and water balance calculations. This is an indication that this data can be used in irrigation scheduling, which can lead to a reduction in irrigation volumes and water saving. Water balance calculations are normally done using weather data and crop factor estimations and since FruitLook captures those aspects as well, it could be a useful tool. However, there is still a need for actual plant water stress monitoring to establish threshold values for optimum irrigation scheduling. Therefore, an integrated approach between FruitLook data and actual field measurements is needed for improved irrigation scheduling and increased WUE_y in the Western Cape region where this data is available.

7.3 Major findings: limitations and novelty value – implications

In order to improve WUE in table grape production for sustainable production, a balance between vegetative and reproductive growth must be maintained. Block D was a vigorous block as concluded from shoot growth, high pruning mass and the standardised opening of the canopy at véraison to increase light interception for improved colour development. For Block D, yield of the first season was the highest, but the second season’s yield was reduced probably due to stricter crop control in the second season in an effort to have fewer but higher quality bunches. Block A had poor production as well as productivity and this could be ascribed to the wetness of the soil, as well as saline soil conditions found in this block. This is an indication that soil conditions and canopy management are important factors affecting WUE. It is a common practice in viticulture to remove leaves at véraison to improve light interception for improved colour development. It is important to avoid severe leaf removal that can have a negative impact on physiological mechanisms, as well as productivity. Also, in the second season, which was drier and warmer, better fruit quality was obtained, indicating that a certain level of water stress during the growing season can improve fruit quality.

The two blocks that were irrigated with a micro-sprinkler irrigation system had a higher irrigation volume and ET. This was in agreement with Myburgh (2012), who reported a higher ET in Thompson Seedless table grapes irrigated with a micro-sprinkler irrigation system compared to drip irrigation in the Lower Orange River region. In a water stressed country such as South Africa, it is probably necessary to consider drip irrigation systems that use less irrigation volumes and reduces evaporation. Furthermore, lower Ψ_S measured in this study indicates that drip irrigation systems can successfully be implemented without forfeiting yield and quality, provided it is well managed. Additionally, deficit irrigation systems can control vigorous vegetative growth, while reproductive growth is maintained or improved, resulting in improved WUE. Thus, tools and methods are needed to measure plant and soil water status in order to schedule irrigation properly and contribute to a higher WUE. The two micro-sprinkler irrigated blocks had a tendency towards a higher WUE_y in the 2014/15 season due to the higher ET and yield measured in these blocks, while Block D, which was irrigated with a drip irrigation system, had a higher WUE_{irr}. Calculations included in this study also indicated over-irrigation in some blocks, especially for the micro-sprinkler irrigated blocks, meaning that irrigation scheduling is not optimal and more needs to be done to reduce irrigation volumes in order to improve WUE in table grape production.

Water footprints provide useful information on the water use of a specific area and strategies to improve WUE can be developed based on this information. When combined with crop yield data, it creates the basis for identifying existing levels of water use efficiency (so called ‘crop per drop’, for example kg/ton of table grapes produced per m^3 of water used). Water footprint analysis is a good starting point for determining the quantity of water needed for a certain crop in a specific area. This information can aid in decision making as to which crop can be produced sustainably with better economic benefits to the production area. Thus, WF can be used as a tool to raise awareness, as well as determine crop efficiency, which can be used in debates and decision making regarding water allocations.

7.3.1 Limitations

The main limitation of this study was that only mature established blocks were used and due to human capacity and equipment availability, more blocks could not be included to have a specified statistical layout, hence resorting to scenario evaluation. Equipment to measure physiological measurements was limited, due to the fact that there was only one IRGA to measure four blocks and all blocks could not be measured at the same time in order to make comparisons between them. This was the reason why only two blocks were selected for the second season to conduct diurnal cycles. The other limitation was equipment calibration issues. The leaf water use efficiency could not be determined, because there was probably a calibration issue with the IRGA, which affected the vapour measurements which may also have affected stomatal conductance, transpiration and VPD values obtained with the IRGA. Furthermore, two different porometers were used to determine stomatal conductance in the second season and one of these porometers had calibration issues. Therefore, that data had to be excluded as well. This is an indication that calibration issues can hamper the adaptability and use of equipment in the field, therefore simple and less sophisticated equipment should be used by producers for field evaluation to guide them with irrigation scheduling. Obtaining reliable weather data was also very problematic. There were three automatic weather stations (AWS) available for the De Doorns area. The AWS situated on the Hex River experimental farm, which was used for the first season, was not available for the second season, due to vandalism and therefore the Modderdrift AWS was used in the second season. At times, weather data of a specific station also seemed to be incorrect or stuck at a certain value for consecutive days, making it unreliable.

7.3.2 Novelty value

Few studies have been conducted on table grape WUE and blue WF and this study can contribute to that limited information availability. For sustainable table grape production, it is very important to determine the WF and WUE in order to fulfil the concept of more crop per drop without forfeiting yield and fruit quality. Most of the studies conducted on table grapes WUE and WF were desktop studies and did not include actual plant growth and physiological measurements. Additionally, most of the global data (Mekonnen & Hoekstra, 2010; Pahlow *et al.*, 2015) available did not make a distinction between the different grape types (table grapes, raisin & wine grapes), which have different trellising systems, as well as different canopy sizes and structures, with different management styles, which can have an effect on vegetative and reproductive growth, as well as crop water use, hence influencing WUE and WF. Furthermore, a comparison of table grape blocks grown under different climatic conditions were made to determine the effect of growing conditions and weather conditions on WF and WUE. This study has proven that higher evaporative demand increases blue water use, which leads to a higher blue WF with a lower WUE_y. The plant based measurements in this study also contribute to the scientific knowledge and understanding of how the grapevine's performance is affected by different soil types and irrigation systems, through direct plant based measurements during critical phenological stages.

Water footprint analysis requires information on crop water use and production at a range of spatial and temporal scales, which is not always available. As already discussed under section 2.4.3 in the literature review, there are different methods to estimate ET. However, remote sensing offers the advantage of being able to estimate crop water use for each pixel of a satellite image. Furthermore, this technique also estimates crop water use based on the grapevine growth tempo and canopy characteristics and does not need to rely on the generalised crop coefficient often used in the industry. Hence, indicating the novelty of FruitLook in irrigation water management.

7.4 Perspectives for future research

In view of the escalating demands on scarce water resources, sustainable table grape production requires a very high WUE (Tomás *et al.*, 2012). Few studies have been done that considered WF and WUE of table grapes, thus more studies are needed that can contribute to this scientific knowledge. Tools that can reliably be used in the vineyard by producers to measure plant and soil water status are needed to schedule irrigation properly and ultimately reduce irrigation volumes and improve WUE. More WF studies are needed to quantify total WF based on actual plant response measurements, while considering the local environment of the studies, rather than using global averages or data sets. This study only determined blue WF along the production chain, hence more studies are needed to quantify the total WF along the entire production and value chain.

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Addendum A

Table A.1: Soil chemical analysis of the four experimental blocks. Increasing shades of green indicates higher values while increasing shades of red indicates lower values. Values are means of 5 soil samples.

Block	Depth	pH $_{(KCl)}$	Resist.	H^+	Stone	P Bray II	K	Na	K	Ca	Mg	Cu	Zn	Mn	B	Fe	C	T-Value
	(cm)		(Ohm)	(cmol/kg)	(Vol %)	(mg/kg)	(mg/kg)	Exchangeable cations (cmol(+)/kg)				(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(%)	
Block A	0 - 30	6.32	1258	0.30	11.80	112	245	0.09	0.62	4.76	1.26	14.26	9.22	80.66	0.28	204.11	0.79	6.80
Block A	30- 60	6.32	924	0.20	16.00	71	134	0.15	0.34	4.76	1.37	8.17	6.40	76.14	0.20	144.82	0.52	6.66
Block A	60 - 90	6.52	752		14.20	47	124	0.27	0.32	5.67	1.76	6.44	8.66	82.40	0.18	175.94	0.46	8.01
Block B	0 - 30	6.16	4560	0.18	15.60	102	78	0.11	0.20	2.36	0.95	11.40	5.40	25.44	0.16	76.46	0.44	3.69
Block B	30- 60	6.00	3862	0.28	26.00	74	89	0.15	0.23	1.97	0.82	9.60	4.24	28.96	0.13	56.57	0.38	3.28
Block B	60 - 90	5.92	2850	0.18	44.40	54	112	0.18	0.29	2.18	0.88	5.70	3.42	13.14	0.17	58.60	0.38	3.63
Block C	0 - 30	6.22	2702	0.20	4.00	102	121	0.10	0.31	3.74	0.84	15.75	7.98	26.02	0.19	137.70	0.77	5.03
Block C	30- 60	6.16	3028	0.25	5.20	78	110	0.17	0.28	3.41	0.71	7.71	5.50	15.78	0.18	164.94	0.54	4.63
Block C	60 - 90	5.82	1928	0.30	4.20	52	72	0.14	0.18	2.36	0.55	3.28	11.96	8.54	0.12	159.18	0.34	3.35
Block D	0 - 30	6.46	2380	0.25	18.20	77	99	0.07	0.25	5.81	0.98	19.17	6.14	16.70	0.30	106.47	1.11	7.17
Block D	30- 60	6.14	3140	0.59	18.80	66	107	0.08	0.27	5.78	0.92	14.54	6.86	12.00	0.24	115.62	1.13	7.17
Block D	60 - 90	6.38	2666	0.39	22.00	49	74	0.08	0.19	4.47	0.87	16.10	6.16	14.82	0.22	110.54	1.04	5.69

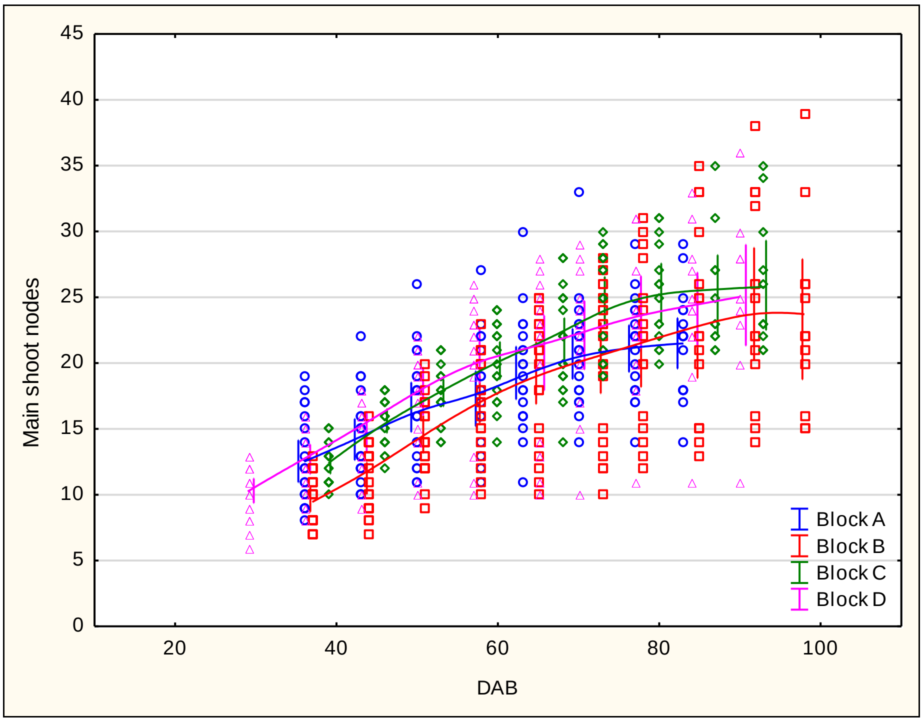

Figure A.1: Main shoot nodes relative to date after budburst (DAB) of the four experimental blocks for the 2013/14 season. A distance weighted least squares fit is drawn.

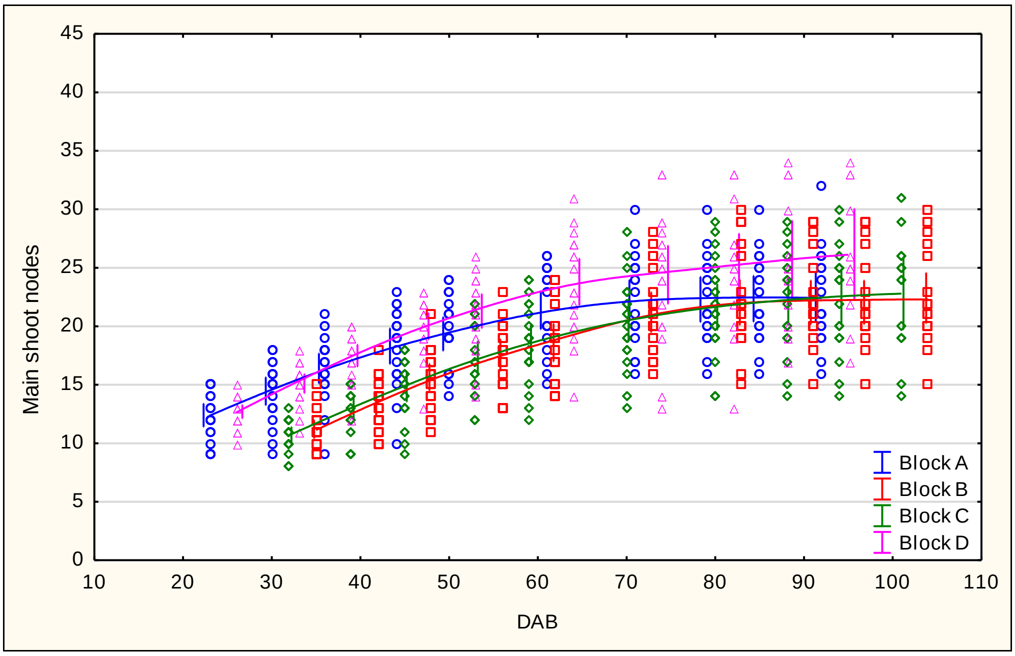

Figure A.2: Main shoot nodes relative to date after budburst (DAB) of the four experimental blocks for the 2014/15 season. A distance weighted least squares fit is drawn.

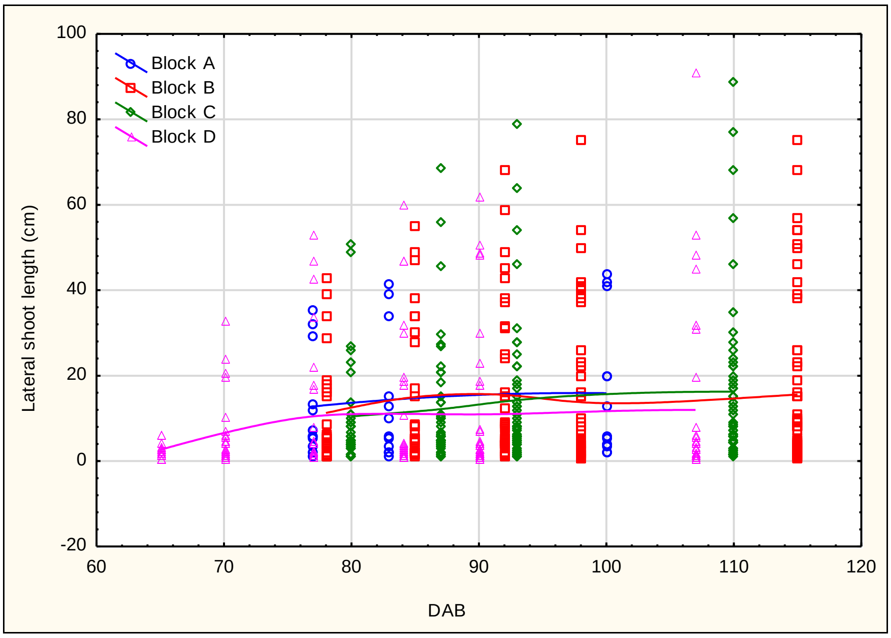

Figure A.3: Lateral shoot length relative to date after budburst (DAB) of the four experimental blocks for the 2013/14 season. A distance weighted least squares fit is drawn.

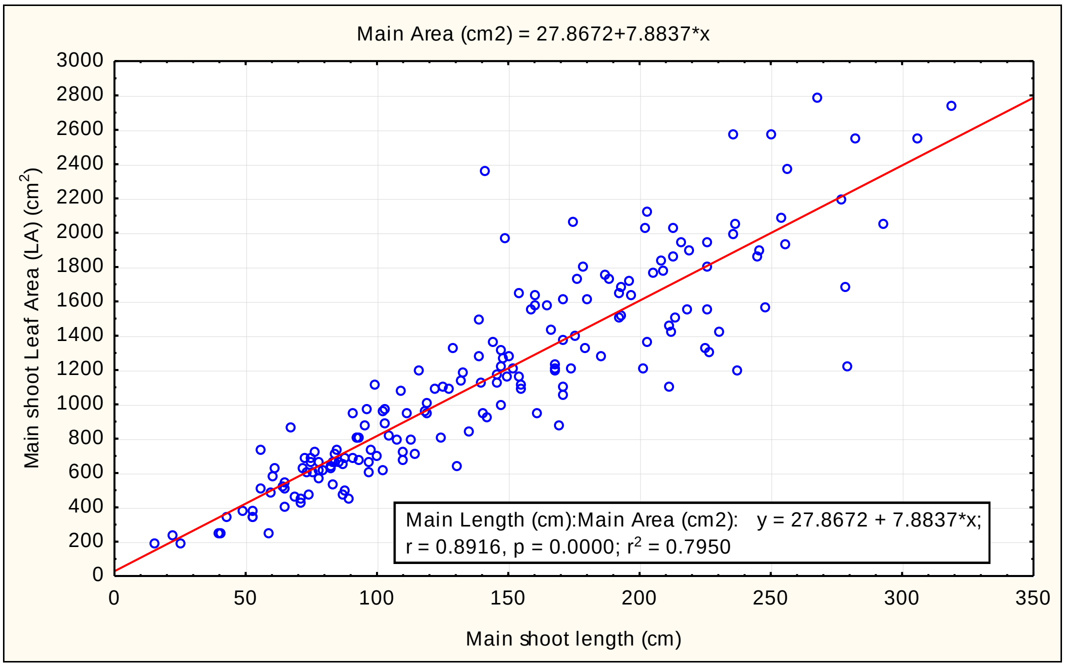

Figure A.4: Relationship between the main shoot leaf area (cm^2) and the main shoot length (cm), r = 0.89, r^2 = 0.80 ($p \leq 0.001$).

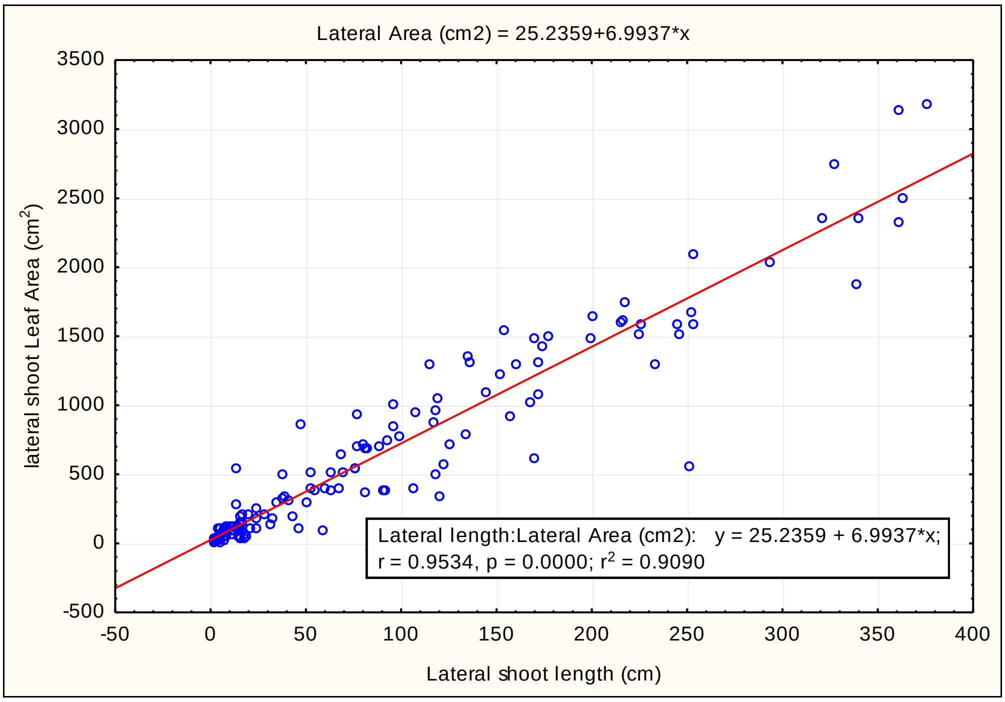

Figure A.5: Relationship between the lateral shoot leaf area (cm$^{2)}$ and the lateral shoot length (cm), r = 0.95, $r^2 = 0.91$ ($p \leq 0.001$).

Addendum B

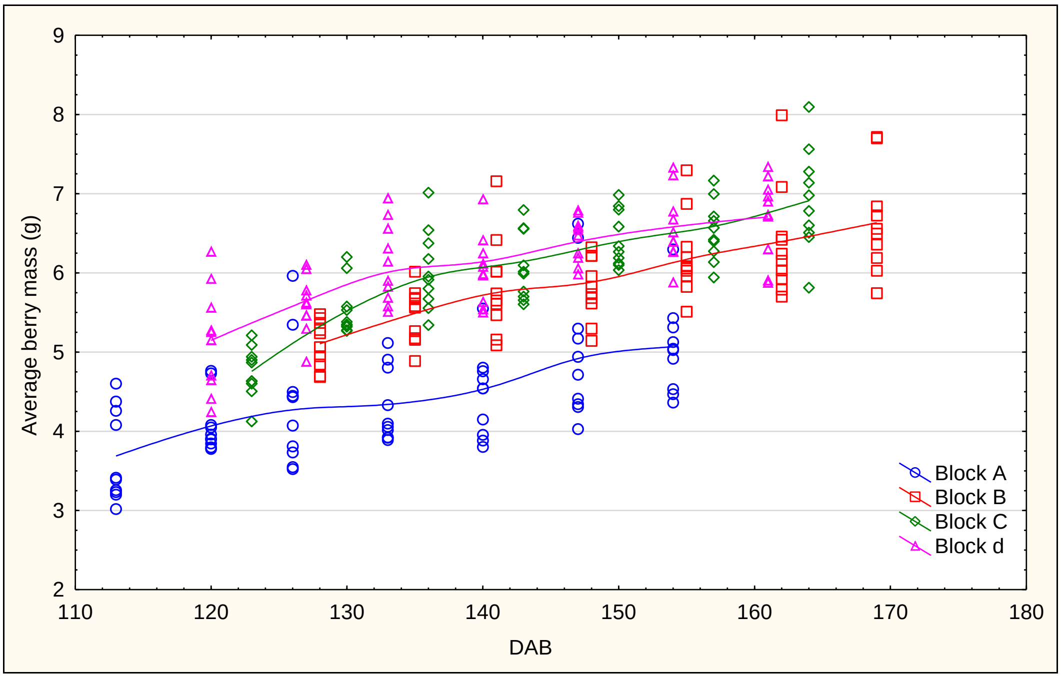

Figure B.1: Average berry mass relative to date after budburst (DAB) of the four experimental blocks measured from véraison to harvest for the 2013/14 season. A distance weighted least squares fit is drawn.

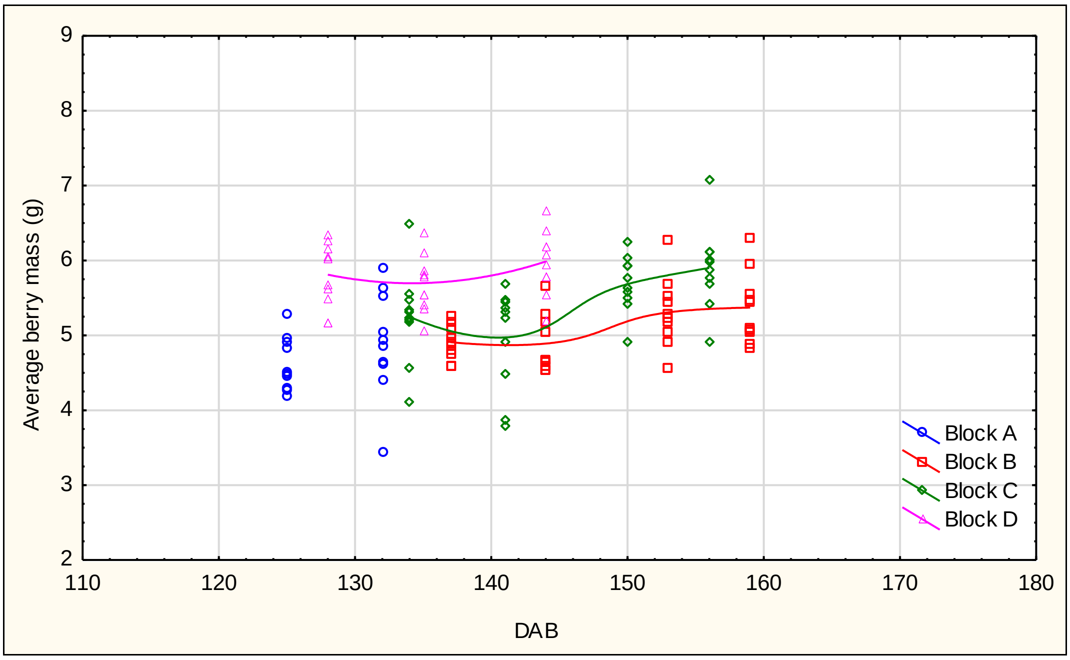

Figure B.2: Average berry mass relative to date after budburst (DAB) of the four experimental blocks measured from véraison to harvest for the 2014/15 season. A distance weighted least squares fit is drawn.

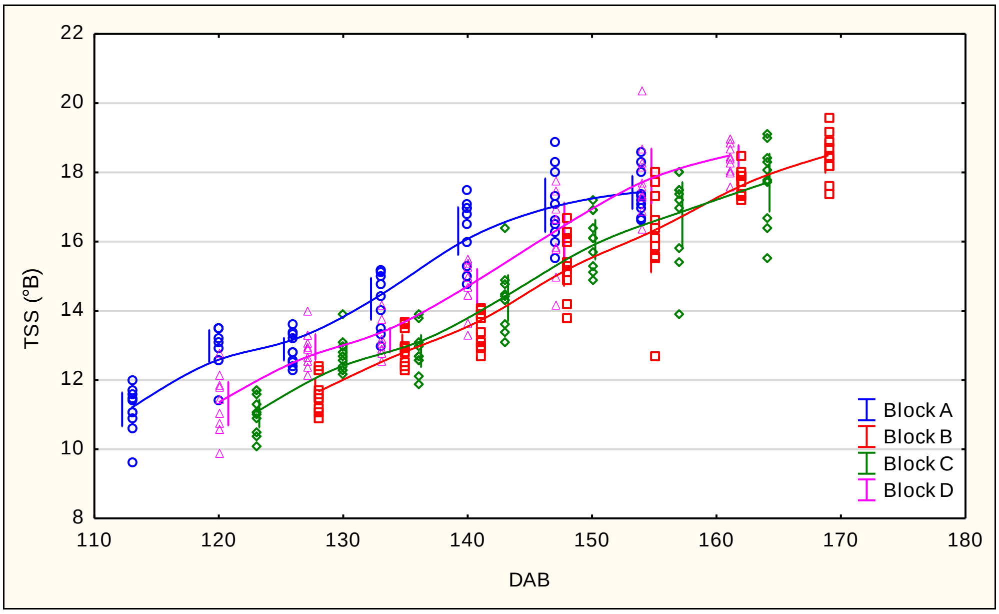

Figure B.3: Berry total soluble solids(TSS) accumulation relative to date after budburst (DAB) of the four experimental blocks measured from véraison to harvest for the 2013/14 season. A distance weighted least squares fit is drawn.

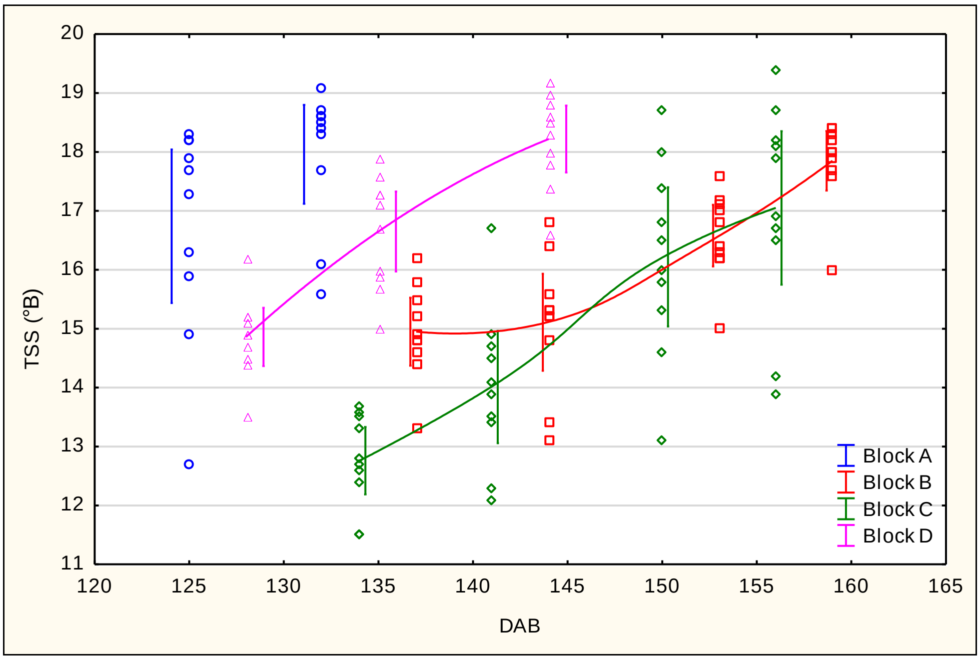

Figure B.4: Berry total soluble solid (TSS) accumulation relative to date after budburst (DAB) of the four experimental blocks measured from véraison to harvest for the 2014/15 season. A distance weighted least squares fit is drawn.

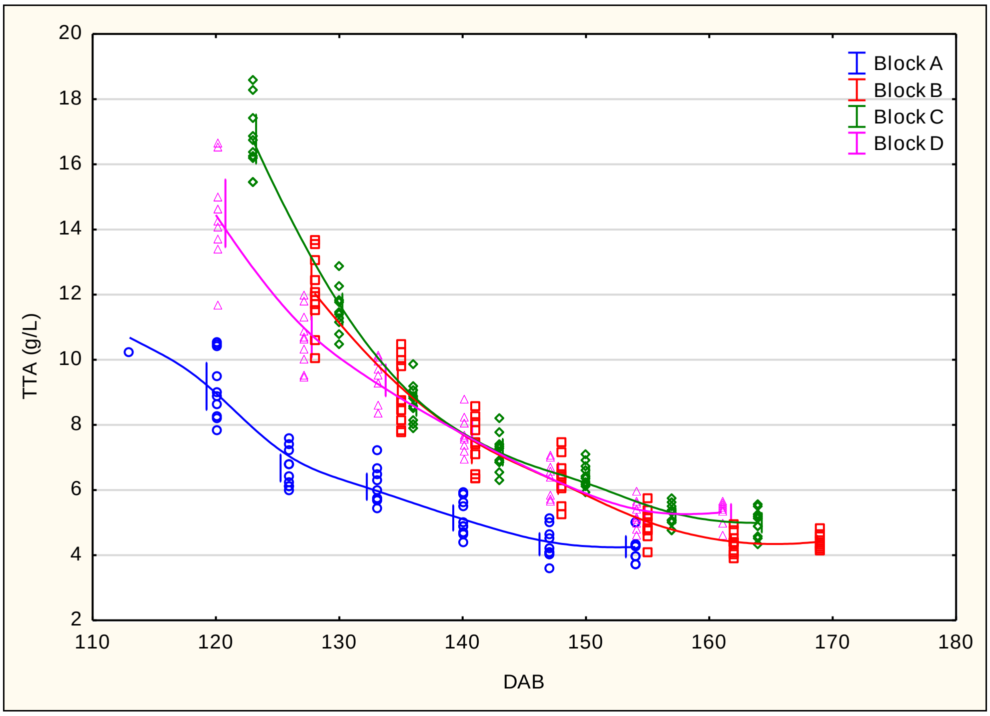

Figure B.5: Total titratable acidity (TTA) in g/L relative to date after budburst (DAB) of the four experimental blocks measured from véraison to harvest for the 2013/14 season. A distance weighted least squares fit is drawn.

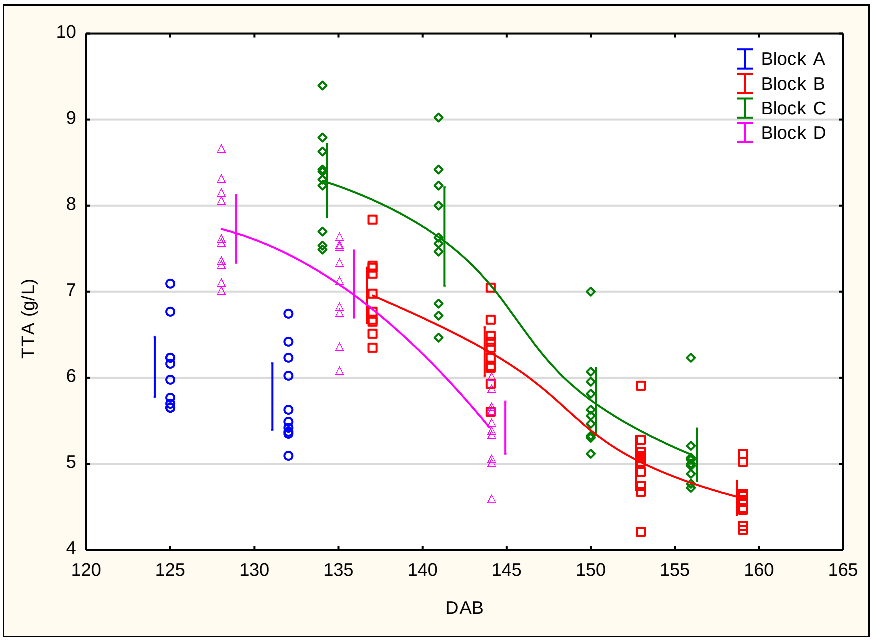

Figure B.6: Total titratable acidity (TTA) in, g/L relative to date after budburst (DAB) of the four experimental blocks measured from véraison to harvest for the 2014/15 season. A distance weighted least squares fit is drawn.

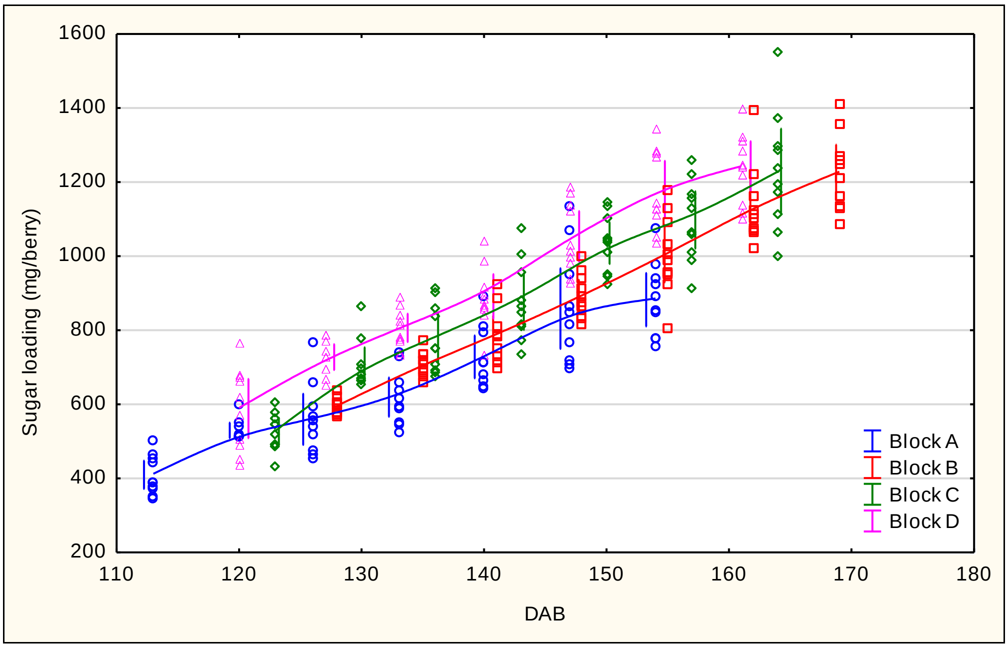

Figure B.7: Berry sugar loading (mg/berry) relative to date after budburst (DAB) of the four experimental blocks measured from véraison to harvest for the 2013/14 season. A distance weighted least squares fit is drawn.

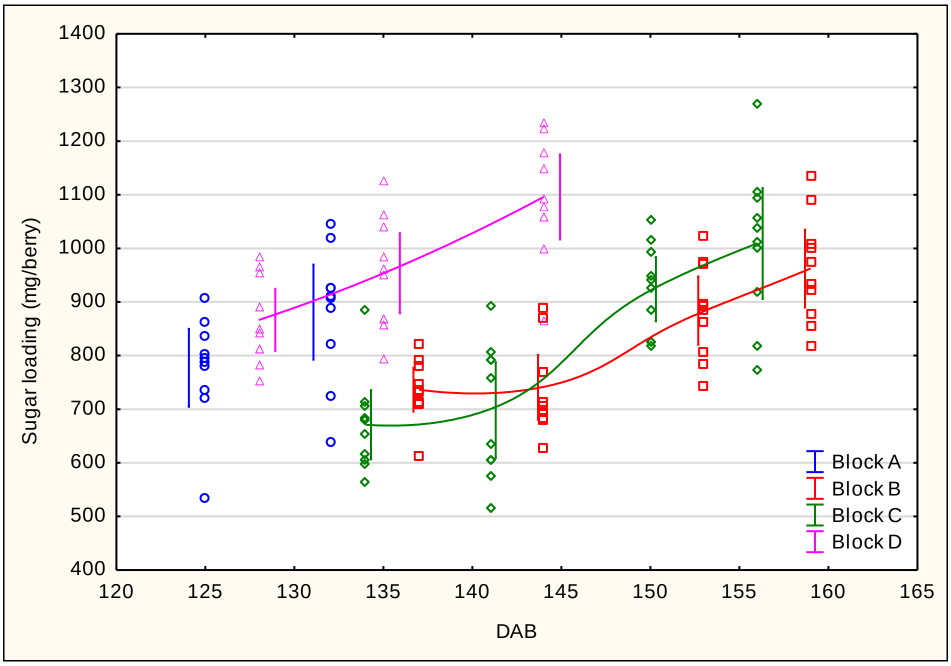

Figure B.8: Berry sugar loading (mg/berry) relative to date after budburst (DAB) of the four experimental blocks measured from véraison to harvest for the 2014/15 season. A distance weighted least squares fit is drawn.

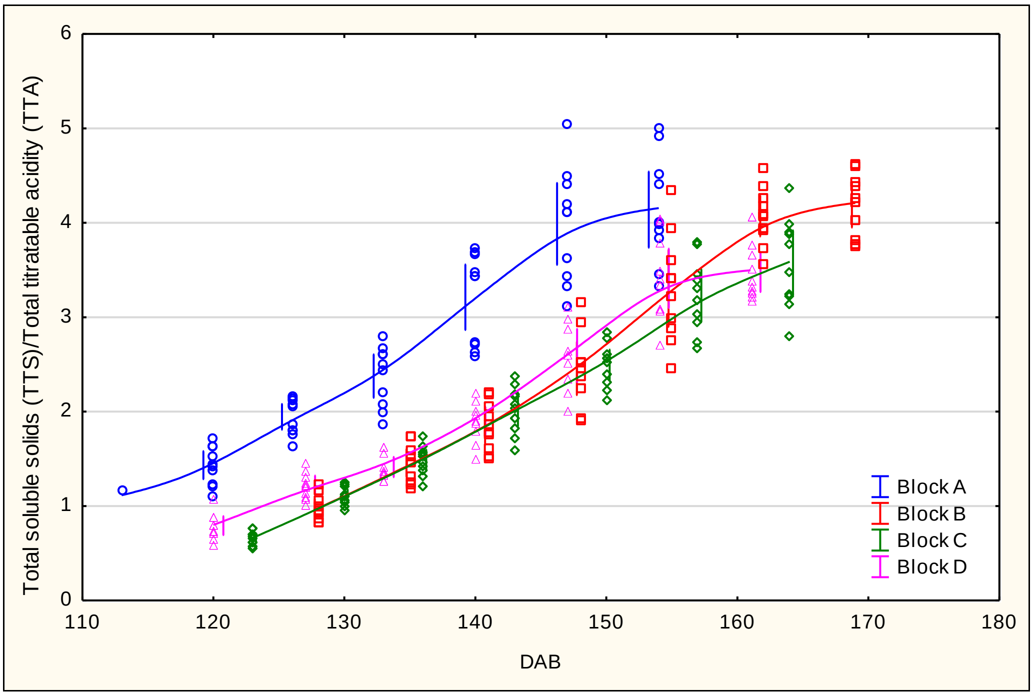

Figure B.9: Total soluble solids (°B): total titratable acidity (TTA) ratio relative to date after budburst (DAB) of the four experimental blocks measured from véraison to harvest for the 2013/14 season. A distance weighted least squares fit is drawn.

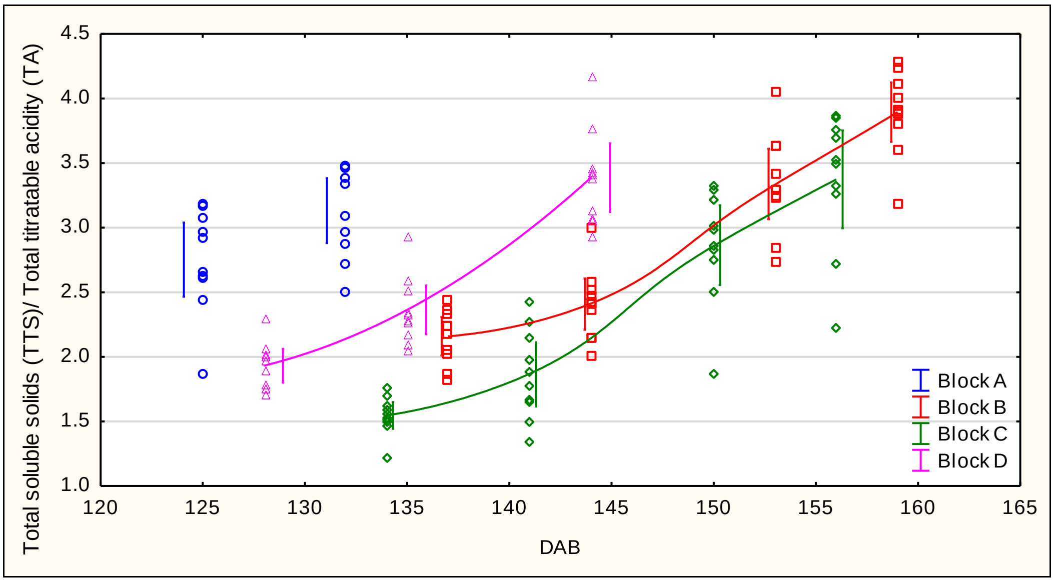

Figure B.10: Total soluble solids (°B): total titratable acidity (TTA) ratio relative to date after budburst (DAB) of the four experimental blocks measured from véraison to harvest for the 2014/15 season. A distance weighted least squares fit is drawn.