Optimising productivity in vineyards and potential effects on grape and wine composition for a specific production goal

by

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DECLARATION

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SUMMARY

In this study three trellis/training systems (double split cordon gable, vertical shoot positioning and sprawling systems) located in a *Vitis vinifera* cv. Shiraz vineyard in Stellenbosch were investigated to determine how grapevine productivity and grape- and wine composition can be altered as a result of differing canopy microclimate, grapevine balance regimes and yield component compensation reactions. Two sprawling training systems (double and standard bud load in relation to the vertically shoot positioned system) were combined in the second season and subjected to a lighter pruning, simulating mechanical pruning. Pruning and harvest data were collected over two growth seasons from each grapevine in the plot, which also displayed within-treatment and vineyard vigour-, yield- and grapevine balance variability. The large number of single-vine replicates made it possible to determine main yield components, such as bud load, budburst percentage, fruitfulness, bunch- and berry size as well as berries per bunch, and to investigate some primary components responsible for grapevine productivity. Shoot growth, shoot characteristics (leaf area, lateral number, internode length, and leaf age), canopy microclimate, physiological measurements, water status and ripening evolution were recorded to establish trends between grapevine balance and associated compensation reactions. Qualitative descriptive analysis was performed on the wines produced from each treatment in the second season.

Increased bud load led to increased shoot numbers and yield, but with decreased bunch mass and grapevine vigour, in terms of total cane- and mean mass per cane and shoot length. The gable trellis system produced the highest yield between treatments in both seasons, but due to trellis conversion completion in the first season, low vigour was present. For this reason, imbalanced grapevine conditions occurred in terms of high yield to cane mass ratios (Y/CM) and low leaf area to yield ratios (LA/Y) and consequently delayed ripening. Nevertheless, the gable trellis system seemed to reach maximum productivity, as the yield between seasons remained relatively similar. The main yield component responsible for yield difference in the first season was the number of bunches produced per shoot (fertility), while increased budburst percentage and bunch mass in the second season affected yield most. More shoots led to decreased fertility and increased bunch mass in this treatment, and improved growth and high yields during the second season resulted in more desirable grapevine balance, thereby not affecting ripening negatively. The two sprawling systems only differed according to shoot number, with the double sprawling system (double the amount of buds) producing twice as many shoots and consequently higher yields. Simulated mechanical pruning, in the second season, decreased grapevine vigour as expected but increased yield considerably as a result of increased fertility. However, imbalanced Y/CM ratios occurred, delayed ripening, and a highly exposed canopy bunch zone which increased the process of leaf degradation and the occurrence of water deficits. The VSP treatment produced highly vigorous grapevines together with low yields in both seasons and as a result increased canopy density and decreased Y/CM ratios.

Grapevine balance, bud load and canopy density were most associated with sensory wine attributes. The intensity of fruity wine attributes increased and vegetative wine attributes

decreased as bud load and Y/CM ratios increased and canopy density decreased. The sprawling treatment displayed the highest Y/CM ratio and bud load as well as the least dense canopy. Therefore the sprawling training system produced wines containing the highest fruity attributes which is generally desirable in new world Shiraz. The dense canopy as a result of vigorous growth, low Y/CM and bud load of the VSP treatment produced wines dominated by vegetal attributes. The gable treatment, which displayed Y/CM ratios, bud load and canopy densities with general values between the VSP and sprawling treatments, produced wines with vegetal and fruity attributes, with the latter probably being more dominant.

Changing trellising-, training- and pruning systems clearly led to the production of different wine styles. Grapevine balance, canopy density and pruning severity should be taken into consideration when attempting to produce wines intended for specific production goals. Therefore, increased yield as a result of alternative pruning-, training- and trellising systems does not necessarily affect wine composition negatively, if not more beneficially, and should be considered as a solution regarding production profitability.

OPSOMMING

In hierdie studie word drie prieelstelsels (dubbel verdeelde kordon gewel, vertikale lootposisionering- en vryloot stelsels), geleë in ʼn *Vitis vinifera* cv. Shiraz wingerd in Stellenbosch ondersoek om te bepaal hoe wingerdstokproduktiwiteit, druif- en wynsamestelling gewysig kan word vanweë verskillende lowermikroklimaat, wingerdstokbalanse asook opbrengskomponent kompensasiereaksies. Twee vryloot prieelstelsels (dubbel- en normale oogladings) is in die tweede seisoen gekombineer en aan ʼn ligter snoei aksie onderwerp, om meganiese snoei na te boots. Snoei- en oesdata van elke stok is ingesamel in die perseel oor ʼn tydperk van twee groeiseisoene, wat variasie in terme van groeikrag, opbrengs en balans ten toon gestel het binne elke behandeling asook tussen behandelings in die eksperimentele wingerd. Die groot aantal enkelstok-herhalings het dit moontlik gemaak om hoof opbrengskomponente, soos ooglading, botpersentasie, vrugbaarheid, tros- en korrelgrootte, sowel as korrels per tros te bepaal en om sekere primêre komponente, verantwoordelik vir wingerdproduksie te ondersoek. Lootgroei, lootkenmerke (blaararea, sylootgetalle, internode lengtes en blaarouderdom), lowermikroklimaat, fisiologiese metings, waterstatus en rypwordingsevolusie is gemeet om tendense tussen wingerdbalans en geassosieerde kompensasie te bepaal. Kwalitatiewe beskrywingsanalises is in die tweede seisoen op die wyne van elke behandeling toegepas.

Toename in ooglading het gelei tot toename in lootgetalle en opbrengs, maar ʼn afname in trosmassa en groeikrag. Die afname in groeikragtigheid was uitgedruk in terme van snoeimassa, massa per loot en lootlengte. Die gewelprieelstelsel het in beide seisoene die hoogste opbrengs gelewer, maar is deur laer groeikrag gekenmerk, meegebring deur die vergroting van die stokraamwerk op die groter prieel. Vir hierdie rede, het ongebalanseerde wingerdtoestande voorgekom in terme van hoë oes tot lootmassaverhoudings (O/LM) en lae blaararea tot opbrengsverhoudings (BA/O) en gevolglik was rypwording vertraag. Nieteenstaande het dit voorgekom asof die gewelprieel maksimum produktiwiteit bereik het, aangesien die opbrengs tussen seisoene relatief konstant gebly het. Die hoof opbrengskomponent verantwoordelik vir die opbrengsverskil in die eerste seisoen, was die hoeveelheid trosse geproduseer per loot (vrugbaarheid), terwyl verhoogde botpersentasie en trosmassa die opbrengs in die tweede seisoen die meeste beïnvloed het. Meer lote het gelei tot verlaagde vrugbaarheid en verhoogde trosmassa in hierdie stelsel, en verbeterde groei en hoër opbrengs gedurende die tweede seisoen het gelei tot ‘n meer gewensde wingerstokbalans, wat rypwording nie negatief beïnvloed het nie. Die twee vryloot prieelstelsels het slegs verskil ten opsigte van lootgetalle, terwyl die dubbel vryloot prieelstelsel (met dubbele aantal oë) twee keer die hoeveelheid lote geproduseer het en gevolglik hoër opbrengste gelewer het. Nagebootste meganiese snoei in die tweede seisoen het wingerdgroeikrag soos verwag laat afneem, maar het opbrengs aansienlik verhoog as gevolg van meer trosse. Nogtans het ongebalanseerde O/LM verhoudings, vertraagde rypwording en ʼn meer blootgestelde lower veral in die trossone voorgekom wat die proses van blaaragteruitgang en die voorkoms van watertekorte/stres verhoog het. Die VLP stelsel het hoë groeikrag wingerdstokke

opgelewer tesame met lae opbrengste in beide seisoene wat gelei het tot verhoogde lowerdigthede en verlaagde O/LM verhoudings.

Wingerdstokbalans, ooglading en lowerdigtheid was die meeste geassosieer met sensoriese wynkenmerke. Die intensiteit van vrugtige wynkenmerke het verhoog en vegetatiewe wynkenmerke het verlaag soos ooglading en O/LM verhoudings verhoog het en lowerdigtheid afgeneem het. Die vryloot stelsel het die hoogste O/LM verhoudings en ooglading gehad, sowel as die minste digte lower. Dit is die rede waarom die vryloot stelsel wyne opgelewer het wat die mees prominente bessie/vrugtige kenmerke gehad het, wat algemeen as gewens beskou kan word in ŉ nuwe wêreld Shiraz. Die digte lower, as gevolg van hoë groeikrag, lae O/LM en ooglading van die VLP stelsel, het wyne opgelewer wat meer prominent groen was. Die gewelstelsel, wat O/LM verhoudings, ooglading en lowerdigtheid opgelewer het met algemene waardes tussen die VLP en vryloot prieelstelsels het wyne tot gevolg gehad met beide groen en bessie kenmerke, met laasgenoemde waarskynlik die mees dominante kenmerk.

Die verandering van prieel-, oplei- en snoeistelsels het duidelik gelei tot die produksie van verskillende wynstyle. Wingerdbalans, lowerdigtheid en die graad van snoei behoort in ag geneem te word wanneer wyne geproduseer word vir spesifieke produksiedoelwitte. Daarom sal verhoogde opbrengs, as gevolg van alternatiewe snoei-, oplei- en prieelstelsels nie noodwendig wynsamestelling negatief beïnvloed nie, indien nie eerder meer voordelig nie, en dit behoort oorweeg te word as ‘n oplossing vir winsgewende produksie.

This thesis is dedicated to my family for their support and encouragement

BIOGRAPHICAL SKETCH

Annette Davel was born in Lydenburg on 11 November 1990. She matriculated at Lydenburg High School in 2008. Annette enrolled at Stellenbosch University in 2009 and obtained the degree BScAgric in Viticulture and Oenology in December 2012. She then enrolled for the MScAgric in Viticulture degree in 2013 at Stellenbosch University.

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PREFACE

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

Chapter I	**General introduction and project aims**
Chapter II	**Literature review** The effect of trellising, training and pruning practices on grapevine yield components
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ADDENDUM

Chapter 1

GENERAL INTRODUCTION AND PROJECT OBJECTIVES

CHAPTER 1: GENERAL INTRODUCTION AND PROJECT OBJECTIVES.

1.1 Introduction

South African wine grape producers are facing increasing pressure to meet the challenge arising from national and international market requirements, regarding the production of quality grapes and wine (Hunter & Archer, 2001). Consequently, higher input costs are invested to meet these requirements. Therefore, the primary producer of the South African wine industry is suffering more than ever in terms of grape production costs and profitability. Since 2010 the industry's average total production cost increased with *ca.* 7% per hectare, mostly due to elevated labour and cultivation costs, increased electricity prices, water tax, reparations, fuel prices and maintenance of implements (Van Wyk & Le Roux, 2012). The financial survival of wine grape growers depends on either increased yields without compromising quality, a reduction of input costs or better product prices – and, if possible, all of the above (Archer, 2011).

The South African wine industry has become somewhat one-dimensional in their adaptation to grapevine growing conditions, which could result in unbalanced grapevines that do not reach optimal potential with regards to either grape yield, berry composition or grapevine longevity. The investigation of alternative trellis- and training systems may help to achieve this goal. Trellis- and training systems, together with the correct pruning practices, can increase the number of buds and improve the effectiveness thereof (Archer, 2011). Possible increased budding on grapevines containing more buds, which are highly fertile, can ultimately lead to increased yield. It is, however, important to take into account the effect increasing the potential yield has on grapevine balance.

Grapevine balance, in the traditional sense of the word, can be defined as the minimum leaf area required to ripen the grapes sufficiently in terms of accumulation of soluble solids (Winkler, 1958). Smart and Robinson (1991) stated that grapevine balance indicates constant quality and yield, and depends on many factors such as crop load (Tassie & Freeman, 1992), light intensity in the canopy (Howell, 2001), training and trellis system (Kliewer & Dokoozlian, 2005) amongst others.

An imbalance in the source-sink relationship in the grapevine can be present with increased vegetative or reproductive growth, leading to vegetative growth (including the roots) dominating reproductive development and *vice versa* (Winkler, 1954). Research has shown that by adjusting and modifying the canopy by means of altered trellis or training systems, fruitful shoots which grow in optimal sunlight conditions can be produced (Kristic *et al*., 2003). Furthermore, the number and size of bunches in proportion to the vegetative growth can be regulated, which eventually results in a balance between leaf area and fruit mass. The trellis system determines the light environment within the canopy (Douglas, 1951; May *et al.*, 1973; Peacock *et al*., 1994; Moreno & Pavez, 2000), and enhanced light conditions will stimulate leaves photosynthetically which is essential for optimal grapevine functioning (Ezzahouani & Williams, 2003). Carbon allocation to the clusters can therefore be optimised, without negatively affecting the growth and development of the other parts of the grapevine (Hunter, 2000).

The correct choice of trellis/training system is important to accommodate vegetative growth and prevent the crowding of shoots to ensure adequate utilisation of resources (Zeeman, 1981), without limiting the leaf area of vigorously growing cultivars (Viljoen, 1951). Increased shading conditions in the canopy may be found when large grapevines are trained to smaller trellis/training systems. This shading can possibly lead to decreased bud fertility or negatively affect grape composition (Shaulis *et al*., 1966).

Another goal is to determine the limits of the compensation capacity of the grapevines related to crop load. A study by Freeman *et al*. (1979) showed that a yield increase was evident up to a certain amount of buds retained, where after no significant increase occurred. There is a possibility that increased crop load effects are associated with changes in vegetative growth, in terms of leaf area and pruning mass (Myers *et al*., 2008), as well as the expression of one or more yield components (Tassie & Freeman, 1992). Archer and Van Schalkwyk (2007) reported definite vigour decrease and yield increases with concomitant increased bud load, where the yield was expressed in more but smaller bunches. The grapevine consists of a balancing act, resulting from an altered canopy, and will affect the manner in which assimilate is distributed and is very important when consistent yields and consequent grape quality is required (Hunter, 2000).

The structure of the grapevine and its canopy can also greatly affect grapevine water status with higher water demand occurring in more open canopies (Williams & Ayars, 2005), such as a sprawling canopy (Stolk, 2014) and, possibly, larger canopies containing higher yields (Van Zyl & Van Huyssteen, 1980). Increased water use may possibly result in increased water deficits, depending on the grapevine's recovery ability (Bondada & Shutthanandan, 2012). As irrigation farming is one of the major contributors of water use in South Africa, there is constant pressure on producers to employ cultural practices that could lead to more effective utilisation of water. Therefore, it is important to establish whether a larger trellis system and an improved canopy microclimate experiences higher water deficits and that the financial benefit of increased yields are not outweighed by the cost of water.

1.2 Project aims

The purpose of the study was to determine the effect of trellis conversion in a Shiraz vineyard on vegetative and reproductive growth parameters, grapevine physiology, grape composition and sensory wine attributes.

Main aim: to investigate the productivity of the grapevine (*Vitis vinifera* L. cv. Shiraz) by means of modification through varying training/trellising systems.

- *Objective 1 - to describe canopy microclimate (canopy light environment) and grapevine water status (soil and plant water status).*
- *Objective 2 - to determine the effect on grapevine yield components.*
- *Objective 3 - to describe the vegetative to reproductive balance with reference to compensation reactions and grapevine adaption.*
- *Objective 4 - to depict grape and wine composition differences by means of ripening evolution and wine sensory evaluation, respectively.*

The significance of this study for the South African wine industry in particular, is to introduce various growing conditions for grapes and to show how the grapevine can be manipulated to obtain balance and optimal productivity by fully ripened grapes thus ensuring optimal vineyard performance and sustainability. This will help producers to choose the best suited trellis system for optimum sunlight utilisation to produce quality and quantity grapes by improving grapevine capacity through enlarged effective leaf surface.

1.3 Literature cited

Archer. E., 2011. Increasing yield from wine grapes 6: Summary. Wynboer Technical Yearbook 2011, 84-85.

Archer, E. & Van Schalkwyk, D., 2007. The effect of alternative pruning methods on the viticultural and oenological performance of some wine grape varieties. S. Afr. J. Enol. Vitic. 28, 107-139.

Bondada, B. & Shutthanandan, J., 2012. Understanding differential responses of grapevine (*Vitis vinifera* L.) leaf and fruit to water stress and recovery following re-watering. Am. J. Plant Sci. 3, 1232-1240.

Douglas, W.S., 1951. ‘n Oplossing vir die swak kleur van Barlinka druiwe. Sagtevrugteboer 1, 12, 17-19.

Ezzahouani, A. & Williams, L.E., 2003. Trellising, fruit thinning and defoliation have only small effects on the performance of 'Ruby seedless' grape in Morocco. J. Hort. Sci. Biotech. 78, 79-83.

Freeman, B.M., Lee, T.H. & Turkington, C.R., 1979. Interaction of irrigation and pruning level on growth and yield of Shiraz vines. Am. J. Enol. Vitic. 30, 218-223.

Howell, G.S., 2001. Sustainable grape productivity and the growth-yield relationship: a review. Am. J. Enol. Vitic. 52, 165-174.

Hunter, J.J., 2000. Implications of seasonal canopy management and growth compensation of the grapevine. S. Afr. J. Enol. Vitic. 21, 81-91.

Hunter, J.J. & Archer, E., 2001. Long-term cultivation strategies to improve grape quality. Viticulture and Enology Latin-American Congress, 12-16 Nov. 2001, Montevideo, Uruguay. VIII (available on CD).

Kliewer, M.W. & Dokoozlian, N.K., 2005. Leaf area/crop weight ratios of grapevines: influence on fruit composition and wine quality. Am. J. Enol. Vitic. 56, 170-181.

Kristic, M., Moulds, G., Panagiotopoulos, B. & West, S., 2003. Growing quality grapes to winery specifications. Winetitles, Adelaide, Australia.

May, P., Sauer, M.R. & Scholefield, P.B., 1973. Effect of various combinations of trellis, pruning, and rootstock on vigorous Sultana vines. Vitis 12, 192-206.

Moreno Y.M. & Pavez, J., 2000. Light environment and canopy assessment parameters within table grape vineyards trained to the overhead trellis in the south- central region of Chile. Acta Hort. 514, 171-178.

Myers, J.K., Wolpert, J.A., & Howell, G.S., 2008. Effect of shoot number on the leaf area and crop weight relationship of young Sangiovese grapevines. Am. J. Enol. Vitic. 59, 422-424.

Peacock, W.L., Jensen, F. & Dokoozlian, N.K., 1994. Training-trellis systems and canopy management of table grapes in California. The University of California Cooperative Extension Tulare County.Publ#TB9-94.

Shaulis, N., Amberg, H. & Crowe, D., 1966. Response of Concord grapes to light, exposure and Geneva double curtain training. Proc. Am. Soc. Hort. Sci. 89, 268-280.

Smart, R.E. & Robinson, M., 1991.Sunlight into wine. A handbook for wine grape canopy management. Winetitles, Adelaide, Australia.

Stolk, R.A., 2014. The effect of irrigation and canopy management on selected vegetative growth and reproductive parameters of *Vitis vinifera* L. cv. Shiraz in the Breede River Valley. MSc Thesis, Stellenbosch University, Private Bag X1, Matieland (Stellenbosch) 7602, South Africa.

Tassie, E. & Freeman, B.M., 1992. Pruning. In: Coombe, B.G. & Dry, P.R. (eds). Viticulture. Vol. 2. Practices. Winetitles, Adelaide, pp. 66-84.

Van Wyk, G., & Le Roux, F., 2012. VinPro production plan- The cost of wine grape cultivation and producer profitability and top performers in difficult times. WineLand Technical Yearbook, March.

Van Zyl, J.L., & van Huyssteen, L., 1980. Comparative studies on wine grapes on different trellising systems: II. Microclimatic studies, grape composition, and wine quality. S. Afr. J. Enol. Vitic. 1, 15-25.

Viljoen, A.S., 1951. Kleur by tafeldruiwe. Sagtevrugteboer 12, 19-21.

Williams, L.E. & Ayars, J.E., 2005. Grapevine water use and crop coefficient are linear functions of shaded area measured beneath the canopy. Agric. Fora. Meteorol. 132, 201-211.

Winkler, A.J., 1954. Effects of overcropping. Am. J. Enol. Vitic. 5, 4-12.

Winkler, A.J., 1958. The relationship of leaf area and climate to vine performance and grape quality. Am. J. Enol. Vitic. 9, 10-23.

Zeeman, A.S., 1981. Oplei:. In: Burger, J.D. & Deist, J. (eds). Wingerdbou in Suid- Afrika. : ARC Infruitec-Nietvoorbij, Private Bag X5026, 7599 Stellenbosch, South Africa. pp. 185-201.

Chapter 2

LITERATURE REVIEW

THE EFFECT OF TRELLISING, TRAINING AND PRUNING PRACTICES ON GRAPEVINE YIELD COMPONENTS

CHAPTER 2: THE EFFECT OF TRELLISING, TRAINING AND PRUNING PRACTICES ON GRAPEVINE YIELD COMPONENTS.

2.1 Introduction

The main objective in viticulture is to obtain a balance between grapevine vegetative growth and yield. This balance is not only critical for optimal and consistent production of high yields at optimal ripeness (Winkler *et al*., 1974), but also to guarantee the sustainability of the grapevine and improve water use efficiency. To achieve such a balance, viticultural practices are implemented for a specific production goal.

An inherent self-regulatory mechanism within the grapevine dictates shoot and fruit growth balance when a specific yield is present (Hunter, 2000). Canopy management is an important viticultural practice where the shoot number and position as well as fruit amounts may be adjusted *i.e.* manipulation of the canopy microclimate as well as yield. Canopy management implementation is also aimed to alter the balance between shoot and fruit growth (Smart & Robinson, 1991). Various long-term cultural practices, such as terroir selection, vine spacing, training of young grapevines, trellising, rootstock/scion combination and row direction, have an effect on grapevine growth, photosynthetic efficiency, yield, grape exposure to sunlight and the composition of the grapes (Hunter, 2001). Decisions pertaining to long-term practices also determine to what extent physiological and environmental stresses can be tolerated (Hunter, 2001), and are accompanied by short-term cultivation practices, in particular seasonal canopy management. The application of seasonal canopy management does not provide a long-term solution to reduce excessive vigour and shade within the canopy, but can have an important effect on grapevine performance, sustainability and grape quality improvement (Kliewer *et al*., 1988; Smart, 1991; Hunter, 2001). With this physical alteration of grapevine balance, it is essential to have knowledge and an understanding of the grapevine components responsible for the specific expression of the season's vegetative growth and yield.

The factors that determine yield are known as yield components and are determined during the previous as well as current growing season (Table 1). The compensation effect of yield components acts in such a way that when the level of one or more of the components is changed, the level of one or more of the other components will also change. Therefore, variation in one or more of the yield components can result in variability in the yield produced per grapevine The impact of cultivation practices and the compensation of yield components determine budburst as well as the capability of these shoots to ripen their grapes optimally. Altered bud load has an important effect on specific yield components. There are various ranges of pruning levels for commercial hand pruning where, for example, increased yields are associated with an increase in the number of buds. However, a plateau is reached where after yield does not increase further due to the compensation of other yield components such as reduced budburst, fertility, set as well as berry size and number (Freeman *et al*., 1979; Heazlewood *et al*., 2006; Archer & Van Schalkwyk, 2007). Various studies have reported similar findings regarding the effect of pruning level on yield components (Balahsubrahmanyam *et al*., 1978; Freeman *et al*., 1979; Zeeman & Archer, 1981; Smart *et al*., 1982; Archer, 1985; Archer & Fouché, 1987; Archer & Hunter, 2010) where increased bud load was not necessarily associated with increased yield.

The objective of this literature review is to provide context regarding grapevine yield components. In addition to this, the effect of pruning severity, training and trellis practices on yield component expression, ripening and water status will be discussed.

Table 1 Yield components and the period in which they are determined (Tassie & Freeman, 1992).

Yield components	**Determined at**	
Location and soil potential (terroir)	Planting	
Rootstock- and scion cultivar	Planting	
Irrigation and fertilization	Planting as well as determined annually	
Number of vines/ha	Planting	
Vigour and capacity	Vine establishment	
Metres canopy/ha	Trellis construction, vine training, vine spacing and vine development	
Number of bunches/shoot (fruitfulness/fertility)	Bunch initiation, previous growing season	
Number of buds/vine (bud load)	Pruning level - winter before growing season	
Bud burst percentage	Satisfactory chilling requirement during May/June	
Number of flowers/bunch	Before and during budburst	Current season
Number of shoots/vine	Budburst	
Number of berries/bunch	Fruit set	
Berry mass	Three phases of berry growth	
Compensation ability	Climate and cultivation practices (previous and current growing season)	

2.2 Yield component terms and determination

Zeeman and Archer (1981) formulated a mathematical relationship between specific yield components and the yield per grapevine (Figure 1). This formula can be used to determine the adjustment of bud load when the crop load per grapevine is known. The five factors that determine the crop load per grapevine are bud load (A), budburst percentage (B), collar buds (C), fertility (D) as well as bunch size and mass (E). These factors are influenced by various variables, namely aspect, slope, soil type, cultivar, macro- and microclimate and cultivation practices (Zeeman & Archer, 1981). According to Zeeman and Archer (1981), producers tend to experience problems applying pruning adjustments, particularly where grapevine vigour is too strong in relation to fruit mass.

$$x = (A \times B + C)(C \times D) \tag{2.1}$$

Where:

$x =$ Crop load per vine,

$A =$ Bud load,

$B =$ Budburst percentage,

$C =$ Collar buds,

$D =$ Fertility and

$E =$ Bunch size and mass

The number of collar buds that will produce shoots and fruit is an unknown factor. In practice it is generally recommended that the shoots originating from collar buds be removed. Subsequently, it is mostly removed from the equation.

Thus:

$$x = (A \times B)(D \times E) \tag{2.2}$$

$Where\ (A \times B) =$ Number of effective buds and

$(D \times E) =$ Potential crop mass per bud

Figure 1 Mathematical formula to determine potential crop load (Zeeman & Archer, 1981).

2.2.1 Bud load

Bud load, also known as “pruning level” or “count nodes” (Tassie & Freeman, 1992), can be defined as the number of buds pruned per grapevine during winter. Bud load is determined during the previous season’s pruning and, more accurately, counted at the current season’s pruning. It is important to note that this does not include buds that are not located on the spurs. The bud load will have an effect on the number of buds bursting in spring.

2.2.1.1 Methods for adjusting bud load

The initial bud load during the first years of optimum production is determined during the development phase of the grapevine. Later on, the bud load needs to be adjusted to accommodate the growth conditions of the vineyard. In particular, this is required when vigour increases annually (more buds per grapevine are required) or, in contrast, when the vigour decreases annually (reduced number of buds per grapevine required). Methods have been developed to help determine the optimal bud load to suit the grapevine's growing conditions. One or both of the following can be used.

The first method is described in Figure 1. This method can be used not only to determine the crop load per grapevine according to the desired yield, but also to target a desired balance level according to the yield to pruning mass ratio as an indicator of the reproductive to vegetative growth relationship in the grapevine (Zeeman & Archer, 1981). Research by ARC Infruitec-Nietvoorbij (Stellenbosch) showed that the most optimal balance between growth and yield was obtained using yield to pruning mass ratios that ranged from 4:1 to 10:1 (Zeeman, 1981). It was also evident that this ratio was dependant on grapevine variety and vigour (the higher end of the ratio where more vigorous grapevines are present). For the same cultivar, varying yield to pruning mass ratios can occur, depending on the growing conditions, *i.e.* a higher ratio is required to achieve balanced growth and yield in more vigorous conditions. It is very important to establish which yield to pruning mass ratio is optimal in terms of sustained production levels, quality and vigour for every vineyard. If this optimal range does not occur, too high yields can lead to reduced grape quality and vigour whereas under-cropped grapevines can be excessively vigorous with decreased bud fruitfulness (Skinkis & Vance, 2013).

Where an increased yield is required to suit the vigour for a specific grapevine, yield to pruning mass ratio needs to be determined. Assuming yield for the current season is 8 t/ha and the cane mass is 2 t/ha, the yield to pruning mass ratio will be 4:1. According to Zeeman and Archer (1981), this value is considered too low for certain conditions and a yield to pruning mass ratio of 6:1 would be more ideal. Consequently, a yield increase from 8 t/ha to 12 t/ha is required. If there is 3000 grapevines/ha, every grapevine should produce 4 kg grapes to achieve 12 t/ha.

Thus, referring to Eq. 2.1 in Figure 1, $x = \ 4 = \ (A \times B)(D \times E)$

The values of $B, D \ and \ E$ are determined from 30 grapevines selected at random from the sample of 3000 grapevines, vines and assuming B, D and E are as follows (Eq. 2.3):

$$B = \ 95\% = 0.95$$

$$D = \ 1.5$$

$$E = \ 150 \ g = 0.15 \ kg$$

The only unknown factor will be A, and it is calculated as follows:

$$x = ABDE$$

$$A = \frac{x}{BDE} \qquad (2.3)$$

In order to calculate the bud load per grapevine, *i.e.* A, the values listed above for B, D and E can be substituted into Eq. 2.3 as follows:

$$A = \frac{4}{0.95 \ \times \ 1.5 \ \times \ 0.15}$$

$A = \ 19$ Buds per vine

Zeeman and Archer (1981) recommended that the reaction of the grapevine to pruning alteration needs to be reviewed for at least three years in order to monitor that there is no decrease in vigour due to the increased yield. Although vigour decreases of up to 35% occurred, these decreases were not evident when grapevines were observed visually. In this regard, they cautioned that visual observations in the vineyard can sometimes be misleading and inaccurate.

The second method is called “balanced pruning” and is widely used (Jordan *et al*., 1966). Balanced pruning embraces one of Winkler's most important principles, namely that a larger grapevine can support a larger number of buds than a smaller grapevine. In other words, this method evaluates pruning decisions based on the growth of the previous season. This concept was first studied on Concord grapevines in Michigan (Partridge, 1925), and it was observed that various vineyards had a wide range of pruning mass values, ranging from 0.05 kg to 3.1 kg per grapevine. Furthermore, when more buds were retained on large grapevines and *vice versa*, more consistent growth appeared. An increase in vegetative growth also led to yield decreases when the pruning mass was higher than 1.4 kg (Partridge, 1925). This could be due to reduced bud fruitfulness, expressed on a per shoot basis, of the highly vigorous grapevines (Reynolds, 2006). The original balanced pruning formula were refined by Nelson Shaulis, where the vigour is classified and correlated to the number of buds to retain, with the main purpose to improve grapevine growth sustainability (Shaulis & Oberle, 1948; Shaulis, 1950).

The pruning mass of canes provides useful information on the grapevine vigour status due to the effect vigour has on the amount (mass) of new wood produced during the growing season (Smart *et al*., 1985). To implement the balanced pruning method, pruning mass per grapevine must be measured in a part of the vineyard first to determine the grapevine vigour level. A certain number of buds are then retained which is dependent on a specific vigour level (Table 2)

There are three vigour levels, namely low, medium and high and either 10, 20 or 30 buds are retained for the first 0.45 kg of pruned shoots as well as an additional 10 buds retained for each 0.45 kg pruning mass beyond the first 0.45 kg of pruned canes depending on the vigour level. For example, a grapevine containing 16 canes with a pruning mass of 1.8 kg will have an average mass per cane of 0.1125 kg, or 112.5 g, which can be classified as 'high vigour'. Using the vigour classification and correlating it with the potential number of buds to retain (Table 2), the final bud load to retain will be 60. The latter value was obtained by adding the 30 buds for the first 0.45 kg and the 30 buds for the remaining 1.35 kg. Reference grapevines within the vineyard block are used to determine which bud load will be adequate. The rationale of this method is to count, prune and weigh the canes of the reference grapevines and use the data collected to calculate the number of buds to retain for all grapevines in the vineyard block. However, no indication on the number of grapevines required for an accurate assessment of the vineyard was provided in the description of the method. Vigour variability within the vineyard can also be a further constraint when using this method and should be taken into account should this method be used.

Table 2 Balanced pruning method (Skinkis & Vance, 2013).

Vigour level	Average cane mass	Number of buds to retain
Low	<10 g	10+10
Moderate	20-40 g	20+10
High	>60 g	30+10

2.2.2 Budburst

Budburst is the process where the first signs of growth occur in the new season when the leaf tips are visible (Eichhorn & Lorenz, 1977). The correct definition for budburst is known as the so called "green tip bud" (the fourth stage), as defined by Eichhorn and Lorenz (1977). It can be accepted that budburst occurs when 50% of the buds on count shoots have reached the "green tip bud" stage. Budburst is the result of the expansion of structures located in the bud such as internodes, leaves, inflorescences and other shoot structures. These structures are already formed in the bud during the previous season. They expand due to cell enlargement, where after cell division occurs as the activity of the apical meristem initiates again and new nodes are formed from the apical meristem of the shoot. It is necessary to have a standardised definition for budburst so that it can provide a standard reference point to compare budburst trials as well as seasons.

2.2.2.1 Non-count shoots

Non-count shoots occur when base buds and/or collar buds (from the base of canes and spurs) burst together with the allocated buds at pruning, which may or may not contain bunches. Non-count shoots include water shoots, originally arising on wood older than one year *i.e.* trunk, crown, and cordon (Tassie & Freeman, 1992). The number of these buds which will burst or contain grapes is not determined. However, it is possible to count them during pruning.

Non-count shoots or water shoots often appear in the case of vigorous grapevines and therefore unbalanced grapevines (Cloete, 2004) or where assimilates are translocated mainly to the vegetative parts of the grapevine (Hunter, 1991). Pruning too severely can also stimulate the appearance of this type of shoot. More non-count shoots, which normally remained dormant in poorly exposed canopies, may also emerge from basal buds when canopy exposure is improved (Kliewer & Smart, 1989).

2.2.2.2 Budburst percentage calculation

Budburst percentage calculation can be approached in three different ways (Iland *et al*., 2011). The first method defines budburst percentage as the total number of shoots per grapevine (including count & non-count shoots) which emerged from the number of buds retained during pruning and is considered the most common (Eq. 2.4):

$$\%\,Budburst = (totalshootspervine \div budload) \times 100 \tag{2.4}$$

This method provides an indication of the grapevine's capacity in relation to the number of buds retained at pruning. In this case, values greater than 100% can occur. This indicates that a high proportion of non-count shoots are present which are normally less fertile than shoots arising from retained buds.

The second method does not include non-count buds and shoots (Eq. 2.5) (Iland *et al.,* 2011). It indicates the budburst percentage as the number of buds from which shoots emerged from the total allocated buds at pruning or the total buds pruned per vine ('count nodes') and the percentage of these buds which will burst ('count shoots'):

$$\% \, Budburst = (amountofcountshoots \div amountofcountnodes) \times 100 \qquad (2.5)$$

The value obtained by using Eq. 2.5 can also be larger than 100%, as more than one shoot can arise from a single count node. However, there is no indication of the number of shoots, other than the count shoots, that are present. Non-count shoots generally emerge on grapevines which were pruned too severely and to not have knowledge of this can have detrimental effects on productivity.

The third method (Eq.2.6) to characterise budburst as the number of buds retained at pruning containing one or more shoots (Antcliff *et al*., 1972):

$$\% \, Budburst = (numberofcountnodeswithoneormoreshoots \div numbercountnodes) \times 100 \qquad (2.6)$$

The value obtained from method three cannot exceed 100%. The proportion of buds not producing a shoot ('blind buds') is indicated by this method where method one and two do not provide this information.

A schematic diagram is given in Figure 2 to illustrate the three different methods to calculate budburst percentage. Figure 2 consists of a grapevine with ten retained buds (two buds per spur, thus five spurs). Count shoots emerged at count nodes 1, 3, 5, 7, 9 and 10, where two shoots burst at count node 7. No shoots emerged at count nodes 2, 6 and 8 and four non-count shoots are present: two at the base of the spur position and two water shoots (originating from reserve buds). This data can therefore be used to calculate the budburst percentage for each method.

$$First\ method: \frac{12}{10} \times 100 = 120\%$$

$$Second\ method: \frac{8}{10} \times 100 = 80\%$$

$$Third\ method: \frac{7}{10} \times 100 = 70\%$$

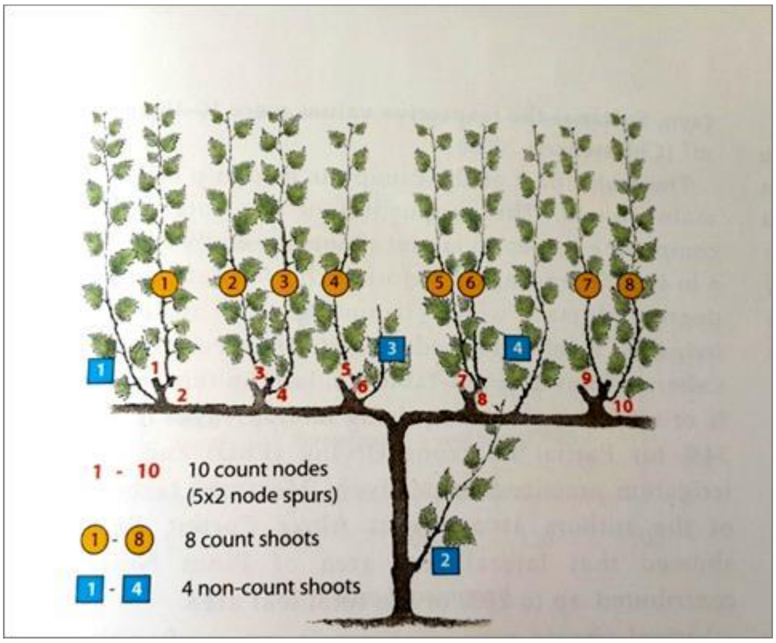


Figure 2 A grapevine containing ten count nodes (on five spurs), eight count shoots and four non-count shoots (Iland *et al*., 2011).

2.2.3 Fertility/fruitfulness

The number of effective buds is an important factor in determining a grapevine's yield performance (Archer, 2011). The grapevine bud can be considered effective with the successful induction of fertility (Archer & Hunter, 2003). Fertility is defined by the number of bunches per shoot which in turn is determined by bunch initiation. Initiation of primordial clusters, known as inflorescences (Figure 3), can differ in amount or be absent in each bud. The formation of inflorescence primordia occurs in three phases, initiating in one growing season (season 1) soon after budburst and completed in the next season as a bunch (season 2) (May & Antcliff, 1963; Swanepoel & Archer, 1988; Sánchez & Dokoozlian, 2005). The process is explained in detail in Mullins *et al*. (1992) and May (2004).

Figure 3 Transverse section of a Sultana bud displaying an immature inflorescence primordia (indicated by arrow) (Bernard & Thomas, 1933).

2.2.3.1 Determination of fruitfulness

Fluctuations in grapevine yield occur on an annual basis (generally 15% to 30% and more) (Thomas, 2006) and can be the result of variation in bunches per vine and/or variation in bunch size. Analyses of a wide range of yield data showed that the number of bunches per grapevine was responsible for up to 60 to 70% of the seasonal variation in yield. In contrast, variation in berries per bunch and berry size accounted for 30% and 10%, respectively, of the seasonal variation (Clingeleffer *et al*., 2001). The reason for this occurrence is the variation of the number of inflorescence primordia, *i.e.* potential bunches, in buds retained during pruning. Bud fruitfulness (Eq. 2.7) can be expressed as the percentage buds with one or more inflorescence primordia but generally it is expressed as the number of bunches produced per count shoot (Hunter & Visser, 1990):

$$Fertility = \frac{Amountofbunchespervine}{amountofshootspervinefromallocatedbudsatpruning\ (count\ shoots)} \tag{2.7}$$

Two methods are generally used to determine the number of potential bunches (Iland *et al.,* 2011). Dormant buds are used in both methods. The first method entails cutting canes into separate nodes and growing each individual cutting until a shoot develops. When sufficient shoots have developed, the inflorescence primordia (bunches) can be observed and counted. This method is not very practical in commercial grape production due to the duration and labour intensity it requires. For the second method, dormant buds are dissected and observed under a microscope. The number of inflorescence primordia is then counted. Usually the primary bud is used for dissection purposes but the secondary bud can be used in cases where the primary bud is necrotic. Commercial laboratories often offer this service as part of their routine analyses portfolio. The sample is generally obtained after leaf fall but can also be taken as early as véraison, as the number of inflorescence does not change in dormant buds from véraison to dormancy. Potential fruitfulness results can be obtained in a short time and decisions regarding pruning can be made. This method is not only beneficial in determining potential bunches in a short period, but also to detect whether the primary bud is active or necrotic and the presence of bud mites can be investigated (Iland *et al*., 2011).

2.2.4 Bunch mass, berry mass and number of berries per bunch

Characteristics of the bunch, regarding the mass and size of bunches and berries as well as the number of berries produced per bunch can be correlated with the characteristics of the flower cluster primordia (see paragraph 2.2.3) formed during bunch initiation. The size of the flower cluster primordia, amongst other factors, determines the potential bunch size and the number of flowers present on the cluster primordia and percentage fruit set determines the number of berries (Iland *et al*., 2011). The size and mass of berries are determined during berry development and are also largely affected by the number of berries per bunch, the number of bunches per grapevine as well as other factors such as genetic origin, fruit set, bunch position, number of pips present per berry, degree of ripeness and irrigation (De Villiers, 1987). The final yield of a vineyard is literally determined by the physical occurrence of these bunch characteristics (and their relationship) together with the number of bunches. It is therefore of great importance to understand its formation as well as factors affecting it.

2.3 Pruning and yield component relationship

Winkler *et al*. (1974) described pruning as the removal of shoots, canes, leaves and other vegetative material of the grapevine. It is usually performed during the dormant season of the grapevine and cannot only be considered as the primary means for crop size regulation, but also to establish and maintain grapevine form and size; determine yield performance by the number of effective buds and create a balance between growth and crop load (Winkler *et al*., 1974; Archer, 2011). By adjusting the number and position of buds during pruning, these aims can be achieved for a specific production goal.

Pruning severity in combination with budding percentage induces the crop load per grapevine in terms of the number of shoots and, consequently, the potential number of bunches per grapevine, modifying the sink strength and affecting the qualitative and quantitative performance of the grapevine (Antcliff, 1965; Morris & Cawthon, 1980; Zeeman & Archer, 1981; Archer, 1983; 1984& 1985). The number of shoots and leaves receiving optimal light conditions determine the total effective leaf area which, in turn, affects the ability of the grapevine to produce a certain mass of dry material *i.e.* photosynthetic efficiency (Archer & Strauss, 1989; Hunter, 1991; Hunter *et al*., 1991). This photosynthetic efficiency determines the amount of carbohydrates produced throughout the season and, therefore, the magnitude of the stored reserves (located in the woody structures of the grapevine) which is utilised to produce new growth from the number of buds allocated at pruning (Quinlan, 1969; Yang & Hori, 1980; Carbonneau *et al*., 1997). It can be said that the shoot number and growth of the current season is an expression of the previous season's photosynthetic efficiency and capacity (Yang *et al*., 1980). The ideal scenario is that the number of buds allocated is in balance with the capacity of the grapevine to avoid the occurrence of higher leaf area per unit weight of canes which might not be capable of supporting the amount of grapes throughout the ripening process (Miller *et al.*, 1996a; Miller *et al.,* 1996b; Howell, 2001).

Optimum productivity is dependent on grapevine capacity and vigour (Downton & Grant, 1992). Capacity refers to the total grapevine dry matter production during the growing season and affects the quantity of fruit the grapevine can produce and ripen (Miller *et al*., 1997). This includes the total crop, leaves, roots and shoots and is indicated by total fruit and shoot mass. Vigour, on the other hand, is the rate of shoot growth, *i.e.* the change in shoot length per unit time (Winkler *et al*., 1974). Furthermore, shoot growth rate is affected by bud number where growth is concentrated or spread into fewer or more shoots, respectively (Winkler, 1934). The principle that applies to pruning is that a grapevine with higher capacity should be left with more buds during pruning compared to a grapevine with lower capacity. Consequently, the more vigorous grapevine is pruned with more buds and the less vigorous one with fewer buds (Winkler *et al*., 1974). On a single shoot level, grapevine capacity and vigour is correlated. For example, a vigorous shoot is likely to produce sufficient source material (leaves) to sustain and ripen its' bunches, ultimately having a higher capacity (Iland *et al*., 2011). On the other hand, vigorous shoots can sometimes be less fertile and have poorer grape quality due to higher leaf area to fruit mass ratios. This leads to overshadowing within the canopy and, consequently, decreased physiological functioning

(Cloete *et al*., 2006; Cloete *et al*., 2008). Regarding the grapevine as a whole, a vigorous grapevine may have a low capacity, while a high capacity grapevine can have low shoot vigour (Iland *et al*., 2011). This is not a fixed occurrence, because a vigorous grapevine exposed to the same amount of sunlight, compared to a lower vigour grapevine, can have a greater total effective leaf area and thus a better potential for producing higher yield and quality (Cloete *et al*., 2006).

Pruning level regulates shoot vigour and the appropriate bud number should be adapted to training/trellising systems and vineyard site potential (Smart & Smith, 1988; Smart *et al*., 1989).

2.3.1 Pruning level

Although two-bud spur pruning (severe pruning) system provides the highest budburst percentage of all pruning systems (Archer, 2011), pruning contributes to an escalation in the labour costs. Therefore, alternative pruning methods have been investigated (Archer & Van Schalkwyk, 2007). The information pertaining to alternative pruning methods in literature includes minimal pruning (Clingeleffer, 1993), mechanical pruning (May & Clingeleffer, 1977; Dry, 1983; Clingeleffer, 1988) and non-pruning (Bakonyi, 1987).

2.3.1.1 Severely pruned grapevines

Severely pruned grapevines (fewer buds retained per grapevine) result in the production of only a few shoots and leaves in spring, leading to increased vegetative growth in terms of long, thick and strong shoots. Shoot growth tends to be more rapid for severely pruned vines, implying increased vigour per definition (Smart & Robinson, 1991), but also decreased capacity for production due to shaded conditions which retards early-season development of leaf area (Winkler *et al*., 1974). Upshall and Van Haarlem (1934) reported that severe or excessive pruning promoted excessive vegetative growth and therefore recommended vigour should be taken into account when pruning.

Higher proportions of non-count shoots can occur with an increased level of pruning severity (Kurtural *et al*., 2006) which may also contribute to the yield at harvest (Morris *et al*., 1984; Morris & Main, 2010). Colby and Tucker (1993) reported that increased pruning severity resulted in decreased inflorescence formation, partly due to increased shady conditions thereby directly affecting the number of bunches produced. Excessive vigour also affect fruiting unfavourably as increased cases of “coulure”, or dropping of flowers without setting, can occur (Winkler, 1934). More branches can occur on the inflorescence of cane-pruned grapevines due to more bunches originating from more distal node positions, which have larger inflorescences than the two basal nodes located on spurs (May & Cellier, 1973). Winkler (1934) first noticed this occurrence by stating that very severe pruning may lead to reduced cluster size, since the clusters located on basal buds usually tend to be smaller without a corresponding increase in berry size. Several studies have reported that the number of bunches per shoot is higher when less buds are retained (Howell *et al*., 1987), but lower when considering bunches per grapevine (Freeman *et al*., 1979; Heazlewood *et al*., 2006; Kurtural *et al*., 2006). Therefore, reduced number of shoots is responsible for decreased bunch numbers, and bud fertility is not significantly affected by severe pruning unless vigorous (shaded) conditions occur. The correct pruning method can impact bud fertility since a balance is created between growth and yield. Hand pruning lead to lower yields overall compared to alternative pruning methods. It seems the low quantity of bunches are accompanied by compensation of increased berry and bunch mass (Freeman *et al*., 1979; Clingeleffer *et al*., 1997; Martin *et al*., 2000).

2.3.1.2 Lighter pruned grapevines

Minimal pruned grapevines can be characterised as non-pruned grapevines which are skirted below the cordon during the dormant season or summer (Archer & Van Schalkwyk, 2007; Iland *et al*., 2011). Successful minimal pruning relies on the grapevine's capacity to self-regulate when pruning is eliminated or reduced significantly. Different methods of mechanical pruning have emerged. This includes attempts to simulate hand pruning as much as possible (Freeman, 1977; Hollick, 1977) and 'hedging', where an increased bud load and change in bearer length occurs.

Shoot growth can be restricted by retaining more buds at pruning (less severe or minimal pruning). Lighter pruning have shown to be very effective in shoot vigour reduction where a large number of short, thin shoots are produced (Smart *et al*., 1989; Lakso, 1999). This can be due to the fact that early shoot growth depends on stored reserves originating in the permanent structures of the grapevine (Yang *et al*., 1980). Fewer reserves are allocated per shoot with an increased demand from many shoots compared to only a few shoots in the case of severe pruning (Smart & Robinson, 1991). In other words, the capacity of grapevines with increased bud load is expressed in more shoots per vine (Archer & Van Schalkwyk, 2007).

The number of buds bursting during spring seems to be negatively correlated with bud load. When the bud number was doubled, shoot number increased by only 25%, thus budburst percentage was reduced (Smart *et al*., 1979). The effect of different pruning levels (and therefore different pruning systems) on budburst percentage was also investigated by Archer and Van Schalkwyk (2007). Bud counts of 24, 72, 191 and 227 per vine retained by hand, mechanical, and minimal and no pruning resulted in budburst percentages of 108%, 60%, 49% and 47%, respectively. It is important to understand that the budburst percentage is not only influenced by the number of buds pruned per grapevine. Poor budburst percentages can also occur when there are unfavourable microclimatic conditions due to overshadowing and increased canopy density together with a too high bud load per grapevine (Sánchez & Dokoozlian, 2005).

Early canopy development and thus larger canopy leaf surface, particularly before bloom, as a consequence of the larger number of smaller shoots was evident (Clingeleffer & Possingham, 1987; Miller *et al*., 1996a; Lakso, 1999). For this reason, increased bud and shoot numbers may lead to increased canopy shading and the grapevine may regulate the number of shoots where some of the bearer buds do not burst due to overshadowing (Van Schalkwyk & De Villiers, 2001). It is thought that the rate of carbon assimilation increases with the greater leaf surface in the early season, hence allowing more total carbon fixation throughout the growing season (Smart, 1985; Downton &Grant, 1992). Lakso (1999) stated that higher sunlight capture and dry matter production in the earlier stages of the season by minimal pruned grapevines manifested in higher sustained yields.

Substantial increases in yield were evident with the use of machine or minimal pruning (Downton & Grant, 1992; Clingeleffer, 1993; Archer & Van Schalkwyk, 2007). Increased bud numbers from mechanical hedging led to increased bunch numbers (Smart *et al*., 1979). Mechanical spur pruning produced high yields (Morris *et al*., 1975; May & Clingeleffer, 1977; Clingeleffer, 1988; Reynolds, 1988; Reynolds & Wardle, 1993; Archer, 1999) but reduced bunch and berry mass (Morris *et al*., 1975; Morris & Cawthon, 1981; Reynolds, 1988), sugar concentration, pH and increased total acidity (Shaulis *et al,* 1975; Anderson *et al.,* 1996). This seems to be a general trend of the grapevine response to alternative pruning methods (Freeman *et al*., 1979; Dry, 1983; Cirami *et al,* 1985; Clingeleffer & Possingham, 1987; Clingeleffer, 1988, Clingeleffer, 1989; McCarthy & Cirami, 1990; Clingeleffer, 1993; Archer & Van Schalkwyk, 2007). Less successful fruit set and, consequently, fewer berries per bunch occurred in studies were the bud numbers were increased. A decrease in bunch mass was also recorded (Smart, *et al*., 1979). In general, a reduction in wine quality was due to colour loss of red varieties (Reynolds & Wardle, 1993). There was a strong negative relationship between the number of berries per bunch and anthocyanin concentration (May, 2000; Heazlewood, 2005).

As mentioned previously, further increase of bud loads beyond a certain level will not increase the yield, due to the compensation effect of one or more of the yield components (Zeeman & Archer, 1981). Therefore, the grapevine adjusts the size of the crop to suit its capacity. A study conducted by Freeman *et al*. (1979) confirmed this phenomenon where yield increases were evident when bud load number per grapevine was increased from 60 to 80 buds. Thereafter, no significant increase in yield was noted. Similar findings have been reported by Smart *et al*. (1982).

It is evident throughout literature that the main factor responsible for variation in yield is the number of bunches produced per grapevine. Less bunches per grapevine are accompanied by the compensative growth of bigger berries and heavier bunches depending on the position of the bud on the shoot. The optimal bud load is thus not a definite number of buds, and may be better defined and practically implemented as a level between a certain minimum or maximum number of buds per grapevine. Furthermore, it is not always easy (especially with spur pruning) to make small up- or downward adjustments on grapevines, especially where compensation (*i.e.* through fertile non-bearer position shoots) occurs.

2.4 Training, trellising and yield component relationship

A training system can be defined as the way in which the grapevine is positioned in a given space (Jackson, 1997). This includes the type of trellis system used for grapevine growth and the manner in which the grapevine is manipulated and/or trained to inhabit the particular trellis system. The trellis system affects the arrangement and volume of the canopy which, in turn, influences canopy density (Smart, 1982; 1984 & 1985). Pruning and shoot/cane positioning can be considered as subdivisions of training (Jackson, 1997). The cultural practice used to correctly space growing shoots in the grapevine canopy is referred to as shoot positioning. Pruning practices takes place during grapevine dormancy, where yield performance is determined by the number of effective buds and the balance between growth and amount of grapes per grapevine are established (Winkler *et al*., 1974; Archer, 2011). Following budburst, the number and size of bunches on the developing shoots determines the potential crop and the efficient leaf area determines the quantity and quality of grapes to be ripened (Petrie *et al*., 2000a; 2000b).

The main goal for the implementation of grapevine training and trellis systems is to achieve optimal productivity which is dependent on grapevine capacity, including root functioning, and vigour (Freeman *et al*., 1992). Sufficient foliage is required to make photosynthesis possible without creating excessive canopy shading, which may negatively affect grape development and ripening (Smart & Smith, 1988; Smart *et al*., 1990; Freeman *et al*., 1992). It is very important that the partitioning of photosynthates between the growth of shoots and fruit should be sufficient to prevent the occurrence of deficient or excessive leaf area relative to yield (Smart *et al*., 1990). Total canopy photosynthesis depends on the intensity of light, climatic conditions, yield and other viticultural practices (Intrieri *et al*., 1997). The amount of light intercepted by the canopy can be correlated with the orientation of the canopy to the sun, canopy architecture and the percentage of exterior and interior leaves which is determined by row orientation and training systems(Freeman *et al*., 1992). The qualitative potential of training systems is assessed by the total exposed leaf area, rather than the total leaf area (Carbonneau *et al*., 1997). The reasoning behind this is that leaf photosynthesis produces the ultimate source of sugar and an appropriate area of exposed leaves requires utilising every source of photosynthetic active radiation (PAR) to fully ripen grapes and stock carbohydrates in the perennial organs. More carbon substrates can be produced and utilised through the process of respiration to produce energy for growth and development (Iland *et al*., 2011). Similarly, maximum grape exposure by means of the training system is important for optimal berry growth and grape composition (Reynolds *et al*., 2004).

The manner in which a specific trellis system incorporates training and pruning practices to effectively accommodate grapevine capacity and vigour is important with regards to effects on microclimate, and consequently photosynthesis and fertility (Smart, 1992). This will, in turn, influence the potential yield as well as grape quality due to the admission of air movement and sunlight required to fully ripen grapes (Smart *et al*., 1990; Smart, 1992).

2.4.1 Bud load

During the training of grapevines, the perennial wood and shoots are arranged in certain positions to alter the leaf area for increased sunlight exposure. This optimises sunlight interception resulting in increased yield potential and favourable leaf area to yield relationships (Reynolds & Van Den Heuvel, 2009). The consistent amount of exposed leaf area to light is dependent on the pruning system, trellis height and bearing unit arrangement. Pruning ensures optimal utilisation of the trellis system by forming strong and uniform cordon arms (Tassie & Freeman, 1992). The number of buds allocated during pruning should be accompanied by correct bearer spacing on each cordon for good distribution of the canopy.

The size of the canopy relates to the vegetative mass of the grapevine and can, amongst other factors, be altered with canopy management methods such as pruning practices as well as methods of training and trellising (Winkler *et al*., 1974; Freeman *et al*., 1992). The position of canes and numbers of buds on each cane is dependent on the type of trellising and training system. An increased pruning level is only effective, in terms of sustainable yield and grape quality, when there is sufficient space for the foliage created by the trellis system (Mullins *et al*., 1992).

Canopy division, *e.g.* the Geneva Double Curtain (GDC), Scott Henry or Ballerina systems, can be implemented to increase the pruning level, regulate shoot vigour and also arrange shoots to fully utilise sunlight energy for photosynthesis (Smart *et al*., 1990). Gandell (1989) investigated the effect of different number of buds per grapevine, but similar buds per metre cordon - the so called 'big vine' effect. Grapevines classified as “big” and “small” were pruned to 96 and 48 buds, respectively. Reduced shoot vigour, less water shoots, thinner shoots with shorter internode lengths, reduced lateral growth and smaller leaf areas of mature leaves were evident for “big” grapevines. Clarifying the 'big vine' effect was that increased bud load per grapevine lead to reduced vigour. Clingeleffer (2009) found that the productive capacity for lighter pruning systems on tall trellis systems increased. This occurs due to the early development of larger, open canopies, which provides higher photosynthetic activity, because leaf gas exchange and photosynthesis are unaffected by the pruning system.

If it is not possible to implement increased bud numbers, different training systems can be used to alter the canopy and reduce unfavourable microclimatic conditions. A study conducted by Irimia and Tardea (2005) confirmed this by showing that two different training systems can have the same total leaf area, but different leaf area exposed to sunlight radiation. For example, a vertical shoot positioned system (VSP) and a sprawling system can have the same total leaf area, but where the VSP canopy is trained upwards in a vertical position, the sprawling canopy is not trained leading to more leaves exposed to sunlight.

2.4.2 Budburst percentage

The main yield component responsible for increased productivity on divided canopies (for most varieties) seems to be increased budburst percentage and, consequently, more shoots per grapevine (Shaulis *et al*., 1966; May *et al*., 1973; Shaulis & Smart, 1974; May *et al*., 1976; Kliewer & Smart, 1989).

Temperatures in winter (chilling) determine the release from winter dormancy and warming during spring (forcing) aid in bud development acceleration after the release of dormancy (Fu mail *et al*., 2012). The ability to break dormancy and initiate budburst also depends on carbohydrate reserves (Iland *et al*., 2011). During dormancy the grapevine is not completely inactive and it requires energy to sustain its life-force. Since there are no leaves, photosynthesis does not take place the grapevine has to rely on stored carbohydrates (mostly as starch and soluble sugars) from the previous season in its' perennial parts. Approaching budburst, the bud acts as a strong sink leading to the mobilisation of carbohydrates and translocation thereof to the different parts of the emerging shoot. The soil temperature during spring is important for grapevine growth and development after dormancy is released (Rogiers & Clarke, 2013). The initial growth stages are dependent on the remobilisation of reserve carbohydrates from the roots (Yang & Hori, 1979; Yang *et al*., 1980) and this may be delayed with the occurrence of low root zone temperatures after dormancy, slowing shoot growth and inflorescence development (Field *et al*., 2009; Rogiers *et al*., 2011). Grapevine growth responses to root temperature are strongly regulated by hormones. Cytokinins produced by roots can be associated with carbohydrate reserve mobilisation at the end of dormancy and are therefore responsible for initial shoot growth (Field *et al*., 2009).The amount of cytokinin produced is mainly dependent on the number of active root growth tips in the soil, especially those of fine roots. The number of growth tips are directly affected by the size of the trellis system (Van Zyl, 1988). There is little information in literature with regards to the effect of trellis/training systems on root-zone temperature, but certain conclusions could be combined to explain this. Hunter and Volschenk (2001) found that converted trellis systems improved soil colonisation by the roots due to an increased number of fine roots. Water uptake ability increases when there are more fine roots (Archer & Hunter, 2004) and this may also lead to warmer root-zone temperatures. Hormonal levels change in response to water deficits and, consequently, root temperature (Emmerson & Powell, 1978; Rabe, 1990; Mullins *et al*.. 1992). The presence of warmer soils was found to increase cytokinin delivery (Field *et al*., 2009). However, if water uptake is increased to the point where the grapevine begins to stress, abscisic acid (ABA) content is increased thereby inhibiting bud growth until re-watering and subsequent soil temperatures decreases (Ndung'u *et al*., 1997). Lower soil temperatures can be found on slanting trellis systems due to increased shading of the soil surface which reduces evaporation (Van Zyl & Van Huyssteen, 1980). However, this occurs only later in the season when the canopy, which is dependent on soil temperatures establishing the number of shoots to develop itself, has developed.

The higher demand from increased number of buds, in the case of lighter pruning methods and divided canopies, may also increase water uptake, consequently warming the soil environment and producing sufficient signals to drive cell division and expansion (Rogiers & Clarke, 2013). However, it is important that enough reserves are present to satisfy this demand and to support growth from bud burst until leaves become self-sufficient (Iland *et al*., 2011). Uneven and poor budburst may occur in cases of too vigorous or poor growth due to increased canopy density and decreased source material, respectively, both decreasing carbohydrate storage. When less shoots emerge, maximal leaf area production is delayed, therefore limiting photosynthetic capacity early in the season and *vice versa*. The larger the leaf area of photosynthetically active leaves, the more carbohydrates are available as reserves to support the following season's growth (Winkler *et al*., 1974).

Smart (1993) emphasised the importance of trellis/training system implementations for the reason that grapevines contain sufficient exposed leaf area relative to the fruit to avoid over cropping and under cropping and consequent reduced carbohydrate storage, which is required for the following season's growth. It is also possible for grapevines to grow in the absence of trellis systems, the deciding factor being in accordance with the producer's specific production goal.

2.4.3 Bud fertility

The bud can be classified as fruitful when the anlagen are induced to form flower cluster primordia (Caroll, 2009). Induction occurs during flowering and it is highly influenced by light, temperature and cytokinins (May, 2000). This is the most critical period due to the direct impact on crop size the following season. Maximum fertility can be achieved when all three factors mentioned above are sufficiently present to avoid any obstruction to bud fertility (Archer, 2011). If the bud is hampered in any way, it could result in reduced size of flower primordia (and consequently eventual bunch size), decreased number of flowers on the flower cluster (and thus less berries per bunch) and less flower cluster primordia (impacting the number of bunches) (Archer, 2011).

Training and trellis factors affecting fertility

Factors such as light and temperature are difficult to manage directly. Training, trellising and pruning methods, amongst other practices, can be adapted to ensure that basal leaves receive optimal conditions regarding the above mentioned factors.

The presence of sufficient sunlight is very important regarding the first and second phase of effective bud formation. Optimal bud fertility is reached at a light intensity of 800 μ E m^{-2} s^{-1}, while almost immediate infertility exist at light intensities less than15 μ E m^{-2} s^{-1} (Archer, 2011). Shady conditions suppress fruit bud initiation and can have a detrimental effect on bud fruitfulness in the following season (Smart & Smith, 1988). Red light, consisting of longer wavelengths, is known to be of less effective light intensity and occurs in dense canopy situations while the shorter wave lengths (blue light) are absorbed (Smart, 1987). If these dense conditions persist, basal buds will not be supplied with adequate light quality, which could lead to reduced fruitfulness. Canopy division may reduce within-canopy shade and create a more favourable microclimate which affects inflorescence primordia initiation and development (and thus bud fertility) by creating more effective sunlight penetration of especially basal shoot positions (Buttrose, 1970; Dry, 2000) and potentially lead to increased yield (Kliewer, 1982; Shaulis, 1982). Larger trellis systems, like the GDC, decreases canopy density, despite the increased number of shoots (Smart, 1982), and thereby increasing bud fruitfulness and consequently yield per grapevine.

The effect of temperature on grapevine fruitfulness is independent of light intensity (Buttrose, 1970). High temperatures promote bud fertility especially during the induction phase (Srinivasan & Mullins, 1981). An increase in tissue temperature as a result of improved canopy exposure could contribute to higher fruitfulness (Dry, 2000). It is said that temperatures between 30-35°C ensure maximum fertility, whereas temperatures below 15-20°C result in low or no fertility depending on the grape variety (Buttrose, 1970; Dunn, 2005). The presence of high temperatures in the case of highly exposed canopies can disturb inflorescence differentiation during bud burst and growth of new shoots. This could result in the formation of a tendril instead of a bunch. More exposed canopies relative to dense shaded canopies may have increased photosynthetic photon flux densities (PPFD), red to far-red light ratios and bunch temperatures which can contribute to increased numbers of flowers/bunch, bunches/shoot and shoots/count node (Bledsoe *et al*., 1988). Higher canopy temperatures may, however, occur in more exposed canopies, but it seems that the most significant contributor to microclimate modification is light quantity and quality (Champagnol, 1984; Smart, 1985).

There is limited information regarding the relationship between water stress and fruitfulness and this can be mainly attributed to difficulties separating water deficit effects from light intensity and temperature. However, Buttrose (1974) showed that continual, severe water stress lead to decreased fertility in the form of less and smaller inflorescence primordia. Prolonged water deficits also have a negative effect on fertility where the flow of xylem sap is hampered. This results in decreased cytokinin concentrations which is required for anlagen development (Mullins *et al*., 1992). Intense ramification leads to formation of bunch primordia while poor ramification leads to formation of tendrils. Some studies have found that higher light interception experienced by more exposed canopies increased water consumption (Williams & Ayars, 2005; Stolk, 2014) and may result in severe water deficits if re-watering does not occur and grapevine recovery is hampered. Nevertheless, moderate stress conditions could result in increased fertility due to reduced shoot growth and thus increased light interception (Iland *et al.,* 2011).

A definite connection exists between vigour and bud fertility. Excessive vigour has been linked to reduced or poor bud fertility (Carbonneau *et al*., 1978). Studies displayed that undifferentiated primordia generally developed into tendrils on rapidly growing shoots *i.e.* vigorous shoots (Boss & Thomas, 2002; Boss *et al*., 2003). Bud fruitfulness is said to increase from the bottom up to the middle of the cane, where it decreases again towards the shoot tip (Huglin & Schneider, 1998). The number of flowers per node (number of inflorescences per bud x number of flowers per inflorescence) were the highest where an average cane pruning mass of 45 g was present (Vasconcelos *et al*., 2009). Such a low cane mass was probably due to a divided canopy, higher bud load or a low vigour grapevine. There also seems to be a correlation between cane diameter and fertility, where the inflorescence number per shoot decreases as diameter decreased (Huglin, 1958; Vasconcelos *et al*., 2009). Bud fertility is associated to the replenishment of carbohydrate reserves produced and stored in the previous season (Mansfield & Howell, 1981; Howell *et al*., 1994; Bennett *et al*., 2005). A decrease in leaf area can impair the fertility during the following season while too dense canopies result in overshadowing of buds and reduce fertility. Reduced fertility can also be present when a grapevine is over cropped and reducing shoot vigour is consequently reduced (Murisier, 1996).

2.4.4 Bunch and berry size and number of berries per bunch

Not a lot of evidence is present specifically on the yield components contributing to the eventual yield produced by certain trellis- and training systems. Van Zyl and Van Huyssteen (1980) found slightly larger berries produced on a slanting trellis. This was mainly the result of lower yield per effective leaf area produced by the grapevines on the slanting trellis. The only conclusion regarding bunch and berry size is that it relates more to the pruning level (see paragraph 2.2.1) implemented on the specific training/trellis system, where severe pruned systems result in heavier/larger bunches and in some cases more berries per bunch, and when a double-cordon trellis system is used this bunch mass will stay the same on a per shoot basis, but will be doubled per vine. Smaller- and more berries per bunch occur at a more favourable microclimate.

The number of berries per bunch is dependent on conditions during flowering and/or fruit set (Iland *et al*., 2011). The impact that training/trellis systems could have on this process is *via* limitations of carbohydrate supply from reserves (grapevine imbalance) and impaired leaf photosynthesis (water stress and light conditions) to the inflorescence (Keller & Koblet, 1994; Lebon *et al*., 2008).If vigorous growth diverts metabolites away from the inflorescence, fruit set may be reduced. Low percentage fruit set can also occur when low light conditions are associated with low temperatures (May, 2004). May and Antcliff (1963) reported a direct effect of shading on crop development, where decreased light intensities produced smaller bunches and berries.

2.4.5 Yield and grape composition

Increased yield is generally evident in divided canopies (horizontal or vertical) compared to non-divided canopies, since the leaf area exposed to sunlight is improved. Therefore, there is better light interception, cane distribution, more optimal temperature for shoots and fruit and increased number of buds are pruned per unit row length (hence increased shoots and bunches) (Shaulis *et al*., 1966; Shaulis & May, 1971; Howell *et al*., 1987; Intrieri, 1987; Reynolds *et al*., 1996; Reynolds *et al*., 2004). Although grapes of more exposed canopies generally displayed higher sugar concentrations, anthocyanins and phenolics, lower total acidity (TA), malic acid, tartaric acid, potassium concentrations and pH occurred (Shaulis *et al*., 1966; Smart & Robinson, 1991). Many reports in literature concluded that the appropriate training system increased yield with concomitant improvement of grape composition (Shaulis *et al*., 1966; Cawthon & Morris, 1977; Carbonneau *et al*., 1978, Howell *et al*., 1991; Reynolds *et al*., 1995; Reynolds *et al*., 2009). However, some studies reported no effect on fruit composition. In a study comparing four different training systems where yield ranged from 7 to 10 t/ha, there was little or no effect on grape composition (Peterlunger *et al*., 2002). Similar results were reported where different canopies increased yield components substantially but did not affect grape composition, (Shaulis & May, 1971; Van Zyl & Van Huyssteen, 1980; Zeeman, 1981). It is important that unless adequate grapevine size is maintained, improved yields cannot be sustained. It is also impossible to successfully increase yield on grapevines grown on a trellis which is too small (Archer, 2011).

An increase in yield in response to canopy architecture alteration may not have any effect on fertility (Dry, 2000). Results from studies regarding responses to increased canopy width (Kasimatis *et al*., 1975) and trellis height (May *et al*., 1973; Weaver & Kasimatis, 1975) support this. The general response to increased canopy width and height, with similar bud numbers, is increased grapevine growth since a higher capacity for assimilation occurs. Therefore, increased grapevine productivity can be achieved mainly by increased bud load per vine as in the case of trellises such as Smart-Dyson, Scott-Henry and Lyre (Archer, 2011). Kliewer (1982) stated that the primary means to affect fruitfulness of grapevines is canopy alteration by means of canopy division. Certain trellises such as the Ballerina increase yield due to enhanced bud fruitfulness (Mellet, 2010), and this is due to improved light conditions in the renewal zone (Kliewer & Smart, 1989). The favourable effects of canopy division, such as with the GDC trellis, have already been reported by several authors (Shaulis *et al*., 1966; May *et al*., 1973; May *et al*., 1976; Wolfe & Brown, 1995; Zabadal & Dittmer, 1998). However, local experiments did not find the same degree of favourable effects on GDC mainly due to it containing highly exposed bunch zones which does not suit the warm South African climate. Improved yields tend to be greater with high capacity grapevines compared to low capacity grapevines (Shaulis *et al*., 1966). Kliewer and Smart (1989) showed a yield increase of approximately 50% was present on divided training systems compared to single canopies. The main yield component responsible for this reported increase appeared to be the number of bunches per grapevine, whereas bunch mass contributed a small proportion. The addition of more shoots per vine and per meter row on high capacity grapevines, together with significant increases of non-count shoots from base buds (on two bud spurs) were mainly responsible for the increased number of bunches produced (Dry, 2000).

It can be concluded that the appropriate choice of training system can increase yield, by increased exposed leaf area to direct radiation as well as increase diffuse radiation interception (Smart, 1973), with no detrimental effect on grape composition.

2.5 Effects of training/trellis adaptation on grapevine water status

The structure of the grapevine canopy determines the interaction with solar radiation, which also relates to crop productivity. How the canopy is positioned and constructed determines the distribution of leaf surfaces exposed to sunlight, which affects light interception and, consequently, carbon assimilation and water deficits (Poni *et al*., 2003; William & Ayars, 2005; Schultz *et al*., 2009). Plant water status depends on the water potential near the root system, canopy size and evaporative demand (Choné *et al*., 2001). The flow of xylem sap to leaf transpiration, in relation to water availability in the soil, determines the occurrence of plant water deficits.

The soil-plant-atmosphere-continuum (SPAC) model proposes that tension must exist for water to be transported through the xylem and also refers to water deficits occurring along the path from roots to leaves (Hillel, 1971). The transport of water in a plant takes place schematically in four steps: soil→root; root→xylem; shoot→leaf (by means of the petiole) and leaf→atmosphere (by means of stomata) (Choné *et al*., 2001). Stomata are considered to be very important as they represent the final destination in the pathway of water from the soil to the atmosphere and play a critical role in water loss regulation. The grapevine regulates the movement of water and uptake of CO_2 by opening or closing the stomata (Wilmer & Fricker, 1996). They modify the rate of transpiration through small changes in stomatal pore size whereby water vapour diffuses. Stomata opening wider result in increased conductance (anonym for resistance) and therefore higher water vapour flow, thus stomatal conductance is proportional to stomatal aperture (Iland *et al*., 2011). Stomatal aperture is not only influenced by wind, vapour pressure deficit, light, humidity, temperature and CO_2 (Peacock *et al*., 2000), but also by water deficits and may be used as an indicator for water stress (Van Zyl, 1984). The occurrence of water deficits generally results in partial stomatal closure which is the main factor minimising transpiration and gas exchange, avoiding possible damage to the grapevine's hydraulic system (Davies & Gowing, 1999; Chalmers, 2009). However, prolonged stomatal closure also limits photosynthetic activity, sugar assimilation and carbohydrate production (Hofäcker, 1978; Chalmers, 2009). There can be a correlation between decreasing stomatal conductance and declining leaf water potential (Ψ_L) in the presence of drying soils, but conductance can also decrease before a change in Ψ_L occurs (Schultz & Matthews, 1997). Grapevine varieties display different stomatal sensitivities and therefore can be categorised based on their ability to manage water status (Schultz, 2003). Shiraz is generally known to display near-anisohydric behaviour, which can be described as limited stomatal control (Schultz, 2003). Near-isohydric cultivars, such as Grenache, conserve the present resources by 'tight-controlled' stomata.

Pre-dawn leaf water potential (Ψ_{PD}) is often used to estimate soil water potential due to assumptions that the plant water status is in equilibrium with the soil water status (Waring & Cleary, 1976). However, some evidence suggests that stomata do not close completely during the night (Bucci *et al*., 2004; Grulke *et al*., 2004; Daley & Phillips, 2006) and this will impair the accuracy of Ψ_{PD} measurements, with Ψ_{PD} values being more negative than the soil water potential (Donovan *et al*., 2003). The recovery of the grapevine may play a role in the occurrence of night time transpiration.

Water stress occurs when the transpiration rate of the leaves exceeds the ability of the grapevine to take up water from the soil and transport it to the leaves (Iland *et al*., 2011). Moderately stressed grapevines are likely to use water more efficiently than non-stressed ones because transpiration is reduced more than photosynthesis. When no water deficits are present, vegetative growth is the main sink and hence reproductive growth is neglected (Strever, 2013). The balance of sources to sinks has an effect on the water stress imposed *i.e.* increased yield will lead to increased effects of water stress (Poni *et al*., 1994). However, water deficits can also control the source to sink balance by reducing components such as berry size and eventual yield (Williams, 2000). The main morphological effects of water deficits are a reduction in leaf area (Stolk, 2014), number of leaves per shoot (Strever, 2013), leaf size and leaf blade thickness (Gomez-Del-Campo *et al*., 2002) and potentially exposed leaf area index (Carbonneau, 1995). Physiologically speaking, an increase in ABA (Davies *et al*., 1986; Peterlunger *et al*., 2000) decreased stomatal conductance (Flexas *et al*., 2007) and thus decreased photosynthesis may occur.

Different canopy alterations and grapevine manipulations has a definite effect on the grapevine water status. The total amount of water transpired and evaporated is known as evapotranspiration (ET) and is dependent on canopy architecture, stomatal conductance, irrigation and the atmospheric conditions (Netzer *et al*., 2009). Other factors impacting ET is wind speed and vapour pressure deficit (VPD), with the latter being greatly dependent on ambient temperature. Thus, increased water consumption during high temperatures is a result of increased radiation and lower relative humidity (Peacock *et al*., 2000). Leaves on the inside of a dense canopy, *i.e.* shaded leaves, are exposed to lower radiation, wind speed and increased humidity, consequently reducing evaporation (Smart, 1985) and decreasing water use efficiency (Medrano *et al.,* 2012). The opposite is therefore true for exposed canopies. The canopy geometry determines the amount of light interception and can be considered a very important determinant of grapevine water use (Williams & Ayars, 2005). Grapevine canopies which are subjected to water stress tend to have lower yields and less leaves in shade (Smart, 1985). Minor modifications such as increased trellis height (and therefore increased light interception) lead to increased water requirements (Redl, 1984; Reynolds & Van den Heuvel, 2009). Training systems impact grapevine water status by alterations in the amount of leaves exposed to sunlight (Reynolds & Van den Heuvel, 2009).

2.6 Ripening

It is evident that a particular training/trellising system creates a certain microclimate where grapes are ripened (Smart, 1982; 1984 & 1985; Smart *et al*., 1990). Leaves exposed to these microclimatic conditions have an important influence on the functioning and quantity of photosynthetic products translocated to bunches. Furthermore, the microclimatic conditions (mostly favourable light conditions) surrounding bunches has an important impact on berry ripening tempo as well as their chemical composition.

Berry development takes place after fertilisation where it follows a double sigmoid curve which is divided in three phases, namely berry formation, véraison (lag phase) and berry ripening (Coombe & Iland, 2004). The concept of sugar loading, which can be defined as the "evolution of the quantity of sugar per berry, expressed as mg per berry, from véraison onwards", is developed and explained in detail by Deloire (2011). It provides an indication of the ripening process by distinguishing the main ripening phases (Hunter & Deloire, 2005). Rapid, continuous sugar loading is related to active functioning leaves, in terms of carbon production and supply to demanding sinks such as berries, laterals *etc*. This phase can be associated with significant vegetative growth and increased berry volume while phenolic maturity is unaffected. An inhibition of ripening occurs when sugar loading is slow and this is indicative of an imbalanced grapevine situation in terms of severe water deficit (Wang *et al*., 2003) or excessive crop load to exposed leaf area (Carbonneau & Deloire, 2001).

Several factors (amongst others) such as irrigation, canopy shade conditions (resulting in reduced sucrose availability), vegetative growth (leaf age & shoot length) and yield (bunch size) can contribute to inhibition of ripening. These factors may lead to decreased sucrose production by leaves, organic acid formation, stimulate the loading and transportation of potassium to berries and increase pH (delaying ripening). The opposite occurs in the presence of water stress. Controlled water deficits imposed early in the season accelerated sugar accumulation and, in conjunction with late season deficits, increased anthocyanin accumulation after véraison (Bravdo *et al*., 1985; Bravdo & Hepner; 1986; Castellarin *et al*., 2007). Young leaves contribute the highest amount of photosynthate during the ripening period and it is important to have a well exposed canopy during this time (Hunter & Archer, 2002). A study indicated that the absence of leaves caused a drastic delay in ripening in terms of growth as well as colour development and affected berry dry mass, sugar content and soluble solids (Petrie *et al*., 2000b). Active sugar loading is followed by a plateau which represents an end of sugar loading and the start of berry maturity (Hunter & Deloire, 2005). Once this plateau is reached, the progression of ripening will be dependent on bunch microclimate, leaf to fruit balance, primary and secondary shoot ratio, grapevine variety and climate (Deloire, 2011). It is important to understand that the plateau, which is highly dependent on cultivar and the prevailing environment, will be reached at different levels of total soluble solids.

Water deficits during berry growth and ripening greatly affect berry size (McCarthy, 1997). Berry size, colour and juice composition are affected by grapevine water status and can affect wine quality negatively (Williams & Matthews, 1990). Berry size is widely recognised as one of the deciding factors of grape quality where the skin to pulp ratio decreases with an increase of berry size (Champagnol, 1998). Water deficits reduced berry size compared to where irrigation was applied continually (Myburgh, 1998; Myburgh, 2003). Water deficits between flowering and véraison generally lead to smaller berries because of the inhibition or reduced tempo of cell division and cell enlargement (Hardie & Considine, 1976; Matthews *et al*., 1987). A study concluded that early water deficits had no effect on cell division and the reduction of berry size and mass were the result of decreased cell volume (Ojeda *et al*., 2001). This decreased cell volume was irreversible when water deficits were applied between flowering and véraison. These results support the hypothesis stating that early water deficits alter the structural properties of cell components and therefore the cell extensibility, limiting cell enlargement. The reduction in turgor pressure due to low water content within plant organs slow cell expansion, cell wall synthesis and cell division (Schultz & Matthews, 1993; Thomas *et al*., 2006). Various authors (Matthews *et al*., 1990; Van Leeuwen & Seguin, 1994) have stated the importance of grapevine water status in determining grape composition. Moderate water stress during ripening appears to reduce leaf area densities due to reduced shoot growth (Chaves *et al*., 2007). In addition to this, bunch microclimate is enhanced which promotes the accumulation of berry solutes (Downey *et al*., 2006). A favourable gradient of total water potential between the fruit and the rest of the plant is required for berry growth to take place.

In conclusion, restricting shady conditions within the grapevine canopy on a training-, trellis- and pruning system together with an appropriate balance between yield and dry pruning mass (Y/PM) is therefore important to prevent ripening inhibition. If an unfavourable Y/PM is unavoidable, ripening could be accelerated with controlling water deficits and berry size can be reduced if required for a specific production goal.

2.7 Conclusions

Knowledge regarding the various expressions of yield components is of great importance when grapevine training/trellising alterations are implemented. Yield components play a crucial role in the grapevine's potential yield and practices such as pruning, training and trellising should be carefully considered to avoid the over- or under expression of certain yield components, and thereby affecting the balance of the grapevine and subsequent desired production goal.

Yield component expression commences with the number of buds retained during pruning. The appropriate bud load is dependent on the space provided by the trellis and training system, grapevine vigour, within-row vine spacing as well as the current financial situation, with minimal pruning displaying labour cost reductions (Archer & Van Schalkwyk, 2007). The applied pruning level together with climatic factors (root and ambient temperature) and stored carbohydrate reserves from the previous season, will determine the number of buds bursting during spring, consequently the number of shoots and therefore the potential crop load. The training and trellis system as well as in-row vine spacing provides an area for the shoots and grapes to develop and the aim should be to optimise sunlight interception, reducing within-canopy shading and increasing canopy photosynthetic efficiency. If this is in place optimal fertility can be induced and consistent yield potential reached over the lifetime of the vineyard.

A point will come when the grapevine reaches its maximum productivity. As a result, yield components compensates by changes in berry size and berry number, which is generally a consequence when bunch numbers are increased. Grapevine alteration will affect the manner in which assimilates are distributed to the various parts of the grapevine and for the grapevine to be sustainable, sufficient vegetative growth should be present to effectively support the quantity of grapes, ensuring optimal ripening and consistent yields for a specific production goal.

2.8 Literature cited

Anderson, P.C., Sims, C.A. & Harrison, J.M., 1996. Influence of simulated mechanized pruning and hand pruning on yield and berry composition of *Vitis rotundifolia* Noble and Welder. Am. J. Enol. Vitic. 47, 292-296.

Antcliff, A.J., 1965. A comparison of cropping levels in the Sultana. Vitis 5,1-9.

Antcliff, A.J., Webster, W.J. & May, P., 1972. The Merbein bunch count, a method to analyse the performance of grapevines. Hort. Sci. 7, 196-197.

Archer, E., 1983. Evaluasie van verskillende snoeimetodes vir Cabernet Sauvignon. Die Wynboer 621, 65-69.

Archer, E., 1984. Invloed van oogladding op die prestasie van wyndruifstokke. Wynboer Tegnies 8, 11-15.

Archer, E., 1985. Wintersnoei van wingerd. Wynboer Tegnies 11, 4-7.

Archer, E.,1999. Meganisering van snoei by wingerd: Vereistes gestel aan die wingerd en reaksie van wingerdstok. Wynboer Tegnies117, 46-48.

Archer, E., 2011. Increasing yield from wine grapes. Wynboer Technical Yearbook 2011, 60-84.

Archer, E. & Fouché, G.W., 1987. Effect of bud load and rootstock cultivar on the performance of *Vitis vinifera* L. cv. Red Muscadel (Muscat noir). S. Afr. J. Enol. Vitic. 8, 6-10.

Archer, E. & Strauss, H.C., 1989. Invloed van oorskaduwing op die prestasie van Cabernet Sauvignon. Wynboer, September. pp. 10-11.

Archer, E. & Hunter, J.J., 2003. Verhoging in opbrengs by wyndruiwe vir spesifieke produksiedoelwitte. WineLand October. pp. 92-103.

Archer, E. & Hunter, J.J., 2004. Vine balance: its importance to successful cultivation. Wynboer, February. pp. 1-12.

Archer, E. & Van Schalkwyk, D., 2007. The effect of alternative pruning methods on the viticultural and oenological performance of some wine grape varieties. S. Afr. J. Enol. Vitic. 28, 107-139.

Archer, E. & Hunter, J.J., 2010. Practices for sustainable viticulture. Part 3. Planting of vines. Wynboer Technical Yearbook 2010, 136-141.

Bakonyi, I., 1987. Non-pruning: a new technique in vineyard management. Austr. Grapegrow. Winem. 280, 112-113.

Balahsubrahmanyam, V.R., Eifert, J. & Diofasi, L., 1978. Nutrient reserves in grapevine canes as influenced by cropping levels. Vitis, 17, 23-29.

Bernard, C. & Thomas, J.E., 1933. Fruit bud studies. II. The Sultana: differentiation and development of fruit buds. Journal of the Council for Scientific and Industrial Research 6, 285-294.

Bennett, J., Jarvis, P., Creasy, G.L. & Trought, M.C.T., 2005. Influence of defoliation on overwintering carbohydrate reserves, return bloom, and yield of mature Chardonnay grapevines. Am. J. Enol. Vitic. 56, 386-393.

Bledsoe, A.M., Kliewer, W.M. & Marais, J.J., 1988. Effects of timing and severity of leaf removal on yield and fruit composition of Sauvignon blanc grapevines. Am. J. Enol. Vitic. 39, 49-54.

Boss, P.K. & Thomas, M.R., 2002. Association of dwarfism and floral induction with a grape 'green revolution' mutation. Nature 416, 847-850.

Boss, P.K., Buckeridge, E.J., Poole, A. & Thomas, M.R., 2003. New insights into grapevine flowering. Funct. Plant Biol. 30, 593-606.

Bravdo, B., Hepner, Y., Loinger, C., Cohen, S. & Tabacman, H., 1985. Effect of irrigation and crop level on growth, yield and wine quality of Cabernet Sauvignon. Am. J. Enol. Vitic. 36, 132-139.

Bravdo, B. & Hepner, Y., 1986. Water management and effect on fruit quality in grapevines. In: Lee, T. (ed). Proc. 6th Aust. Wine Ind. Tech. Conf., July 1986, Adelaide, Australia. pp. 150-158.

Bucci, S.A., Scholz, G., Goldstein, G., Meinzer, F.C., Hinojosa, J.A., Hoffman, W.A. & Franco, A.C., 2004. Processes preventing nocturnal equilibration between leaf and soil water potential in tropical savanna woody species. Tree Physiol. 24, 1119-1127.

Buttrose, M.S., 1970. Fruitfulness in grapevines: the response of different cultivars to light, temperature and day length. Vitis 9,121-125.

Buttrose, M.S., 1974. Climatic factors and fruitfulness in grapevines. Hort. Abstracts 44, 319-326.

Carbonneau, A., 1995. La surface foliaire exposée potentielle. Guide pour sa mesure. Le Progrès Agricole et Viticole 112, 204-212.

Carbonneau, A., Casteran, P. & Leclair. P., 1978. Essai de determination en biologie de la plante entiere de relations essentielles entière le bioclimat naturel, la physiologie de la vigne et composition du raisin. Méthodologie et premiers résultats sur les systèmes de conduite. Ann. Amelior. Plant. 28,195-221.

Carbonneau, A., Lebon, E., Mahbrouk, H. & Sinoquet, H., 1997. Interactions: canopy shape x vigour level: consequences on architecture and microclimate of the grapevine. Acta. Hort. 526, 91-105.

Carbonneau, A. & Deloire, A., 2001. Plant organization based on source-sink relationship: new finding on developmental, biochemical and molecular responses to environment. In: Molecular Biology & Biotechnology of Grapevine. Kluwer Academic Publishers, pp. 263-280.

Caroll, D., 2009. What causes a bud to produce a bunch, or not? Practical Winery & Vineyard Journal, November.

Castellarin, S.D., Matthews, M.A., Di Gaspero, G. & Gambetta, G.A., 2007. Water deficits accelerate ripening and induce changes in gene expression regulating flavonoid biosynthesis in grape berries. Planta. 227, 101-112.

Cawthon, D.L., & Morris, J.R., 1977. Yield and quality of Concord grapes as affected by pruning severity, nodes per bearing unit, training system, shoot positioning, and sampling date in Arkansas. J. Am. Soc. Hort. Sci. 102, 760-767.

Chalmers, Y., 2009. Insights into the relationships between yield and water in wine grapes. In: Water and vine: Managing the challenge. Fact sheet 5, GWRDC.

Champagnol, F., 1984. Elements de physiologie de la vigne et du viticulture generale. F. Champagnol. Montpellier, France.

Champagnol, F., 1998. Criteres de qualite de la vendange. In: C. Flanzy (Ed): Oenologie Fondements Scientifiques et Technologiques. Lavoisier Tec & Doc . Paris. 653-659.

Chaves, M.M., Santos, T.P., Souza, C.R., Ortuno, M.F., Rodrigues, M.L., Lopez, C.M., Maroco, J.P. & Pereira, J.S., 2007. Deficit irrigation in grapevine improves water-use efficiency while controlling vigour and production quality. Ann. Appl.Biol. 150, 237-252.

Choné, X., Van Leeuwen, C., Dubourdieu, D. & Gaudillère, J.P., 2001. Stem water potential is a sensitive indicator of grapevine water status. Ann. Bot. 87, 477-483.

Cirami, R.M., McCarthy, M.G. & Furkaliev, D.G., 1985. Minimum pruning of Shiraz vines - effects on yield and wine colour. Austr. GrapegrowWinem.263, 24-26.

Clingeleffer, P.R., 1988. Response of Riesling clones to mechanical hedging and minimal pruning of cordon trained vines - implications for clonal selection. Vitis27, 87-83.

Clingeleffer, P.R., 1989. Update: Minimal pruning of cordon trained vines. Aust. Grapegrow. Winem. 282, 78-83.

Clingeleffer, P.R., 1993. Vine response to modified pruning practices. In: Pool, R.M. (ed). Pruning mechanization and crop control. Proc. 2nd Nelson J. Shaulis Gr. Symp., July 13-14 1993, New York, U.S.A. pp. 20-30.

Clingeleffer, P.R., 2009. Influence of canopy management systems on vine productivity and fruit composition. In: Anon. Recent advances in grapevine canopy management symposium, 16 July 2009, Davis, U.S.A. pp. 13-20.

Clingeleffer, P.R. & Possingham, J.V., 1987. The role of minimal pruning of cordon trained vines in canopy management and its adoption in Australian viticulture. Austr. Grapegrow. Winem. 280, 7-11.

Clingeleffer, P. R., Sommer, K.J., Kristic, M., Small, G. & Welsh, M., 1997. Winegrape crop prediction and management. Wine Industry Journal12, 354-359.

Clingeleffer, P.R., Martin, S., Kristic, M. & Dunn, G.M., 2001. Crop development, crop estimation and crop control to secure quality and production of major wine grape varieties: A national approach. Final report to Grape and Wine Research and Development Corporation (Australia).

Cloete, H., 2004. The effect of shoot heterogeneity on the physiology and grape composition of Shiraz/Richter 99 grapevines. Thesis, Stellenbosch University, Private Bag X1, Matieland (Stellenbosch) 7602, South Africa.Cloete, H., Archer, E. & Hunter, J.J., 2006. Shoot heterogeneity effects on Shiraz/Richter 99 grapevines. I. Vegetative growth. S. Afr. J. Enol. Vitic. 27, 65-75.

Cloete, H., Archer, E. & Hunter, J.J., 2006.Shoot heterogeneity effects on Shiraz/Richter 99 grapevines. I. Vegetative growth.S. Afr. J. Enol. Vitic. 27, 68-75.

Cloete, H., Archer, E. & Hunter, J.J., 2008. Shoot heterogeneity effects on Shiraz/Richter 99 grapevines. II. Physiological activity. S. Afr. J. Enol. Vitic. 29, 1-8.

Colby, R.S. & Tucker, D.R., 1993. Some effects of severity of pruning on growth and production in the Concord grape. III. Agr. Exp. Sta. Bull. pp. 393.

Coombe, B.G. & Iland, P., 2004. Grape berry development and winegrape quality. In: Dry, P.R. & Coombe, B.G. (eds). Viticulture.Vol. 1. Resources. (2nd edition) (eds.). Winetitles, Adelaide, Australia. pp. 210-248.

Daley, M.J. & Phillips, N.G., 2006. Interspecific variation in nighttime transpiration and stomatal conductance in a mixed New England deciduous forest. Tree Physiol. 26,411-419.

Davies, W.J., Metcalfe, J., Lodge, T.A. & Da Costa, A.R., 1986. Plant growth substances and the regulation of growth under drought. Aust. J. Plant Physiol. 13, 105-125.

Davies, W.J. & Gowing, D.J.G., 1999. Plant responses to small perturbations in soil water status. In: Press, M.C., Scholes, J.D. & Barker, M.G. (eds). Physiological plant ecology, Blackwell Science, Oxford, UK. pp. 27-89.

Deloire, A., 2011. The concept of berry sugar loading. WineLand Technical Yearbook,. 93-95.

De Villiers, F.S., 1987. A comparative ampelographic and ampelometrical study on clusters of different wine grape cultivars. MSc Thesis, Stellenbosch University, Private Bag X1, Matieland (Stellenbosch) 7602, South Africa.

Donovan, L.A., Richards, J.H. & Linton, M.J., 2003. Magnitude and mechanisms of disequilibrium between predawn plant and soil water potentials. Ecology 84,463-470.

Downey, M.O., Dokoozlian, N.K. & Kristic, M.P., 2006. Cultural practice and environmental impacts on the flavonoid composition of grapes and wine: a review of recent research. Am. J. Enol. Vitic. 57, 257-268.

Downton, W.J.S. & Grant, W.J.R., 1992. Photosynthetic physiology of spur pruned and minimal pruned grapevines. Aust. J. Plant Physiol. 19, 309-316.

Dry, P.R., 1983. Grapevine response to mechanical pruning. In: Lester, D.C. & Lee, T.H. (eds). Coonawarra Viticulture: proceedings of a seminar, 8 June 1983, Coonawarra, Australia. pp. 7-12.

Dry, P.R., 2000. Canopy management for fruitfulness. Aust. J. Grape Wine Res. 6, 109-115.

Dunn, G., 2005. Factors that control flower formation in grapevines. In: DeGaris, K., Dundon, C., Johnstone R. & Partridge S. (eds). Proceedings of seminar 'Transforming flowers to fruit', Insert date and year, insert place, insert country. pp. 11-18.

Eichhorn, K.W. & Lorenz, D.H., 1977. Phönologische entwicklungsstadien der rebe, *Nachrichtenbl. Deut. Pflanzenschutz.29*, 119-120.

Emmerson, J. G. & Powell, L.E., 1978. Endogenous abscisic acid in relation to rest and bud burst in three *Vitis*species. J. Am. Soc. Hort. Sci. 103, 677-680.

Field, S.K., Smith, J.P., Holzapfel, B.P., Hardie, W.J. & Emery, R.J.N., 2009. Grapevine response to soil temperature: xylem cytokinins and carbohydrate reserve mobilization from budbreak to anthesis. Am. J. Enol. Vitic. 60, 164-172.

Flexas, J, Diaz-Espejo, A., Galmés, J., Kaldenhoff, R., Medrano, H. & Ribas-Carbó , M., 2007. Rapid variations of mesophyll conductance in response to changes in CO_2 concentration around leaves. Plant, Cell Environ. 30, 1284-1289.

Freeman, B.M., 1977. Griffith experiments in mechanical pruning. In: Anon. (ed). Proc. 3rd Aust. Wine Ind. Tech. Conf., August 1977, Albury, Australia. pp. 55.

Freeman, B.M., Lee, T.H. & Turkington, C.R., 1979. Interaction of irrigation and pruning level on growth and yield on Shiraz vines. Amer. J. Enol. Vitic. 30, 218-223.

Freeman, B.B., Tassie, E. & Rebbechi, M.D., 1992. Training and trellising. In: Coombe, B.G. & Dry, P.R. (eds). Viticulture. Vol. 2. Practices. Winetitles, Adelaide. pp. 42-65.

Fu mail, Y.H., Campioli, M., Deckmyn, G. & Janssens, I.A., 2012. The impact of winter andspring temperatures on temperate tree budburst dates: results from an experimental climate manipulation. PLoS ONE 7(10): e47324. doi:10.1371/journal.pone.0047324.

Gandell, M., 1989. Effect of node number on shoot devigoration. In: insert editor (ed). Sunlight into wine. A Hhandbook for wine grape canopy management. Winetitles, Adelaide, Australia. pp. 34.

Gomez-Del-Campo, M., Ruiz, C. & Lissarrague, J.R., 2002. Effect of water stress on leaf area development, photosynthesis, and productivity in Chardonnay and Airén grapevines. Am. J. Enol. Vitic. 53, 138-143.

Grulke, N.E., Alonso, R., Nguyen, T., Cascio, C. & Dobrowolski, W., 2004. Stomata open at night in pole-sized and mature ponderosa pine: implications for O_3 exposure metrics. Tree Physiol. 24, 1001-1010.

Hardie, W. J & Considine, J. A., 1976. Response of grapes to water deficit stress in particular stages of development. Am. J. Enol. Vitic. 27, 55-61.

Heazlewood, J.E., 2005. Stabilizing the yields of Pinot noir grape vines in Tasmania. Final Report to Grape and Wine Research and Development Corporation (Australia).

Heazlewood, J.E., Wilson, S., Clark, R.J. & Gracie, A.J., 2006. Pruning effects on Pinot Noir vines in Tasmania (Australia). Vitis 45, 165-171.

Hillel, D., 1971. Soil and water - physical principles and processes. Academic Press, New York and London.

Hofäcker, W., 1978. Investigations on the photosynthesis of vines, influence of defoliation, topping, girdling and removal of grapes. Vitis 17, 10-22.

Hollick, R.R., 1977. Machine use in mechanical pruning. In: Anon. (ed). Proc. 3rd Aust. Wine Ind. Tech. Conf., August 1977, Albury, Australia. pp. 54.

Howell, G. S., 2001. Sustainable grape productivity and the growth- yield relationship: A review. Am. J. Enol. Vitic. 52, 165-174.

Howell, G. S., Mansfield, T.K. & Wolpert, J.A., 1987. Influence of training system, pruning severity, and thinning on yield, vine size, and fruit quality of Vidal blanc grapevines. Am. J. Enol. Vitic. 38, 105-122.

Howell, G.S., Miller, D.P., Edson, C.E. & Striegler, R.K., 1991. Influence of training system and pruning severity on yield, vine size, and fruit composition of Vignoles grapevines. Am. J. Enol. Vitic. 42, 191-198.

Howell, G.S., Candolfi-Vasconcelos, M.C. & Koblet, W., 1994. Response of Pinot noir grapevine growth, yield, and fruit composition to defoliation the previous growing season. Am. J. Enol. Vitic. 45, 188-191.

Huglin, P., 1958. Recherches sur les bourgeons de la vigne: Initiation florale et developpement vegetatif. Ann. Amelior. Plant. 8, 113-272.

Huglin, P. & Schneider, C., 1998 (2nd ed). Biologie et Ecologie de la Vigne.. Lavoisier Tech&Doc, Paris.

Hunter, J.J., 1991. Die invloed van loofbestuur op druifkwaliteit. In: Anon. Short course in oenology, 27-28 August 1991, Nietvoorbij, Stellenbosch.

Hunter, J.J., 2000. Implications of seasonal canopy management and grwoth compensation in grapevine. S. Afr. J. Enol. Vitic. 21, 81-91.

Hunter, J.J., 2001. Grapevine physiology. Private Bag X5026, Stellenbosch, 7599. E-mail hunterk@arc.agric.za.

Hunter, J.J. & Visser, J.H. 1990. The effect of partial defoliation on growth characteristics of *Vitis vinifera* L. cv. Cabernet Sauvignon II. Reproductive Growth. S. Afr. J. Enol. Vitic. 11, 18-25.

Hunter, J.J., De Villiers, O.T. & Watts, J.E., 1991. The effect of partial defoliation on quality characteristics of *Vitis vinifera* L. cv. Cabernet Sauvignon grapes. I. Sugars, acids and pH. S. Afr. J. Enol. Vitic. 12, 42-50.

Hunter, J.J. & Volschenk, C.G., 2001. Effect of altered canopy:root volume ratio on grapevine growth compensation. S. Afr. J. Enol. Vitic. 22, 27-30.

Hunter, J.J. & Archer, E., 2002. Paper actual de la gestió del fullatgei perspectives futures (Status of grapevine canopy management and future prospects). ACE Rivista d'Enologia. 19, 5-11.

Hunter, J.J. & Deloire, A., 2005. Relationship between sugar loading and berry size of ripening Syrah/R99 grapes as affected by grapevine water status. Gesco XIV me journ es du groupe europ en d’tude des systemes de conduite de la vigne, Geisenheim, Allemagne, 23-27 Aot, 127-133.

Iland, P., Dry, P., Proffitt, T. & Tyerman, S., 2011. The grapevine: from the science to the practice of growing vines for wine. Patrick Iland Wine Promotions Pty Ltd 2011. Adelaide, Australia.

Intrieri, C., 1987. Experiences on the effect of vine spacing and trellis training system on canopy microclimate, vine performance and grape quality. Acta. Hort. 206, 69-87.

Intrieri, C., Poni, S., Rebucci, B. & Magnanini, E., 1997. Effects of canopy manipulations on whole-vine photosynthesis: Results from pot and field experiments. Vitis 36, 167-173.

Irimia, L. & Tardea, C., 2005. The exposable leaf area and the leaf index, which characterize the grapevine training systems in the avereşti wine-growing centre, Huşi vineyard. University of Agricultural Sciences and Veterinary Medicine of Iaşi. 42-46.

Jackson, D., 1997. Pruning and training. Lincoln University Press. Lincoln University, Canterbury, New Zealand.

Jordon, T.D., Pool, R.M., Zabadal, T.J. &Tomkins, J.P., 1966. Cultural practices for commercial vineyards. Miscellaneous Bulletin 111. Cornell University.

Kasimatis, A.N., Lider, L.A. & Kliewer, W.M., 1975. Influence of trellising on growth and yield of Thompson Seedless vines. Am. J. Enol. Vitic. 26, 125-129.

Keller, M. & Koblet, W., 1994. Is carbon starvation rather than excessive nitrogen supply the cause of inflorescence necrosis in *Vitis vinifera* L. Vitis 33, 81-86.

Kliewer, W.M., 1982. Vineyard canopy management: A review. In Webb, A.D. (ed). Grape and Wine Centennial Proceedings, Insert the date and 1982, Davis, USA. pp. 342-352.

Kliewer, W.M., Marois, J.J., Bledsoe, A.M., Smith, S.P., Benz, M.J. & Silvestroni, O., 1988. Relative effectiveness of leaf removal, shoot positioning, and trellising for improving winegrape composition. In: Insert editor, Proc. Sec. Int. Cool Climate Vitic. Oenol. Symp., Jan. 1988, Auckland, New Zealand. pp. 123-126.

Kliewer, W.M. & Smart, R.E., 1989. Canopy manipulation for optimising vine microclimate, crop yield and composition of grapes. In: Wright, C.J. (ed). Manipulation of fruiting.. Butterworth, London.

Kurtural, S.K., Dami, I.E. & Taylor, B.H., 2006. Effects of pruning and cluster thinning on yield and fruit composition of `Chambourcin' grapevines. Hort. Technology 16, 233-240.

Lakso, A.N., 1999. Physiology of minimal versus normal pruning of Concord grapes. Proc. Mich. State Hort. Soc. 128, 138-141.

Lebon, G., Wojnarowiez, G., Holzapfel, B., Fontaine, F., Vaillant-Gaveau, N. & Clément, C., 2008. Sugars and flowering in the grapevine (*Vitis vinifera* L.). J. Exp. Bot. 59, 2565-2578.

Mansfield, T.K. & Howell, G.S., 1981. Response of soluble solids accumulation, fruitfulness, cold resistance, and onset of bud growth to differential defoliation stress at véraison in Concord grapevines. Am. J. Enol. Vitic. 32, 200-205.

Martin, S. R., Dunn, G.M., Hoogenraad, T., Kristic, M.P., Clingeleffer, P.R. & Ashcroft, W.J., 2000. Crop forecasting in cool climate vineyards. In: a. (ed). Proc. 5th International Symposium on Cool Climate Viticulture and Oenology, insert date 2000, Melbourne, Australia.

Matthews, M.A., Anderson, M.M. & Schultz, H.T., 1987. Phenologic and growth responses to early and late season water deficits in Cabernet franc. Vitis 26,147-160.

Matthews, M.A., Ishii, R., Anderson, M.M. & O'Mahony, M., 1990. Dependence of wine sensory attributes on vine water status. J. Sci. Food Agric. 51, 321-335.

May, P., 2000. From bud to berry, with special reference to inflorescence and bunch morphology in *Vitis vinifera* L. Aust. J. Grape Wine Res.6, 82-98.

May, P., 2004. Flowering and fruit set in grapevines. Published by Lythrum, Adelaide in association with the Phylloxera and Grape Industry Board of South Australia and the Grape and Wine Research and Development Corporation, Adelaide, Australia.

May, P. & Antcliff, A.J., 1963. The effect of shading on fruitfulness and yield in the Sultana. J. Hort. Sci. 38, 85-94.

May, P. & Cellier, K.M., 1973. The fruitfulness of grape buds. II. The variability in bud fruitfulness in ten cultivars over four seasons. Ann. Amelior. Plant. 23, 13-26.

May, P. & Clingeleffer, P.R., 1977. Mechanical pruning of grapevines. Aust. Wine Brew. Spirit Rev. 96, 36-38.

May, P., Sauer, M.R. & Scholefield, P.B., 1973. Effect of various combinations of trellis, pruning, and rootstock on vigorous Sultana vines. Vitis 12,192-206.

May, P., Clingeleffer, P.R. & Brien, C.J., 1976. Sultana (*Vitis vinifera* L.) canes and their exposure to light. Vitis 14, 278-288.

May, P., Clingeleffer, P.R., Scholefield, P.B. & Brien, C.J., 1976. The response of the grape cultivar Crouchen (Australian syn. Clare Riesling) to various trellis and pruning treatments. Aust. J. Agric. Res. 27, 845-856.

McCarthy, M.G., 1997. The effect of transient water deficit on berry development of cv. Shiraz (*Vitis vinifera* L.). Austr. J. Grape and Wine Res. 3, 102-108.

McCarthy, M.G. & Cirami, R.M., 1990. Minimal pruning effects on the performance of selections of four *Vitis vinifera* cultivars. Vitis 29, 85-96.

Medrano, H., Pou, A., Tomás, M., Martorell, S., Gulias, J., Flexas, J. & Escalona, J.M., 2012. Average daily light interception determines leaf water use efficiency among different canopy locations in grapevine. Agr. Water Manage. 114, 4-10.

Mellet, J., 2010. Ballerina system for sustainable increased production. Wynboer Technical Yearbook 2010: 25-26.

Miller, D.P., Howell, G.S. & Flore, J.A., 1996a. Effect of shoot number on potted grapevines. I. Canopy development and morphology. Am. J. Enol. Vitic. 47, 244-250.

Miller, D.P., Howell, G.S. & Flore, J.A., 1996b. Effect of shoot number on potted grapevines. II. Dry matter accumulation and partitioning. Am. J. Enol. Vitic. 47, 251-256.

Miller, D.P., Howell, G.S. & Flore, J.A., 1997. Influence of shoot number and crop load on potted Chambourcin grapevines. II. Whole-vine vs. single-leaf photosynthesis. Vitis 36, 109-114.

Morris, J.R., Cawthon, D.L., & Fleming, J.W., 1975. Effect of mechanical pruning on yield and quality of Concord grapes. Ark. Farm. Res. 24, 12.

Morris, J.R. & Cawthon, D.L., 1980. Yield and quality response of Concord grapevines to training systems and pruning severity in Arkansas. J. Am. Soc. Hort. Sci. 105, 307-310.

Morris, J.R. & Cawthon, D.L., 1981. Yield and quality response of Concord grapes (*Vitis labrusca*L.) to mechanized vine pruning. Am. J. Enol. Vitic.32, 280-282.

Morris, J.R., Sims, C.A., Bourque, J.E. & Oakes, J.L., 1984. An investigation of training system, pruning severity, spur length, and shoot positioning on Cynthiana/Norton grapes. Am. J. Enol. Vitic. 35, 23-27.

Morris, J.R. & Main, G.L., 2010. An investigation of training system, pruning severity, spur length, and shoot positioning on Cynthiana/Norton grapes. Am. J. Enol. Vitic. 61, 445-450.

Mullins, M.G., Bouquet, A. & Williams, L.E., 1992. Biology of the Grapevine. Cambridge University Press, Cambridge.

Murisier, F., 1996. Optimalisation du Rapport Feuille-Fruit de la Vigne pour Favoriser la Qualité du Raisin et l'Accumulation des Glucides de Réserve. Relation entre le Rendement et la Chlorose. PhD Thesis No.11729, Swiss Federal Institute of Technology, Switzerland.

Myburgh, P.A., 1998. Water consumption of South African vineyards: A modelling approach based on the quantified combined effects of selected viticultural, soil and meteorological parameters. PhD Dissertation, Stellenbosch University, Private Bag XI, Matieland (Stellenbosch) 7602, South Africa.

Myburgh, P.A., 2003. Responses of *Vitis vinifera L.* cv. Sultanina to level of soil water depletion under semi arid conditions. S. Afr. J. Enol. Vitic. 24, 16-24.

Ndung’u, C.K., Shimizu, M., Okamoto, G. & Hirano, K., 1997. Abscisic acid, carbohydrates, and nitrogen contents of ‘Kyoho’ grapevines in relation to bud break induction by water stress. Am. J. Enol. Vitic. 48, 115-303.

Netzer, Y., Yao, C., Shenker, M., Bravdo, B.A. & Schwartz, A., 2009. Water use and the development of seasonal crop coefficients for Superior Seedless grapevines trained to an open-gable trellis system. Irrig. Sci. 27, 109-120

Ojeda, H., Deloire, A. & Carbonneau, A., 2001. Influence of water deficits on berry growth. Vitis 40, 141-145.

Partridge, N.L., 1925. Growth and yield of Concord grape vines. Proc. Am. Soc. Hort. Sci. 22, 84-87.

Peacock, W.L., Williams, L.E. & Christensen, L.P., 2000. Water management and irrigation scheduling. In: Christensen, L.P. (ed). Raison production manual. Regents of the University of California. Division of Agriculture and Natural resources. pp. 121-123

Peterlunger, E., Buccella, A. &Iacono, F., 2000. Physiological changes in grapevine during adjustment to water stress: ABA, leaf gas exchanges and root hydraulic conductivity. In:. Bravdo, B.A (ed.). Proc. Fifth Intl. Symp. Grapevine Physiol. pp. 201-206

Peterlunger, E., Celotti, E., Da Dalt, G., Stefanelli, S., Gollino, G. & Zironi, R., 2002. Effect of training system on Pinot noir grape and wine composition. Am. J. Enol. Vitic. 53, 14-18.

Petrie, P.R., Trought, M.C.T. & Howell, G.S., 2000a. Growth and dry matter partitioning of Pinot Noir (*Vitis vinifera* L.) in relation to leaf area and crop load. Aust. J. Grape Wine Res. 6, 40-45.

Petrie, P.R., Trought, M.C.T. & Howell, G.S., 2000b. Fruit composition and ripening of Pinot Noir (*Vitis vinifera* L.) in relation to leaf area. Aust. J. Grape Wine Res. 6, 46-51.

Poni, S., Intrieri, C. & Silvestroni, O., 1994. Interactions of leaf age, fruiting, and exogenous cytokinins in Sangiovese grapevines under non-irrigated conditions. I. Gas exchange. Am. J. Enol. Vitic.45, 71-78.

Poni, S., Magnanini, E. & Bernizzoni, F. 2003. Degree of correlation between total light interception and whole-canopy net CO_2 exchange rate in two grapevine growth systems. Aust. J. Grape Wine Res. 9, 2-11.

Quinlan, J.D., 1969. Mobilization of ^{14}C in the spring following autumn assimilation of $^{14}CO_2$ by an apple rootstock. J. Hort. Sci. 44, 107-110.

Rabe, E., 1990. Stress physiology: the functional significance of the accumulation of nitrogen-containing compounds. J. Hortic. Sci. 65, 231-243.

Redl, H., 1984. Der Einfluss der Erziehungshöhe auf das Blattwasserpotential bei der Rebsorte Grüner Veltliner. Mitt. Klosterneuburg 34, 47-50.

Reynolds, A.G., 1988. Response of Okanagan Riesling vines to training system and simulated mechanical pruning. Am. J. Enol. Vitic. 39, 205-212.

Reynolds, A.G., 2006. Impact of trellis/training systems and cultural practices on production efficiency, fruit composition, and vine balance. Associazione Wine Community. pp. 1-21.

Reynolds, A. G. & Van den Heuvel, J. E., 2009. Influence of grapevine training systems on vine growth and fruit composition: A review. Am. J. Enol. Vitic. 60, 251- 268.

Reynolds, A.G. & Wardle, D.A., 1993. Yield component path analysis of Okanagan Riesling vines conventionally pruned or subjected to simulated mechanical pruning. Am. J. Enol. Vitic.44, 173-179.

Reynolds, A.G., Wardle, D.A. & Naylor, A.P., 1995. Impact of training system and vine spacing on vine performance and berry composition of Chancellor. Am. J. Enol. Vitic. 46, 88-97.

Reynolds, A.G., Wardle, D.A. & Naylor. A.P., 1996. Impact of training system, vine spacing, and basal leaf removal on Riesling. Vine performance, berry composition, canopy microclimate, and vineyard labor requirements. Am. J. Enol. Vitic. 47, 63-76.

Reynolds, A.G., Wardle, D.A., Cliff, M.A. & King, M., 2004. Impact of training system and vine spacing on vine performance, berry composition, and wine sensory attributes of Seyval and Chancellor. Am. J. Enol. Vitic. 55, 84-95.

Rogiers, S.Y., Holzapfel, B.P. & Hardie, W.J., 2011. Soil temperature moderates grapevine carbohydrate reserves after bud-break and conditions fruit set responses to photoassimilatory stress. Functional Plant Biology 38, 899-909.

Rogiers, S.Y. & Clarke, S.J., 2013. Vegetative growth and cluster development in Shiraz grapevines subjected to partial root-zone cooling. AoB PLANTS 5: plt036; doi:10.1093/aobpla/plt036. Epub 2013 Oct 24.

Sánchez, L.A. & Dokoozlian, N.K., 2005. Bud microclimate and fruitfulness in *Vitis vinifera* L. Am. J. Enol. Vitic. 56, 319-329.

Schultz, H.R., 2003. Differences in hydraulic architecture account for near-isohydric and anisohydric behaviour of two field-grown *Vitis vinifera* L. cultivars during drought. Plant, Cell & Environ. 26, 1393-1405.

Schultz, H.R. & Matthews, M.A., 1993. Growth, osmotic adjustment and cell - wall mechanics of expanding grape leaves during water deficits. Crop Sci. 33, 287-294.

Schultz, H.R. & Matthews, M.A., 1997. High vapour pressure deficit exacerbates xylem cavitation and photoinhibition in shadegrown Piper auritum H.B. & K. during prolonged sunflecks. I. Dynamics of plant water relations. Oecologia 110, 312-319.

Schultz, H.R., Pieri, P., Poni, S. & Lebon, E., 2009. The eco-physiology of grapevine canopy systems - learning from models. In: Anon. Recent advances in grapevine canopy management symposium, 16 July 2009, Davis, U.S.A. pp. 7-12.

Shaulis, N.J., 1950. Cultural practices for New York vineyards. Cornell Extension Bulletin 805.

Shaulis, N.J., 1982. Responses of grapevines and grapes to spacing of and within canopies. In: Webb, A.D. (ed.) Proc. Grape and Wine Centennial Symposium, 18-21 June 1980, Davis, U.S.A. pp. 353-361.

Shaulis, N.J. & Oberle, G.D., 1948. Some effects of pruning severity and training on Fredonia and Concord grapes. Proc. Am. Soc. Hort. Sci. 51, 263-270.

Shaulis, N., Amberg, H. & Crowe, D., 1966. Response of Concord grapes to light, exposure and Geneva double curtain training. Proc. Am. Soc. Hort. Sci. 89, 268-280.

Shaulis, N.J. & May, P., 1971. Response of ‘Sultana’ vines to training on a divided canopy and to shoot crowding. Am. J. Enol. Vitic. 22, 215-222.

Shaulis, N.J. & Smart, R.E., 1974. Grapevine canopies: management, microclimate and yield responses. In: insert editor/s. (ed). Proc. XIX International Horticultural Congress (Volume II),1974, Warsaw, Poland.pp. 254-264.

Shaulis, N.J., Pollock, J., Crowe, D.E. & Shepardson, E.S., 1975. Mechanical pruning of grapevines: progress 1968-1972. Proc. New York State Hort. Sci. 118, 61-69.

Skinkis, P.A. & Vance, A.J., 2013. Understanding vine balance: An important concept in vineyard management. Oregon State University. EM9068. pp. 1-12.

Smart, R.E., 1973. Sunlight interception by vineyards. Am. J. Enol. Vitic. 24, 141-147.

Smart, R.E., 1982. Vine manipulation to improve wine grape quality. In: Anon (eds) Proc. University of California, Davis, Grape and Wine Centennial Symposium. Davis, California. University of California. pp. 362-375.

Smart, R.E., 1984. Canopy microclimates and effects on wine quality. In: Anon. (eds). Proc. of the 5th Australian Wine Industry Technical Conference, Perth, WA, Australia. Aust. Wine Research Institute. pp. 113-132.

Smart, R.E., 1985. Principles of grapevine canopy microclimate manipulation with implications for yield and quality. A review. Am. J. Enol. Vitic., 36, 230-239.

Smart, R.E., 1987. Canopy management to improve yield, fruit composition and vineyard mechanisation. A review. In: T.H. Lee (ed.), Proc. 6th Aust. Wine Ind. Tech. Conf., 14-17 July 1986, Adelaide, Australia. 205-211.

Smart, R.E., 1991. Canopy management developments in Australia and New Zealand. Aust. Grapegrow. Winem. 4, 101 - 104.

Smart, R.E., 1992. Canopy management. In: Coombe, B & Dry, P. (eds.). Viticulture, Vol. 2. Practices. Winetitles, Adelaide. pp. 85-103.

Smart, R.E., 1993. Two golden rules of viticulture. Practical Winery and Vineyard, September/October, 42-44.

Smart, R.E., Kyloh, S.R. & Brien, C., 1979. Roseworthy experiences with mechanical pruning. In: Smart, R.E. &. Kyloh, S.R. (eds.). Workshop Proc. Mechanical Pruning of Grapevines Roseworthy Agric. College, Insert place, Adelaide, Australia. pp. 14-17.

Smart, R.E., Shaulis, N.J. & Lemon, E.R., 1982. The effect of Concord vineyard microclimate on yield II. The interrelations between microclimate and yield expression. Am. J. Enol. Vitic. 33, 109-116.

Smart, R.E., Robinson, J.B., Due, G.R. & Brien, C.J., 1985. Canopy microclimate modification for the cultivar Shiraz. I. Definition of canopy microclimate. Vitis 24, 17-31.

Smart, R.E. & Smith, S.M., 1988. Canopy management: identifying the problems and practical solutions. In: Anon. (ed). Proc. 2nd International Cool Climate Viticulture and Oenology Symposium, Auckland, N.Z. pp. 109-115.

Smart, R.E., Dick, J.K. & Gravett, I.M., 1989. Shoot devigouration by natural means. Proc. 7th Aust. Wine Ind. Tech. Conf., Adelaide, Australia. pp. 58-65.

Smart, R.E. Dick, J.K., Gravett, I.M. & Fisher, B.M., 1990. Canopy management to improve grape yield and wine quality - Principles and practices. S. Afr. J. Enol. Vitic. 11, 3-17.

Smart, R.E. & Robinson, M., 1991.Sunlight into Wine. A Handbook for Wine grape Canopy Management. Winetitles, Adelaide, Australia.

Srinivasan, C. & Mullins, M.G., 1981. Physiology of flowering in the grapevine - a review. Am. J. Enol. Vitic. 32, 47-63.

Stolk, R.A., 2014. The effect of irrigation and canopy management on selected vegetative growth and reproductive parameters of *Vitis vinifera* L. cv. Shiraz in the Breede River Valley. MSc thesis, Stellenbosch University, Private Bag X1, Matieland (Stellenbosch) 7602, South Africa.

Strever, A.E., 2013. Functioning of grapevine canopies with regards to water deficits/ water use. In: Viticulture 322. Department of Viticulture and Oenology, University of Stellenbosch, Pribat bag etc.

Swanepoel, J.J. & Archer, E., 1988. The ontogeny and development of *Vitis vinifera* L. cv. Chenin blanc inflorescence in relation to phenological stages. Vitis 27, 133-141.

Tassie, E. & Freeman, B.M., 1992. Pruning. In: Coombe, B.G. & Dry, P.R. (eds). Viticulture. Vol. 2. Practices. Winetitles, Adelaide. pp. 66-84.

Thomas, R.M., 2006. Grapevine fruitfulness. Final report to Grape and Wine Research and Development Corporation (Australia). Cooperative Research Centre for Viticulture, Australia. pp. a-b.

Thomas, T.R., Shacke, I.K.A. & Matthews, M.A., 2006. Direct in-situ measurement of cell turgor in grape (*Vitis vinifera* L.) berries during development and in response to plant water deficits. Plant Cell Environ. 29, 993-1001.

Upshall, W.H. & Haarlem, J.R., 1934. Yield and quality of fruit from strongly vegetative Concord grapevines. Sci. Agric. 14, 438-440.

Van Leeuwen, C. & Seguin, G., 1994. Incidences de l'alimentation en eau de la vigne, appreciee par l'etat hydrique du feuillage, sur le developpement de l'appariel vegetatif et la maturation du raisin. J. Int. Sci. Vigne Vin.28, 81-110.

Van Schalkwyk, D. & De Villiers, F.S., 2001. The influence of production levels and bud load on the quality of wine and wine grape cultivars in the Robertson area: Sauvignon Blanc. Wynboer Technical.

Van Zyl, J.L., 1984. Interrelationships among soil water regime, irrigation and water stress in the grapevine (*Vitis vinifera* L.). Dissertation, Stellenbosch University, Private Bag X1, Matieland (Stellenbosch) 7602, South Africa.Van Zyl, J.L. & Van Huyssteen, L., 1980. Comparative studies on wine grapes on different trellising systems: II. Microclimatic studies, grape composition, and wine quality. S. Afr. J. Enol. Vitic. 1, 15-25.

Van Zyl, J.L., 1988. The grapevine root and its environment. Van Zyl, J.L. (comp.). Tech. Comm. 215. Dept. Agric. Develop., Pretoria, RSA.

Van Zyl, J.L. & Van Huyssteen, L., 1980. Comparative studieson wine grapes on different trellising systems: I. Consumptivewater use. S. Afr. J. Enol. Vitic.1,7-14.

Vasconcelos, M.C., Greven, M., Winefield, C.S., Trought, M.C.T. & Raw, V., 2009. The flowering process of *Vitis vinifera*: A review. Am. J. Enol. Vitic. 60 , 411-434.

Wang, Z.P., Deloire, A., Carbonneau, A., Federspiel, B. & Lopez, F., 2003. Anin vivo experimental system to study sugar phloem unloading in ripening grapeberries during water deficiency stress. Ann. Bot. 92, 523-528.

Waring, R.H. & Cleary, B.D., 1976. Plant moisture stress: evaluation by pressure bomb. Science 155, 1248-1254.

Weaver, R.J. & Kasimatis, A.N., 1975. Effect of trellis height with and without crossarms on yield of Thompson Seedless grapes. J. Am. Soc. Hort. Sci. 100, 252-253.

Williams, L.E., 2000. Grapevine water relations. In: Christensen, L.P. (d). Raisin production manual. ANR Publications. Publication no 3393. pp. 121-126.

Williams, L.E. & Matthews, M.A., 1990. Grapevine. In: Stewart B.A. and Nielsen D.R. (eds). Irrigation of agricultural crops. Agronomy monograph No. 30. Madison: ASA-CSSA-SSSA. 1, 19-55.

Williams, L.E. & Ayars, J.E., 2005. Grapevine water use and the crop coefficient are linear functions of the shaded area measured beneath the canopy. Agric. For. Meteorol. 132, 201-211.

Wilmer, C. & Fricker, M., 1996. Stomata. Volume 2 of Topics in plant functional biology. Springer Science & Business Media.

Winkler, A.J., 1934. Pruning vinifera grapevines. Calif. Agric. Extension Serv. Circ. 89, 1-68.

Winkler, A.J., Cook, J.A., Kliewer, W.M. & Lider, L.A., 1974. General viticulture. University of California Press, Berkley, U.S.A.

Wolfe, D. & Brown, G.R., 1995. Influence over a ten-year period of training systems on yield and fruitfulness on table grape cultivars. Fruit Var. J. 49, 79-81.

Yang, Y.S. & Hori, Y., 1979. Studies on the translocation of accumulated assimilates in 'Delaware' grapevines. III. Early growth of new shoots as dependent on the current year reserves. Tohuku J. Agric. Res. 31, 120-129.

Yang, Y.S., Hori, Y. & Ogata, R., 1980. Studies on the translocation of accumulated assimilates in 'Delaware' grapevines. II. Retranslocation of assimilates accumulated during the previous growing season. Tohuku J. Agric. Res. 31, 109-119.

Zabadal, T.J. & Dittmer, T.W., 1998. Vine management systems affect yield, fruit quality, cluster compactness, and fruit rot of Chardonnay grape. Hort. Science 33, 806-809.

Zeeman, A. S., 1981. Oplei: In: Burger, J. & Deist, J. (eds). Wingerdbou in Suid- Afrika. ARC Infruitec-Nietvoorbij, Private Bag X5026, 7599 Stellenbosch, South Africa. pp. 185-201.

Zeeman, A. S. & Archer, E., 1981. Stokontwikkeling, wintersnoei en somerbehandeling. In: Burger, J. & Deist, J. (eds). Wingerdbou in Suid- Afrika. ARC Infruitec- Nietvoorbij, Private Bag X5026, 7599 Stellenbosch, South Africa. pp. 202-233.

Chapter 3

RESEARCH RESULTS

OPTIMISING PRODUCTIVITY IN VINEYARDS AND POTENTIAL EFFECTS ON GRAPE AND WINE COMPOSITION FOR A SPECIFIC PRODUCTION GOAL

CHAPTER 3: INTERACTIVE EFFECTS OF GROWTH MANIPULATION IN GRAPEVINE (*VITISVINIFERA* L.) CV. SHIRAZ.

3.1 Introduction

Grape producers are pressured to meet consumer requirements to produce grapes with desired flavour and cultivar characteristics for a specific wine style. There is a perception that low yielding grapevines tend to produce higher quality wines. The fact of the matter is that the producer still needs to survive financially and although high quality wines may occur with low yielding grapevines, the quantity of grapes does not necessarily meet the production costs. Therefore, it is essential to maximise grapevine productivity without negatively affecting grape quality (Keller *et al*., 2008). Reaching equilibrium between these objectives requires thorough knowledge regarding yield management, grapevine balance and financial returns (Preszler *et al*., 2013). It is however, not always true that only low yielding grapevines have favourable grapevine balance. Adequate grapevine balance, whether on high yielding or low yielding grapevines, should consist of sufficient and efficient vegetative growth and functioning (including roots). This is required to sustain yield, without exceeding the amount of grapes and increasing canopy density. Increased canopy density may affect ripening unfavourably, decrease bud fertility and consequently grapevine sustainability (Smart & Robinson, 1991; Howell, 2001). The same is true with regards to exceeding the amount of grapes in relation to vegetative growth.

Increasing yield of grapevines is accompanied by changes within the grapevine. Trellising-, training- and pruning systems are common viticultural practices altering grapevine growth, yield, canopy microclimate and consequently grape- and wine composition (Smart, 1985). These practices all have an effect on the reproductive to vegetative ratio and the crop load (Naor *et al*., 2002). Grapevine balance alteration can in return change assimilate partitioning, accumulation and utilisation in the areas where grapes are produced (Hunter, 2000). It is crucial to have knowledge to what extent these changes occur to avoid disruption to balances in other parts of the grapevine.

Various studies have stated that crop load can be expressed either as the equivalent of the yield to pruning cane mass ratio (Fisher *et al*., 1977; Bravdo *et al*., 1984, 1985a, 1985b; Jackson & Lombard, 1993) or the yield per unit leaf area (May *et al*., 1969; Kliewer, 1970; Kliewer & Antcliff, 1970; Kliewer & Weaver, 1971; Kaps & Cahoon, 1992). The first attempt to describe the levels of grapevine balance, with reference to the ratio between fruit to wood, was performed by M. L. Ravaz (Ravaz, 1911). Partridge (1925) referred yield and pruning mass as “reproductive yield and vegetative yield” and suggested that a calculation can be made to determine grapevine balance by weighing pruned canes of one year which provides an estimation of grapevine growth capacity and the capability to optimally ripen a particular crop size in the next year. Patridge called it the “Growth-yield relationship”. He noted that grapevine balance can also be obtained by other factors than the pruning level such as applying a suitable training system. In some cases, canopy division is required to increase pruning level, resulting in vigour regulation as well as providing an optimal light environment by means of shoot positioning. Currently, the ratio between yield and cane mass (Y/CM) is still known as a good indicator for grapevine balance (Ravaz, 1911; Smart, 1985; Smart & Robinson, 1991; Kliewer & Dokoozlian, 2000).

A more complex model was developed by Carbonneau (1997) which incorporates grapevine reserve status. According to this model, the measurement of cane mass is related to the available reserves in the grapevine and can provide an indication of the growth expected in the following season. In this regard, exposed leaf area is a good descriptor for canopy structure (Carbonneau, 1997). This can be used as the ratio of exposed leaf area to fruit mass where information about growth, yield and quality is required for crop load calculation. The ratio of exposed leaves to non-exposed leaves also influences the leaf area to yield threshold (Dokoozlian & Kliewer, 1995), and must be taken into account with the determination of effective leaf area.

According to Smart (1985), a good correlation between cane mass and leaf area exists and can thus be a practical indicator of assimilate availability. A number of studies reported that yield and cane mass as well as leaf area to fruit mass ratios are highly correlated with each other and concluded that, as long as this correlation is present, crop load can serve as a sign of grapevine balance (Kliewer & Weaver, 1971; Kliewer & Dokoozlian, 2000; Naor *et al*., 2002).

It is clear that grapevine balance determination makes use of reproductive and vegetative growth parameters. Reproductive growth refers to everything concerning fruit production referred to as yield components, affecting crop size. Vegetative growth refers to the organs that provide the energy to produce the fruit, affecting vine size. Grapevine growth can be divided into above and underground growth, the canopy growth and root growth respectively (Iland *et al*., 2011). According to Smart and Robinson (1991), a balance exists between canopy growth and root growth, as well as canopy growth and fruit growth. Healthy and large root systems are known to produce extensive shoot systems. If the shoot growth is enlarged the root system capacity needs adapt to support the enlarged above ground growth with the reserves stored from the previous season. In some cases this conversion can lead to decreased canopy growth due to insufficient amount of reserves. Canopy growth can be determined with cane mass measurements as well as leaf area measurements; however no easy way exists to determine root growth (Iland *et al*., 2011).The alteration of root size and root distribution is not easily measurable regarding grapevine balance. However, Smart (2001) suggested the use of pruning mass per vine or pruning mass per meter of row, where a poor root system can be characterized by values <0.5 kg per meter row and a strong root system by >1.0 kg per meter row.

The environment, in which the grapevine grows, with reference to the soil (*e.g*. soil fertility, soil water holding capacity, drainage) climate (*e.g*. sunlight hours, temperature range, wind, humidity, rainfall) and topography (*e.g*. altitude, slope aspect), is also an important concept of grapevine balance (Hunter, 2001; Chien, 2009). Improved grapevine growth uniformity may be obtained with better buffering of environmental and physiological stress conditions which can occur if viticultural practices (*e.g.* trellising, training, pruning) are properly executed (Hunter, 2001). When the grapevine does not function uniformly it makes it difficult to predict the behaviour of the grapevine within its specific environment and may lead to undesirable grape and wine composition. Therefore both the environment and cultivation practices affect grapevine vegetative and reproductive balances, canopy microclimate in terms of bunch sunlight exposure, grape ripening and grape and wine quality (Hunter, 2001).

The objective of this study was to assess the interactive effects of grapevine growth manipulation by means of alternative trellis-, training-, and pruning systems on micro-climate, shoot characteristics, grapevine balance (pruning mass, harvest parameters, yield components) and water status and determine how these changes could affect resulting wine composition**.**

3.2 Materials and methods

3.2.1 Experiment vineyard, layout and treatments

This study was carried out in a twelve-year-old Shiraz/101-14 *Mgt* vineyard situated at the Welgevallen Experiment farm Stellenbosch University, South Africa (33 56’S, 18 52’E, 157 m mean height above sea level) during the 2012/13 and 2013/14 growing seasons. Stellenbosch falls within the coastal wine grape region of the Western Cape which is characterised by a Mediterranean climate with long, dry summers. Based on the growing degree days (GDD) from September until March (Winkler, 1962), the specific locality is in climatic region III (Le Roux, 1974). More details on the vineyard are supplied in Table 3.

Three training and trellising treatments were monitored with regards to grapevine microclimate, vegetative- and reproductive growth, and yield components. The compensation reaction of the grapevine was assessed through monitoring shoot growth, leaf area and -age, bunch- and canopy microclimate, plant water status (predawn LWP) and yield components. Finally, sensory evaluation was performed on the wines produced from the grapes harvested from each treatment. Canopy light conditions as well as morphological and physiological measurements were conducted.

The design of the experiment consisted of three different training systems namely the double split cordon gable system, 7-wire vertical shoot positioned (VSP) hedge trellis system and a sprawling training system (Figure 4-6). The vines were split cordon trained at a height of 155 cm from ground level. In the 2012/13 season, the sprawling system was sub-divided into two pruning systems thereby obtaining a double sprawling system and the normal single sprawling system. The aim of the sprawling pruning system in the 2013/14 growing season was to determine whether an increase in bud load would lead to either an increase in yield, a decrease in vegetative growth or a decrease in yield due to reduced bud fertility, the latter measurable in the 2015 harvest (*i.e.* if increased yield is proportional to increased bud load). The pruning methods applied are described in Table 4. Regarding the second season of the trial, *i.e.* the 2013/14 season, only one sprawling system was applied namely the single/normal sprawling system. The number of

VSP grapevines (control) was reduced and sprawling grapevines increased (thus VSP vines from the 2012/13 season were converted to sprawling grapevines in the 2013/14 season) during the 2013/14 season for winemaking purposes (Figure 89 & Figure 90 in the Addendum).

Trellis/training modification treatments were laid out as indicated in Figure 89 and Figure 90 in the Addendum. For each particular treatment, there were three indicator grapevines where all bunches were removed during flowering to evaluate the shoot growth of the grapevine without the influence of bunch formation. Plastochron measurements were used to indicate the shoot growth of the indicator grapevines.

Tinytag® temperature/relative humidity sensors housed in radiation shields were placed above the canopy four rows east from the measured grapevines as well as Tinytag® Talks located within the bunch zone of each treatment (Figure 91 in the Addendum). Two neutron probe measurement sites were located in the area of each treatment (Figure 89 & Figure 90 in the Addendum).

Grapevine phenology determined during the 2012/13 and 2013/14 seasons for the different treatments is given in Table 26 to Table 31 in the Addendum. Codes describing the different treatments are provided in Table 5.

It would have been ideal to present a randomised block design but due to the difficulty replicating the gable trellis between other trellis systems, this could not be implemented.

Table 3 Characteristics of the experiment vineyard located on the Welgevallen Experiment Farm in Stellenbosch.

Descriptor	**Stellenbosch**
Cultivar	Shiraz
Clone	SD9C
Rootstock	101-14 *Mgt* (*Vitis riparia x Vitis rupestris*)
Year established	2000
Row orientation	North-South
Terrain	Flat
Grapevine spacing	2.7 x 1.5 m
Trellis/training system	7-wire hedge VSP trellis system with three sets of moveable canopy wires Double split cordon gable trellis system Sprawling training system
Irrigation system	Pressure compensated drip system

Table 4 Pruning method applications for the different treatments during the 2012/13 and 2013/14 growing season.

Treatment	Method
*VSP (both seasons)	• Standard (two bud spurs). • Serves as a control.
*Gable Season one (2012/13)	• Standard (two bud spurs). • Double split cordon (double amount of spurs per grapevine, same amount per meter canopy row as control).
*Gable Season two (2013/14)	• Short and weak shoots pruned as one bud bearer. • Motivation- strong winds in Nov/Dec 2012 lead to poor shoot growth and probably not enough reserves stored to support the amount of grapes and compensate for the loss of shoot growth.
Sprawling Season one (2012/2013)	• Single sprawling - pruned with standard method (two bud spurs). • Double sprawling- dual two bud spurs on the same spur position ("buck horn system"). • Only one wire to support canopy.
Sprawling Season two (2013/2014)	• Simulate mechanical pruning- average length of 15-20 cm spurs, not a specific number of buds (Figure 4). • Motivation- small difference between VSP and sprawling treatments in the 2012/13 season. • Shoots heavily topped at berry pea size. • Canopy supported by only one wire. • All shoots growing on the cordon was kept.

*Renewal was applied and shoots growing on the cordon were removed.

Figure 4 Simulated mechanical pruning on the sprawling training system during the 2013/14 season in experimental vineyard.

Figure 5 An example illustrating the difference between the sprawling and VSP canopies. Photo was taken prior to harvest in the 2013/14 season.

Figure 6 Examples illustrating the gable trellis system during season 2013/14. Photograph taken prior to harvest in the 2013/14 season.

Table 5 Codes describing the different trellis/training treatments applied to Shiraz/101-14 Mgt grapevines during the 2012/13 and 2013/14 growing seasons.

Treatment	**Code**
Gable	GA
VSP	VSP
Single sprawl	SS
Double sprawl	DS
Sprawl	S
Gable indicator	GAI
VSP indicator	VSPI
Single sprawl indicator	SSI
Double sprawl indicator	DSI
Sprawl indicator	SI

3.2.2 Climate measurements

3.2.2.1 Macroclimate

Temperature data was obtained from a weather station located approximately 1.5 km from the experimental vineyard (Heritage Garden, Infruitec, Stellenbosch, Lat -33.92714; Long 18.87226, alt 112 m, courtesy of the Institute for Soil, Climate and Water of the Agricultural Research Council in Pretoria. Heat units/ thermal time (TT) were expressed in degree days (°C.day^{-1}) (Schultz, 1992) and was calculated daily from budburst using Equation 2.8. The base temperature represented a theoretical lower limit for growth of the grapevine which was accepted to be 10°C (Strever, 2012). The accumulation of heat units commenced at phenological stage EL5 according to the Eichhorn-Lorenz system, as adapted by Coombe (1995). This stage, hereafter referred to as budburst, corresponded to the stage when 50% of the shoots were 2 cm long, their first leaves had unfolded and were a length of approximately 20 mm. After this stage, leaf and shoot measurements could be conducted easily.

Equation 2.8 Thermal time calculation

$$\boldsymbol{TT = \sum_{i=1}^{n} \frac{(Tmax, i + Tmin, i)}{2} - Tb}$$

Where: TT - Thermal time/ heat units

T max - maximum temperatures

T min – minimum temperatures

T_b - base temperature

3.2.2.2 Mesoclimate measurements

A temperature/relative humidity sensor (Tinytag® model TGP-4500, Gemini Data Loggers, West Sussex, UK) housed in a radiation shield (Tinytag® model LS-1, Gemini Data Loggers, West Sussex, UK) was placed above the canopy (four rows east from the measured grapevines) and logged data at15 minute intervals. The sensor's temperature measurement range is between -25°C and +85°C, with a relative humidity measurement range of between 0% and 100%.

3.2.2.3 Microclimate measurements

A temperature sensor (Tinytag® Talk 2 model TK-4023, Gemini Data Loggers, West Sussex, UK) was placed near a representative exposed bunch in the bunch zone of each treatment during season 2013/14 (approximate positions indicated in Figure 91in the Addendum). Due to technical difficulties, logging only commenced (intervals of 15 minutes) from 19/12/2013 until harvest.

3.2.3 Soil and plant water status measurements

Soil water content was measured at three depths, namely 0-30 cm, 30-60 cm and 60-90cm by means of the neutron scattering technique using a neutron probe (HYDROPROBE 503DR, CPN®, California). Measurements were taken weekly throughout the growing season at the positions indicated in Figure 89 and Figure 90 given in the Addendum.

A Scholander pressure bomb was used to measure the pre-dawn leaf water potential (Ψ_{PD}) of all the treatments (Scholander *et al.*, 1965) from mid-December (berry pea size) in both seasons. Measurements were taken weekly, and commenced at 03:00. Six expanded, primary shoot leaves were quantified for each treatment and placed into a pressure chamber. A combination of water constraint classes obtained from Carbonneau (1998) and Deloire *et al*. (2004) were used and adapted (Strever, 2012) to classify the readings obtained from the pressure bomb (Table 6).

Table 6 Predawn leaf water potential classification values (adapted by Strever, 2012).

Class	Ψ_{PD} range (-KPa)	Plant water status classification
1	0-200	Water stress absent
2	200-400	Mild to moderate water stress
3	400-600	Moderate to severe water stress
4	600-900	Severe water stress
5	900+	Critical water stress

3.2.4 Light measurements

Measurements of canopy light interception were done at ripening during the 2012/13 season, and at berry pea size, véraison and ripening during the 2013/14 growing season. The photosynthetic active radiation (PAR) measurements were accompanied by red to far-red ratio (R:FR) and sun fleck measurements. In the 2013/1 season, all three measurements were performed on the same day.

3.2.4.1 Photosynthetic active radiation (PAR)

An AccuPAR LP-80 Ceptometer (Decagon Devices, Inc., Pullman, WA, USA), which measured in units of $\mu E.m^{-2}.s^{-1}$ (expressed as a ratio of ambient radiation), was used to evaluate the difference in sunlight interception in the canopies of each treatment.

The PAR measurements were performed in the morning at 10:00; midday at 14:00 and in the afternoon at 16:00. Ambient measurements were performed in the North, South, East and West directions, followed by canopy bunch zone measurements for each treatment. During the 2012/13 season, seven grapevines (replicates) were measured per treatment, whereas in the 2013/14 season, five replicates were measured for each treatment.

3.2.4.2 Red/Far-Red light

The red to far-red ratio sensor (Skye instruments, Powys, UK) were set to measure the ratio of red to far red light (R:FR; 660:730nm), in the same positions as for the PAR measurements (see paragraph 3.2.4.1). The sensor was placed at three different positions namely the left cordon, the split of the cordon and the right cordon. These measurements were only performed in the 2013/14 growing season.

3.2.4.3 Sunfleck measurements

Sunflecks were quantified in the 2013/14 season by means of the AccuPAR LP-80 Ceptometer. The ceptometer was placed on the soil surface at the same grapevines which were used for the measurements in paragraph 3.2.4.1 and 3.2.4.2. Although measurements were taken at the same time as the above mentioned measurements, measurements were taken on the opposite sides of the canopy. At 10:00, measurements were done on the western side, and at 16:00 measurements were done on the eastern side of the canopy. The reason for this was at those particular times, the canopy shadow would be spread out on the soil surface and the sunflecks clearly visible.

3.2.5 Stomatal conductance ($mmol.m^{-2}.s^{-1}$) and chlorophyll content index (CCI) measurements

A SC-1 leaf porometer (SC-1 Leaf Porometer, Decagon devices, Inc., Pullman, WA, USA) was used to measure leaf stomatal conductance by measuring the vapour flux from the leaf, through stomata and out into the environment. Measurements occurred on young leaves located in the apical part of the canopy and older leaves (situated at nodes five to seven) exposed to sunlight and shade. An ADC CCM-200 plus chlorophyll content meter (CCM-200 plus, ADC BioScientific Ltd, Hoddesdon, UK) was used to determine the chlorophyll content index (CCI) for the same leaves used to determine the stomatal conductance. The stomatal conductance and CCI measurements consisted of six replicates for each leaf classification (leaf exposure and age). The porometer was placed on the various leaves and the stomatal conductance (mmol.m^{-2}.s^{-1}) and temperature (°C) were noted. These measurements, together with the measuring of CCI, were performed between 11:00 and 14:00 on a clear day and repeated for all the treatments. Measurements commenced during ripening throughout the 2012/13 season and were performed at weekly intervals. Measurements were performed at three phenological stages during the 2013/14 season (berry pea size, véraison and during ripening).

The treatments had different budburst dates during season 2013/14 and the graphs were therefore constructed according date and not days after budburst (DAB) (Table 7).

Table 7 Days after budburst (DAB) corresponding with the stomatal conductance and CCI measurement dates during season 2013/14 for the different treatments.

Date	DAB- Gable& VSP	DAB- Sprawl
11/12/2013	65	72
21/01/2014	106	113
25/02/2014	141	148

3.2.6 Vegetative measurements

3.2.6.1 Pruning

The number of canes and spurs per grapevine were counted and weighed for all the grapevines in every treatment (Figure 92 &

Figure 93 in the Addendum). During the 2013/14 season, the bearing and non-bearing canes of 50% of the grapevines per treatment were counted and weighed for 20 grapevines per treatment. Detailed cane measurements were performed on ten canes per treatment, where cane length and mass, lateral length and mass and nodes per cane were determined.

The fertile cane percentage was determined by counting the number of canes with bunch stems and canes per grapevine at pruning. Approximately 30 to 60 grapevines per treatment were used as reference. This method provides an indication of the percentage of fertile canes. This will then be the determination of variation in fertile canes per grapevine and was executed by counting the bearing and non-bearing canes separately at pruning. This was called the fertile cane percentage and calculated as in Eq. 2.9:

$$Fertile\ cane\ \% = \frac{number\ of\ fruit\ bearing\ canes}{(Total\ number\ of\ canes)} \times 100 \tag{2.9}$$

3.2.6.2 Plastochron index (PI), leaf plastochron index (LPI) and leaf age measurements

Random grapevines were selected in each treatment where two shoots per vine, one on each side of the split cordon, were tagged in the beginning of the season for plastochron measurements. A total of three indicator grapevines (100% bunch removal between flowering and berry set) were used per treatment. In the 2012/13 season, five grapevines were selected for the gable and VSP treatments. Since there were fewer grapevines in the double- and single sprawling treatments, only three grapevines were sampled. In the 2013/14 season, all the treatments contained five marked grapevines. Separate plastochron measurements were performed on the two split cordons of the gable, where one shoot was chosen for each split cordon. Shoot length, amount of nodes from the base of the shoot and the lengths of the main leaf veins (L1) were measured on each tagged shoot. A reference point of 30 mm and 25 mm was used for the 2012/13 and 2013/14 growing season, respectively. The vein length of the first leaf closest to the shoot tips, which was larger than 25 mm/30 mm, was recorded as the Ln value, while the first leaf smaller than the reference point, was recorded as the Ln+1 value. The plastochron measurements were measured every seven to 10 days from the beginning of the season (2012/13) and after budburst measurements (2013/14) up to a constant shoot length (end of vegetative growth). The plastochron index (PI) was calculated using Eq. 2.10, where n is the number of nodes just longer than the chosen reference length, R being the reference length, Ln representing the organ length just longer than the reference and Ln+1 the organ just shorter than the reference length (Hill & Lord, 1990). The LPI can then define the developmental age of each leaf on the shoot measured and was calculated using Equation 2.11, with *i* being the node number of the leaf in question (Strever, 2012).

Leaf age was calculated for the treatments in the 2013/14 season according to the method described by Strever (2012). The slopes (b) of PI relative to DAB were calculated up to when shoot growth ceased. The inverse of the slope (1/b) was multiplied with the LPI per measured shoot for the different treatment measurement dates to obtain the leaf age for a specific leaf position (Table 8). The mean leaf age for the various measured shoots was calculated according to treatment and measurement date.

As the budburst dates of the respective treatments differed during the 2013/14 season, graphs displaying the obtained results were drawn according to date and not days after budburst (DAB). The specific date corresponding to DAB is displayed in Table 8.

.

Equation 2.10 Shoot plastochron index calculation

$$\boxed{PI = n + \frac{\log(Ln) - \log(R)}{\log(Ln) - \log(Ln + 1)}}$$

Equation 2.11 Leaf plastochron index calculation

$$\boxed{LPIi = PI - i}$$

Table 8 Days after budburst (DAB) corresponding with the plastochron and shoot length (cm) measurement dates during the 2013/14 season for the different treatments.

Date	DAB- Gable& VSP	DAB- Sprawl
6/11/2013	30	37
13/11/2013	37	44
20/11/2013	44	51
27/11/2013	51	58
4/12/2013	58	65
11/12/2013	65	72
17/12/2013	71	78
2/01/2014	87	94
8/01/2014	93	100
15/01/2014	100	107
24/01/2014	109	116

3.2.6.3 Destructive shoot measurements

In The 2012/13 growing season, ten shoots were randomly selected for each of the gable and VSP treatments and five shoots for the single sprawling and double sprawling treatments, respectively. Only five shoots were selected for the respective sprawling treatments to make up a total of ten shoots for both these similar treatments. During the 2013/14 growing season, ten shoots were selected in the sprawling treatment. Plastochron measurements were done (mentioned above) on the collected shoots. All the primary leaves on each shoot were removed as close to the petiole as possible. The leaves were numbered from the base of the shoot to the top, starting at node 1. The main vein lengths (L1) from where the petiole ends and leaf begins, to the tip of the leaf for all the numbered leaves were measured. All the laterals and lateral leaves were removed, counted and measured to obtain the total lateral number, total lateral length and total lateral leaves per shoot. The leaf areas of the primary and lateral leaves were determined by using an electronic leaf surface area meter (Delta-T devices Ltd, Cambridge, UK) to obtain the leaf area for each of the numbered primary leaves and the total lateral leaf area. Destructive measurements were performed at three phenological stages during both growing seasons (berry pea size, véraison and during ripening/before harvest).

3.2.7 Reproductive measurements

3.2.7.1 Berry sampling

Berries were sampled prior to the onset of véraison, *i.e.* when the sugar levels in the berries were between 5 and 10 degrees Balling (°B), up to harvest on a weekly basis (refer to Table 26-30 in the Addendum).

The treatments were split into two field replicates, where ripening sampling took place. One hundred berries were collected per replicate, of which 50 were weighed and the volume determined using the water displacement method. Berry mass was determined by weighing the samples with a three decimal digital scale (Precisa, Type. 280-9826, PAG Oerlikon AG, Zurich, Switzerland) and placed into plastic bags in a -80°C freezer for colour and phenolic analysis at a later stage. The other 50 berries were liquidised with a household blender and the clear juice was separated from other berry materials for the determination of ripeness parameters. The juice Balling was measured with a digital pocket refractometer (Atago PAL-1, Tokyo, Japan). Following this, 25 ml of the juice was transferred into a 100 ml marked glass holder using a glass pipette. Thereafter, 25 ml of distilled water was also pipetted into the glass holders so that there was 50 ml of diluted grape juice in each particular holder. The titratable acidity (TA) and pH of samples was determined using an automatic titration device (Metrohm 785 DMP Titrino, Herisau, Switzerland) connected to a bench pH meter (Crison Basic 20 with Crison 5531 PT1000 electrode, Barcelona, Spain).

The treatments displayed different budburst dates during season 2013/14 and the graphs was therefore constructed according date and not days after budburst (DAB) (Table 9).

Table 9 Days after budburst (DAB) corresponding with the ripening measurement dates during season 2013/14 for the different treatments.

Date	DAB-Gable& VSP	DAB-Sprawl
21/1/2014	106	113
30/1/2014	115	122
6/2/2014	122	129
12/2/2014	128	135
21/2/2014	137	144
27/2/2014	143	150
6/3/2014	150	157
13/3/2014	157	164
18/3/2014	162	169
28/3/2014	172	179
4/4/2014	179	186
8/4/2014	183	190

3.2.7.2 Harvest

All bunches from each grapevine in the trial were harvested, counted and weighed, using a three decimal field scale (Viper SW 35 LA, Mettler-Toledo Pte Ltd, Ayer, Singapore), to determine the yield per grapevine (kg) (Figure 92 & Figure 93 in the Addendum) and the average bunch mass per grapevine. Berry sampling (see paragraph 3.2.7.1) were also performed for each treatment on the day of harvest. The harvested grapes for each treatment were microvinified. Harvest dates are given in Table 10.

Table 10 Harvest dates and corresponding days after budburst (DAB) for the treatments during both seasons.

Season	Treatment	Harvest date	DAB
2012/13	Gable	26/3/2012	181
	VSP	25/3/2012	180
	Double sprawl	14/3/2012	169
	Single sprawl		
2014/13	Gable	8/4/2013	183
	Sprawl		190
	VSP	4/4/2013	179

3.2.7.3 *Yield component calculations*

Yield components were calculated using the equations provided in Table 11 for all the treatments using sampling, pruning and harvest data in both seasons.

Table 11 Yield component calculations.

Yield components	Calculation
A - Bud load	$\mathit{Number\ of\ spurs\ per\ grapevine} \times \mathit{expected\ number\ of\ buds\ per\ spur\ (see\ paragraph\ }3.2.1)$
B - Budburst percentage (%)	$\mathit{Number\ of\ canes\ per\ vine\ counted\ at\ pruning} \div \mathit{bud\ load} \times 100$
D - Fertility	$\mathit{Number\ of\ bunches\ per\ vine\ counted\ at\ harvest} \div \mathit{number\ of\ canes\ per\ vine\ counted\ at\ pruning}$
E - Average bunch mass	$\mathit{Yield\ per\ vine\ at\ harvest} \div \mathit{number\ of\ bunches\ per\ vine\ counted\ at\ harvest}$
Average mass per berry at harvest	$\mathit{Fresh\ berry\ mass\ of\ }50\mathit{\ berries\ sampled\ at\ harvest} \div 50$
Estimated number of berries per bunch	$\mathit{Average\ bunch\ mass} \div \mathit{average\ berry\ mass}$

3.2.8 Grapevine balance ratios

Cane mass (determined during pruning) and yield (determined during harvest) was determined on a per vine basis for all the grapevines within the plot layout (Figure 92 & Figure 93 in the Addendum). The yield to cane mass ratio (Y/CM) was determined, as well as the leaf area (data obtained from destructive measurements) to determine a per vine ratio of the leaf area to yield

(LA/Y). An indication of fruit and vegetative growth balance could therefore be provided as well as the incorporation of grapevine balance thresholds as determined in literature (Table 12).

Table 12 Indices used to indicate vine balance (Iland *et al*., 2011).

Index	**Description**	**Optimal value**	**References**
Ravaz index (Y/CM)	Yield per vine (kg)/ cane mass per vine (kg)	<10-12 6-10 7-10 4-10 4-10 5-10	Bravdo *et al*. (1984, 1985) Intrieri & Filipetti (2001) Reynolds (2001) Kliewer & Dokoozlian (2001) Zeeman & Archer (1981) Smart (2001)
Leaf area/ yield ratio (LA/Y)	Total leaf area per vine (cm^2)/ yield per vine (g)	6 -15 10 -15 8 -14 7 -14 10 -12 8 - 20 (single canopy - trellis) 5 - 8 (divided canopy- trellis)	Smart & Robinson (1991) Intrieri & Filipetti (2001) Kliewer & Dokoozlian (2001) Howell (2001) Hunter & Visser (1990a) Kliewer & Dokoozlian (2005) Kliewer & Dokoozlian (2005)

3.2.9 Phenolic measurements

Total red pigments and total phenolics in the berries and wine were analysed using a LKB Biochrom Ultraspec II E UV/Visible Spectrophotometer (LKB Biochrom Ltd, Cambridge, UK). These measurements were conducted for all the treatments in the 2013/14 season.

3.2.9.1 Grapes

Total red pigments and total phenolics were determined by means of the spectrophotometric method described by Iland *et al*. (2000a). The samples were collected from each of the two field replicates of the three treatments (Gable, VSP and sprawl). Each field replicate was further sub-divided into three technical replicates. These measurements were conducted on berries obtained from the harvest of the 2013/14 season. After two months the frozen berry samples (n=50; -80°C) were defrosted, weighed and homogenised using a Ultra-Turrax T25 high speed homogeniser (Janke & Kunkel GmbH & Co, Germany) for three minutes, cleaned and for 30 seconds again at medium speed. The homogenate was mixed. Following this, *ca.* 1 g of each sample was weighed and the mass recorded so that the mass of each sample was known. Thereafter, the sample was transferred into a 15 ml centrifuge tube. Acidified ethanol (50% v/v aqueous ethanol adjusted to pH 2.0) was added to the homogenate and mixed periodically every ten minutes for one hour. After one hour the mixture was centrifuged (Beckman, Model J2-21, Beckman Instruments Inc., Palo Alto, CA, USA) at 10 000 rpm for 10 minutes and 0.5 ml of the extract was pipetted into test tubes where 5 ml of 1M HCL was added and incubated for one hour (dilution step). After the incubation, the absorbance of the diluted HCl extract was measured in a 1 cm cell at 520 nm (anthocyanins) and 280 nm (total phenolics). The final anthocyanin and total phenolic concentrations were determined by various calculations illustrated by Iland *et al*. (2000a). The values obtained from this method were expressed as units per gram berry mass and per berry.

3.2.9.2 Wine

In the 2013/4 growing season, wines were prepared from the harvested grapes of the field replicates of the three treatments. These wines were made at Department of Viticulture and Oenology (DVO) experimental cellar, Stellenbosch University. Wines were only made in the 2013/14 season.

The wines were assessed for colour density, modified colour density, colour hue, modified colour hue, total red pigments and total phenolics according to the methods described in Iland *et al*. (2000b). Wine total acidity, malic acid, lactic acid, pH, volatile acidity, glucose, fructose, ethanol and glycerol were determined using a WineScan FT 120 instrument (FOSS Electric A/S, Hillerod, Denmark).

3.2.10 Sensory evaluation

The aroma and flavour properties of six Shiraz wines from the 2013/14 season (three treatments each consisting of two field replicates) were profiled by means of quantitative descriptive analysis (QDA) (Lawless & Heymann, 1998).

The sensory evaluation was conducted in September 2014 which comprised of a panel consisting of 12 people (age 22-50) who regularly taste wines. The panellists were selected according to availability, interest in wine sensory evaluation and previous experience in wine evaluation. The panel were prompted to familiarise with the product and generate attributes that describe the differences between the set of products. In other words, descriptive terms which captured differences in the wines in terms of aroma (perceived smell) and/or palate attributes (taste/mouth feel) were provided. Reference standards were prepared according to these terms and used during the formal training of the panel. The standards were prepared by physically placing the descriptive attribute, such as raspberries, in a dark bottle. With this, panellists could gain familiarity with the specific attribute.

The panel was trained according to the consensus method (Lawless & Heymann, 1998). They were trained to recognise certain wine attributes after reducing the initial attribute list to achieve a list that described the wines comprehensively and accurately. The panellists gained familiarity with the recognition of the selected attributes and the scoring thereof. Finally, these defined attributes were rated according to intensity on a line scale. Six training sessions of one hour each occurred over the course of three days with two sessions per day accompanied by a 15 minute break in between sessions. No references were provided for the mouth feel and taste attributes as all the panellists had extensive training in that area of wine tasting. Qualitative descriptive analysis training was regarded as complete when the discrimination ability, repeatability, and homogeneity of the panellists' performance were adequate and consensus reached on the range of sensory attributes and scalar value of each attribute (Lawless & Heymann, 1998).

The final sensory tasting sheet included 13 aroma, four flavour and four mouthfeel attributes (Table 13).The final tasting session was performed under temperature-controlled conditions (21°C ± 2°C). The samples consisted of 30 ml each and were presented in tulip-shaped standard clear ISO wine tasting glasses covered by a Petri dish lid (Kimix, South Africa).There were three technical replicates for each experimental wine; therefore 18 wines (sample) were tasted in total. Each sample contained a three-digit code in randomised order according to a balanced block design. A 100 mm unstructured line scale was used to analyse the 18 samples for the 13 respective sensory attributes and four flavour and mouth feel attributes (Table 13). The panellists could refresh their palate with distilled water and unsalted crackers in between samples.

Data from the descriptive analysis was statistically analysed using analysis of variance (ANOVA) to determine which attributes was significantly different. Thereafter, a principle component analysis (PCA) was conducted on the significant attributes to provide a map of these significant attributes (Valera & Ares, 2012).

Table 13 List of attributes defined by tasting panel for the sensory evaluation of six Shiraz wines on 18 September 2014.

	Aroma	**Flavour**	**Mouth feel**
Attributes	Red Berries	Berry Taste	Sweet
	Blackberry	Spicy Taste	Sour
	Blackcurrant	Smokey/ Tarry Taste	Bitter
	Prune	Cooked Vegetable Taste	Astringent
	Black pepper		
	Tea/ Tobacco		
	Bay leaf/ Eucalyptus		
	Jalapeno/ Gherkin		
	Cooked vegetables		
	Dairy		
	Soy sauce		
	Tar/ Smokey		
	Horsey/ Plaster		

3.2.11 Statistical analysis

The aim of this study was to determine various trends of measurements between treatments as well as within treatments rather than a statistical correct study describing significant differences. This is because the experimental layout did not consist of a randomised block design which would have been difficult due to logistic factors such as the presence of different trellis systems.

3.3 Results and discussion

3.3.1 Climate measurements

3.3.1.1 Macroclimate

The mean temperatures during the growing seasons (Figure 7) indicate increasing temperatures up to 80 DAB (15/12/12 and 19/12/13). Thereafter there was a decrease in mean temperatures of approximately 8°C occurred up to 105 DAB (09/01/13 and 13/01/14). Overall, the lowest minimum temperatures occurred in the beginning of the 2012/13 season (Figure 8), and reached 2°C on 18 DAB (14/10/12) and 6 °C on 60 DAB (11/25/12). The overall highest maximum temperatures occurred from 0 to 60 DAB and 140 DAB (17/02/13), reaching over 40°C, during the 2013/14 season (Figure 9).

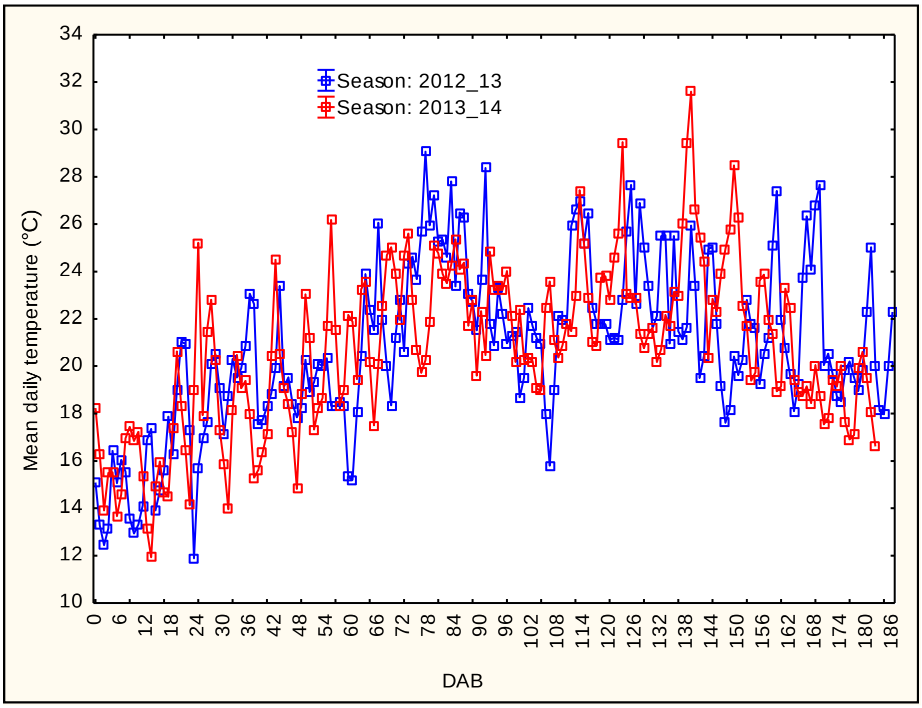


Figure 7 Mean daily temperature relative to date of budburst (DAB) in both seasons from budburst to harvest (end of March).

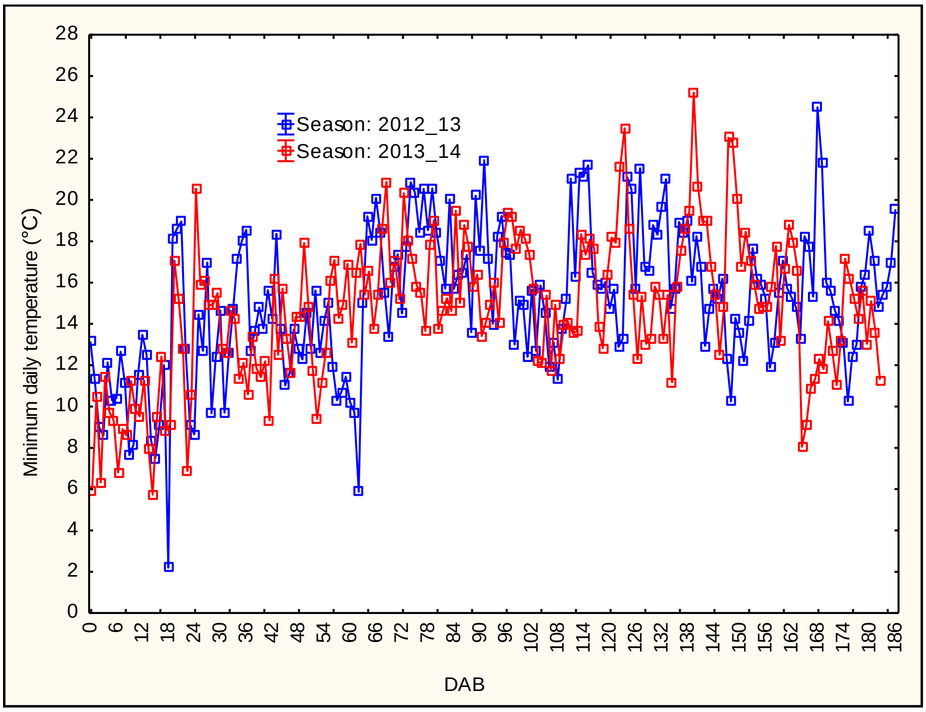


Figure 8 Minimum daily temperature relative to days after budburst (DAB) in both seasons from budburst to harvest (end March).

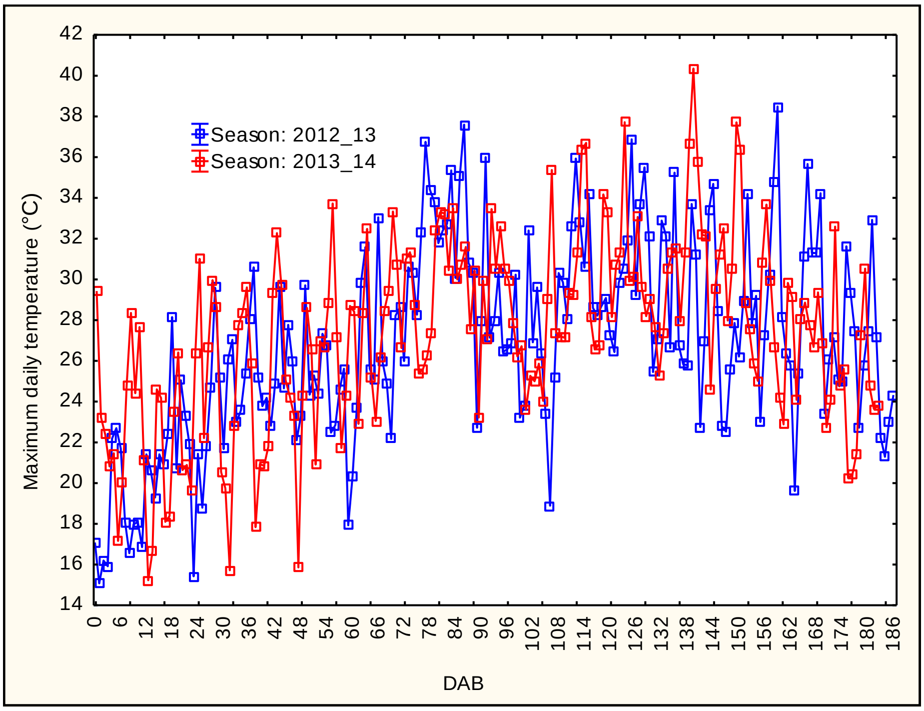


Figure 9 Maximum daily temperature relative to days after budburst (DAB) in both seasons from budburst to harvest (end March).

There are various classification systems which can be used to classify or describe the temperature conditions of grapevine growing areas. The Growing degrees days (GDD) results seem to show similar temperature accumulation for both seasons (Figure 10), although there is a slightly higher accumulation for season 2013/14 around 60 to 80 DAB as well as 150 to 170 DAB. Both seasons reached a maximum GDD of 2000 and can be characterised as an IV region (Table

14) according to the Winkler index which was adapted to suit the Western Cape wine growing regions (Le Roux, 1974). It states that such a region is likely to produce standard quality table wine. It will therefore be interesting to see whether results from the experiment wines made from the different trellis systems will confirm the above statement with regards to sensory wine evaluation. Unfortunately, GDD cannot be compared to the bunch microclimate of the different treatments as data was only obtained from mid-December (19/12/13) and therefore there was no budbreak data. However, the bunch micro-climate for each treatment and mean ambient temperatures were compared, starting from the above mentioned date, and all show similar degree day accumulation, with the GA treatment showing slightly higher values than the rest (Figure 11).

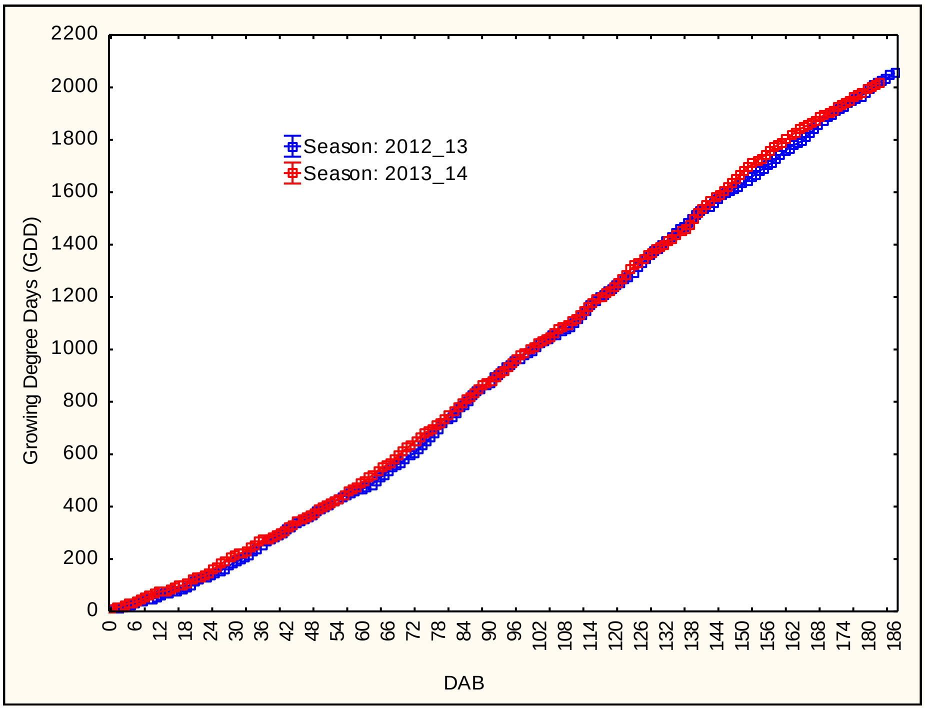


Figure 10 Growing degree days (GDD) relative to days after budburst (DAB) in both seasons from budburst to end of March (2012/13 budburst date four days earlier than season 2013/14).

Table 14 Growing degree days (GDD) climatic classification adapted for the Western Cape wine growing regions (Le Roux, 1974).

Degree Days (°C)	Region	Viticulture potential
<1389	I	Quality red and white wine
1389-1666	II	Good quality red and white table wine
1667-1943	III	Red and white table wine and port
1944-2220	IV	Dessert wine, sherry and standard quality table wine
>2200	V	Dessert wine and brandy

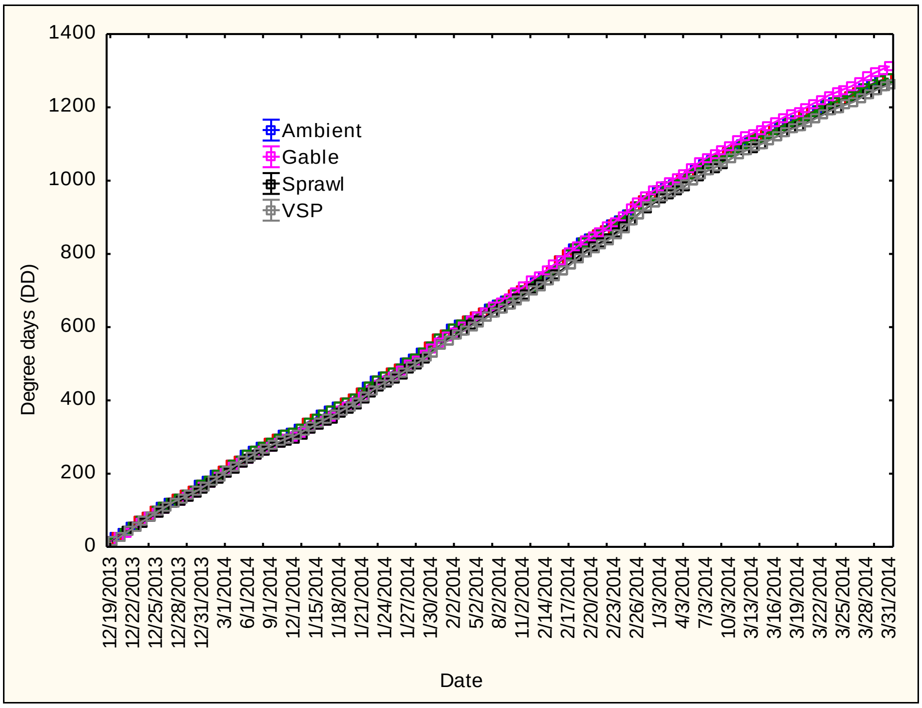


Figure 11Degree days (DD) from 19/12/13 for the bunch microclimate of the treatments and macroclimate (ambient temperature).

During the 2012/13 season many vineyards in Stellenbosch were affected by strong winds (Conrad Schutte, personal communication). The mean wind speed for the different seasons is given in Figure 12and it is clear that stronger winds occurred during the 2012/13 season. These strong winds had a great effect on the GA treatment during November and December 2012 (60-80 DAB) as the wind damaged shoots to such an extent that there was not enough foliage to sustain the amount of grapes. Climatic data confirmed that the strongest winds occurred around that time (Figure 12).

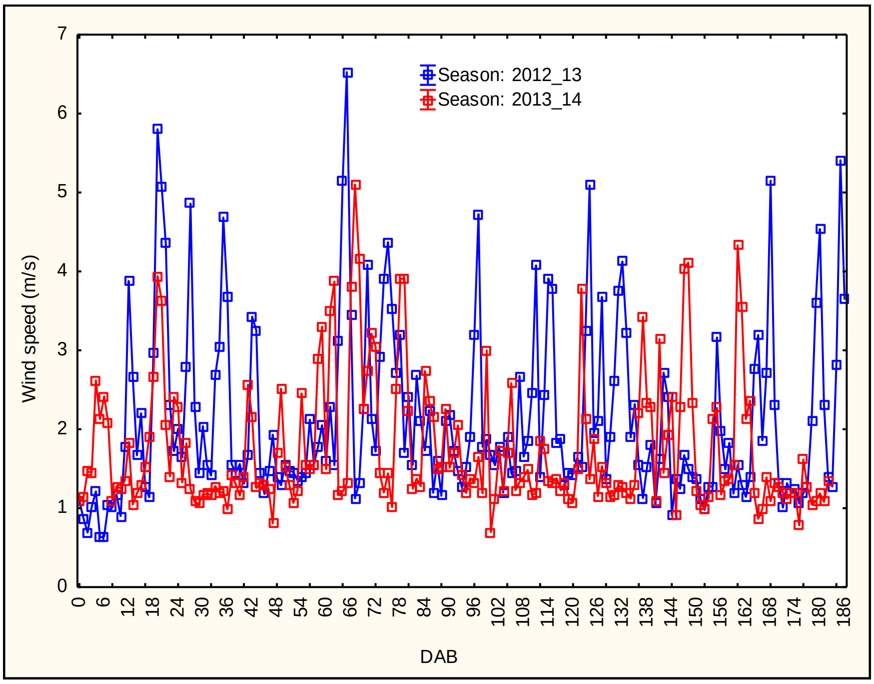


Figure 12 Wind speed relative to days after budburst (DAB) during both seasons.

Rainfall seemed to be similar for both seasons in the winter months (Jun-Aug) before the growing season commenced (Table 15). The total monthly rainfall was higher for the 2013/14 season in comparison to the 2012/13 season when the combined monthly rainfall during winter and the growing season is taken into account (Table 15). Similar monthly rainfall for September and December occurred in the 2012/13 and 2013/14 seasons whereas rainfall was higher in October 2012, February 2013, November 2013, January and March 2014 (Table 15). The high monthly rainfall during October and February in the 2012/13 season were due to very high daily rainfall on 23 DAB (19/10/12) and 136-138 DAB (9-11 Feb'13), respectively (Figure 13). High rainfall in November during the 2013/14 season occurred on 46 to 48 DAB (15-17 Nov'13). The harvest of red grape cultivars was particularly challenging in the 2013/14 season due to rain occurring when the grapes were ready to be harvested. This led to berry sugar concentration fluctuations and grapes struggling to achieve desired ripeness, as well as delayed harvest dates. This is evident from the high rainfall during March (Table 15) or 166 to 182 DAB (Figure 13). Although there was also high rainfall during February 2013, ripening and harvest was not affected to the same extent as in the 2013/14 season. The reasons for this was that high rainfall was only present during three consecutive days in February and during the early stages of ripening, while the rainfall during March in season 2014 occurred every day for 16 consecutive days and in the time of harvest.

Table 15 Mean monthly and total rainfall (mm) measured during the winter months before the growing season and the season itself of 2012/13 and 2013/14.

Season	**Jun (mm)**	**Jul (mm)**	**Aug (mm)**	**Sept (mm)**	**Oct (mm)**	**Nov (mm)**	**Dec (mm)**	**Jan (mm)**	**Feb (mm)**	**Mar (mm)**	**Total (mm)**
2012/13	136	128	166	99	76	11	2	22	72	18	730
2013/14	166	88	220	98	40	126	5	44	2	41	830

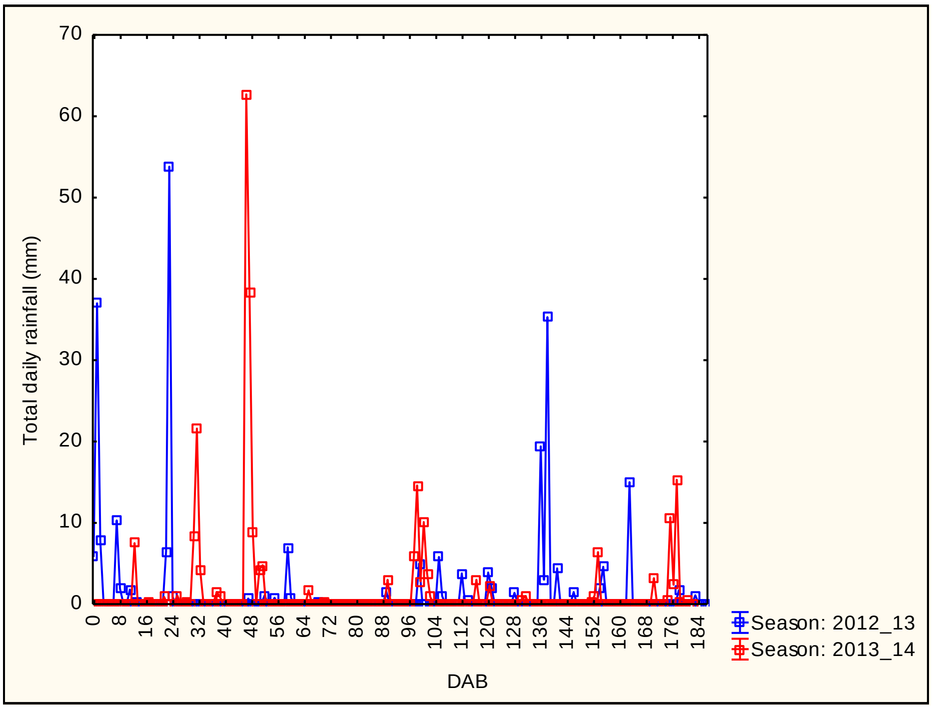


Figure 13 Total daily rainfall relative to days after budburst (DAB) from budburst to 31 May during the 2012/13 and 2013/14 growing seasons.

3.3.1.2 Bunch microclimate

The degree hour accumulation was calculated in the same manner as degree day accumulation, but only using the mean hourly temperature from 19/12/13 up to harvest. It was evident that the bunches of the GA treatment displayed higher temperature accumulation than the bunches of the S and VSP treatments (Figure 14).

Higher mean daily bunch temperatures of the GA treatment occurred during February compared to the other treatments (Figure 15). The canopy of the GA treatment may be less dense resulting in increased bunch exposure to sunlight or the canopy may be constructed in such a way that the bunches receive longer periods of light during the day. The date is used rather than DAB due to different budburst dates of the respective treatments.

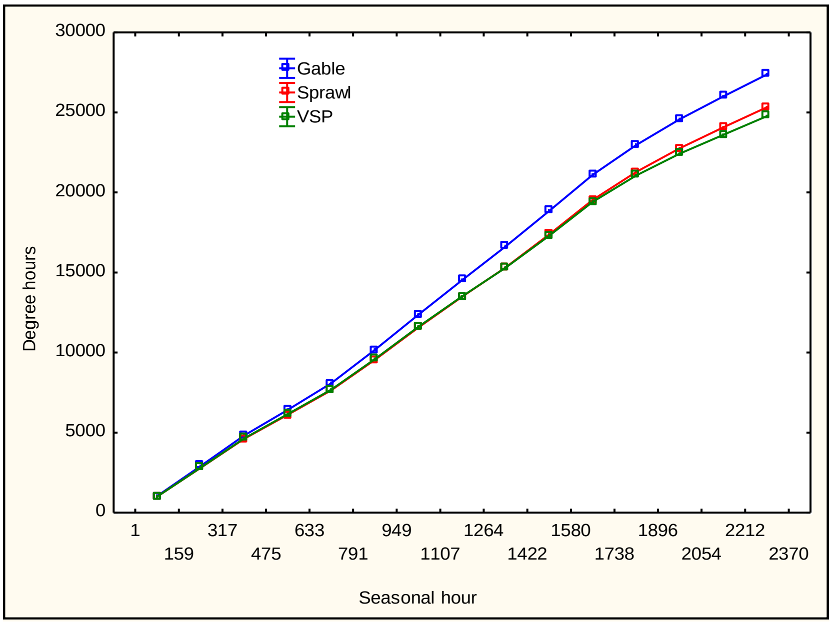


Figure 14 Degree hour accumulation from bunch temperatures obtained from 19/12/13 for the treatments of the 2013/14 season.

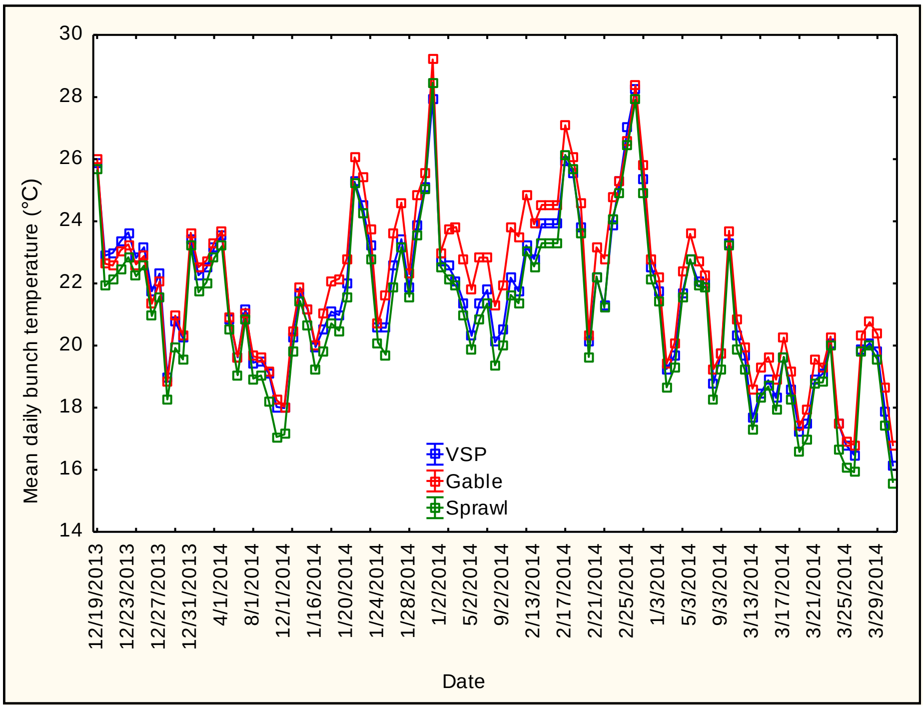


Figure 15 Mean daily bunch temperature relative to date from 19/12/13 for the treatments during the 2013/14 season.

3.3.1.3 Bunch temperature differences

The mean daily temperature differences between the bunch microclimate for the different treatments and the mean daily ambient temperature (Figure 16) indicates that there are differences between the different trellising and training systems and the ambient. Of all the treatments, the most similar mean temperature to the ambient was measured for the VSP treatment. The GA was the only treatment which had higher mean temperatures from the ambient around mid-January to February (Figure 16). The maximum temperature difference, especially during February, seemed to be pivotal to this (Figure 17). The high bunch numbers of the GA treatment could have possibly resulted in an increase in the density of the bunch zone which consequently, restricted aeration and thereby restricting the cooling of bunches to a greater extent. There was an irregular peak for the maximum bunch temperatures of the VSP treatment during end of February (Figure 17). Faulty sensor measurements could have occurred. In general, the treatments displayed higher maximum temperatures relative to the ambient from mid-January onwards.

The minimum bunch temperatures measured for all the treatments were generally lower than the ambient (Figure 18). The minimum bunch temperatures of the GA treatment was similar to the ambient temperature which can be ascribed to the higher cordon as cooling during the night commence from the soil surface. Since the cordon heights of S and VSP treatments were similar, it was probably not the reason for the lower minimum temperatures. However, higher bunch exposure of the canopy of the S treatment (due to downward bent shoots) could have resulted in decreased temperatures during the night due to better bunch aeration.

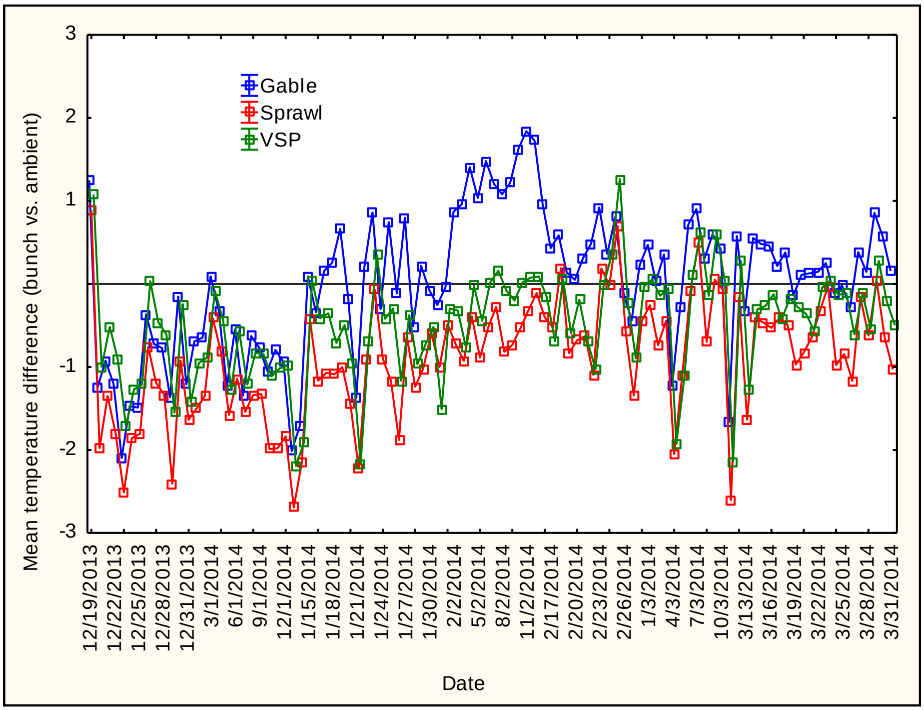


Figure 16 Mean temperature difference (bunch temperature vs. ambient temperature) relative to date from 19/12/13 in the 2013/14 season.

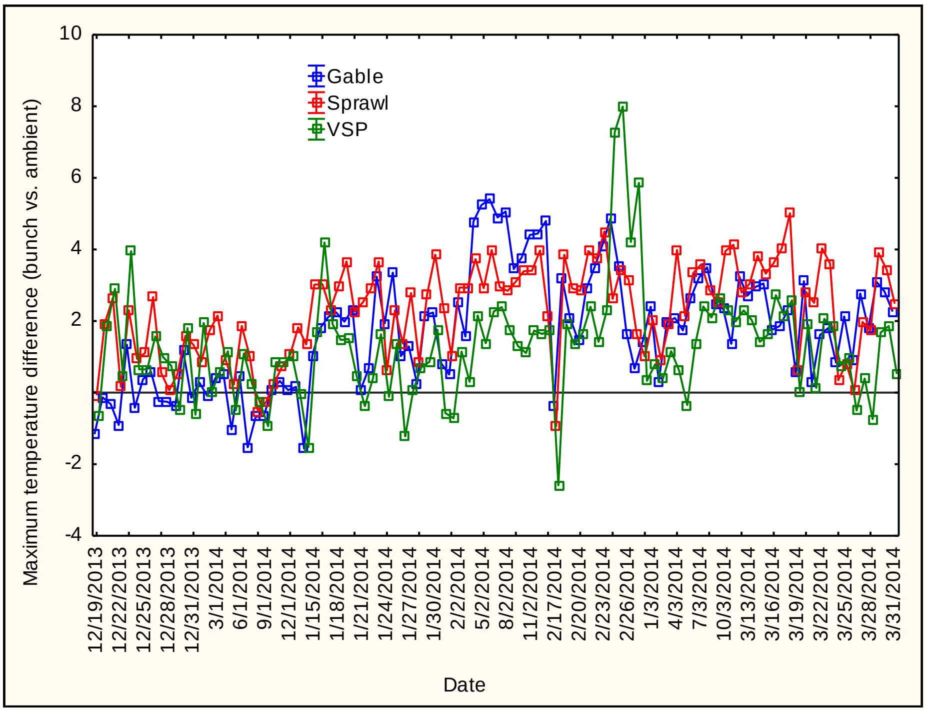


Figure 17 Maximum temperature difference (bunch temperature vs. ambient temperature) relative to date from 19/12/13 in the 2013/14 season.

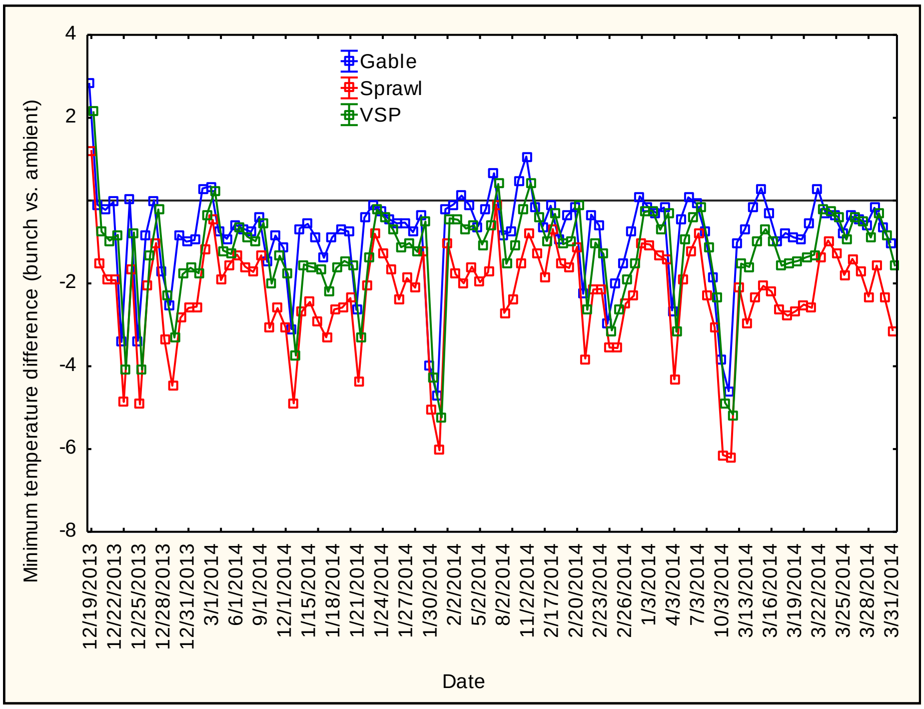


Figure 18 Minimum temperature difference (bunch temperature vs. ambient temperature) relative to date from 19/12/13 in the 2013/14 season.

3.3.2 Soil and plant water status

3.3.2.1 Soil water status

The soil was drier in the 2013/14 season compared to the 2012/13 season (Figure 19-21). It could be due to increased vegetative growth and less irrigation, with regards to frequency and amounts, during the 2013/14 season (Figure 22). However, the rainfall during the 2013/14 season was higher than the previous season (Table 15). The maximum daily temperature was slightly higher during the 2013/14 season from 121 DAB (Figure 9), which may explain the drier soil conditions. The sudden increase in soil moisture after ±156 DAB during season 2012/13 can be due to irrigation of 15 hours on 155 DAB (Figure 22). High rainfall occurred between 133-142 DAB during the 2012/13 season (Figure 13) and can also explain the increased soil water content in the top soil layer (Figure 19). The reduction in soil water content from 29-100 DAB during season 2013/14 was during the time of reproductive development where increased water is required for growth.

A definite trend in soil water was evident for the different treatments throughout both seasons (Figure 19-21). Soil water content for the GA treatment was drier in both seasons for all the soil layers measured, while the VSP and S treatments had the wettest soil layers (0-90 cm) in the 2012/13 and 2013/14 season, respectively. It is expected that grapevines on larger trellis systems with increased crop load, such as the GA treatment, would have a larger moisture demand (Van Zyl & Van Huyssteen, 1980). Unfortunately, root studies could not be performed during the study, but it may be that the conversion of the gable trellis system and possibly the adjustment of source to sink relationships (Hunter & le Roux, 1992; Edson *et al*., 1993) led to better root colonization of the soil volume, improving the absorptive capacity of the root system (Richards, 1983). The soil water content was similar between the GA and VSP treatments in the 0-30 cm soil layer during the 2013/14 season (Figure 19). This indicated that the highest concentration of roots of the VSP grapevines occurred in the top soil layer. Interestingly, the sprawling and VSP treatments responded differently between the two seasons, with the VSP treatment containing the wettest soil during the 2012/13 season while this response is switched during the 2013/14 season.

There was a substantial difference in the neutron probe readings of the two probes which were installed per treatment. This trend was particularly evident for the S treatment, (vertical bars display min-max values) and indicated the extent of within vineyard soil variability within the experiment block. Only one neutron access tube was installed for the DS and SS treatments in the 2012/13 season. However, as the DS and SS treatments of the 2012/13 season were combined into one treatment in 2013/14 (S), there were two probe positions for the sprawling treatment in the 2013/14 season.

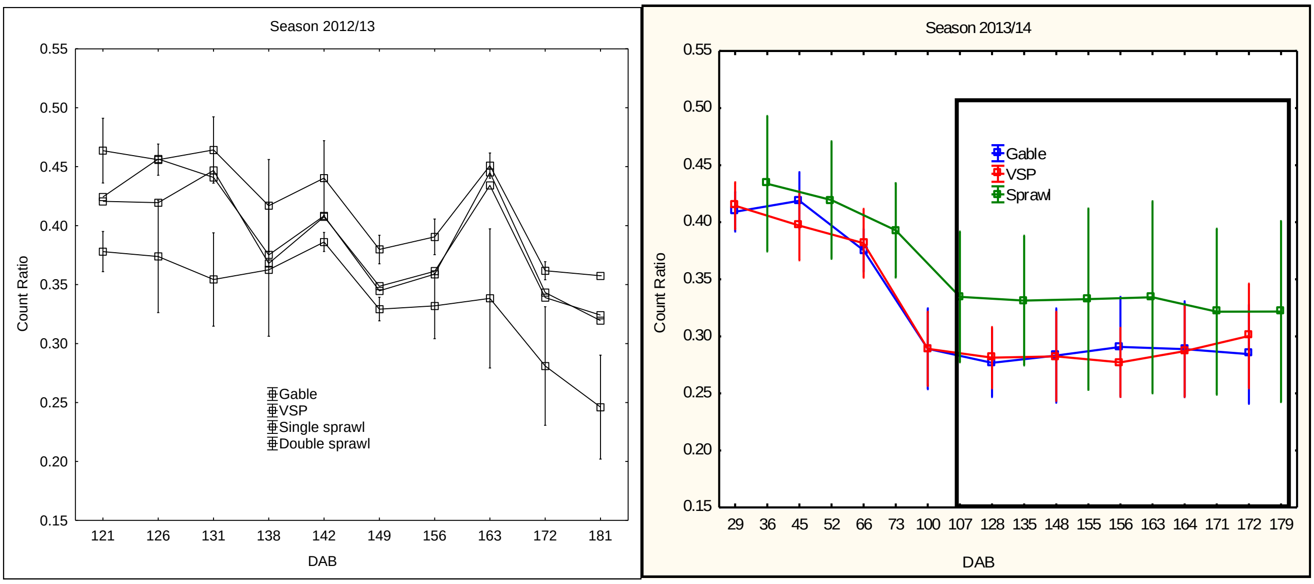


Figure 19 Neutron count ratios (CN) relative to date after budburst (DAB) for 0-30 cm depth shown for the treatments in season 2012/13 and 2013/14 (Means calculated for two neutron probe positions). Demarcated box represent same DAB compared to season 2012/13. Vertical bars denote min-max values.

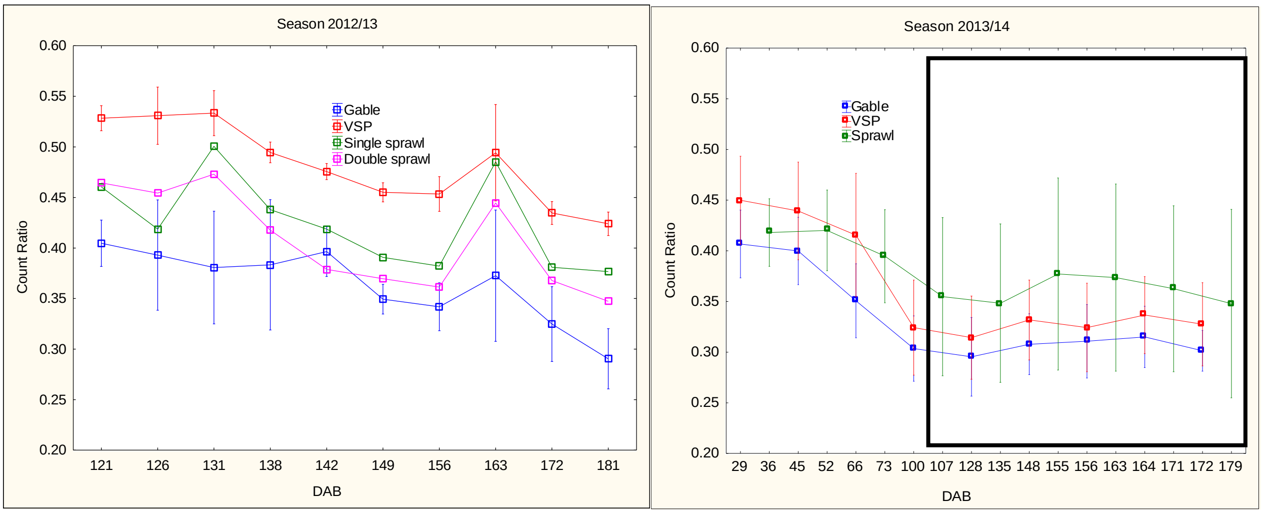


Figure 20 Neutron count ratios (CN) relative to date after budburst (DAB) for 30-60 cm depth shown for the treatments in season 2012/13 and 2013/14 (Means calculated for two neutron probe positions). Demarcated box represent same DAB compared to season 2012/13. Vertical bars denote min-max values.

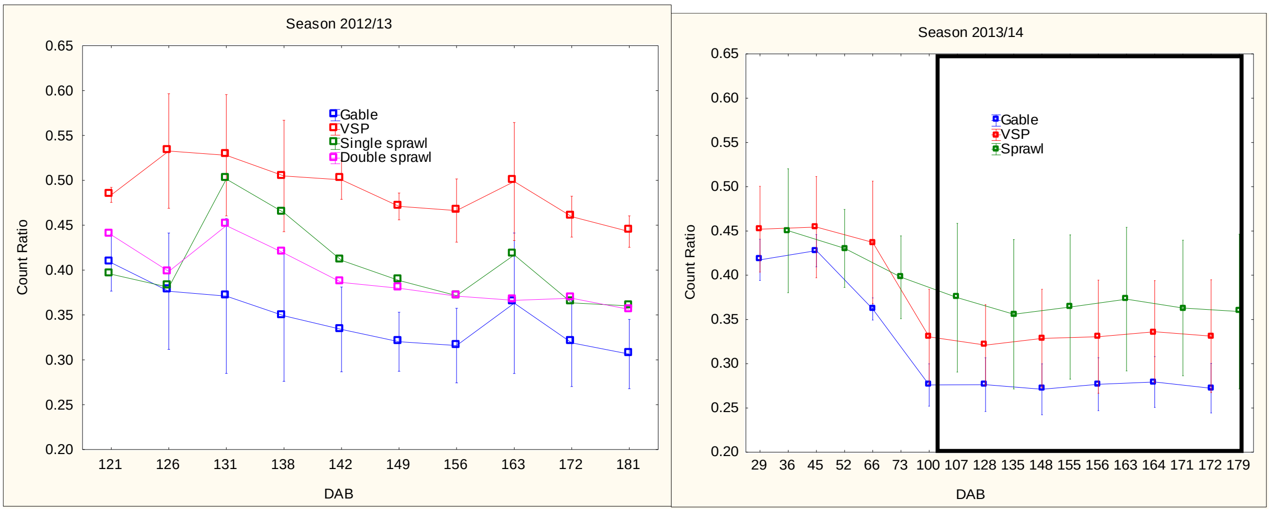


Figure 21 Neutron count ratios (CN) relative to date after budburst (DAB) for 60-90 cm depth shown for the treatments in season 2012/13 and 2013/14 (Means calculated for two neutron probe positions). Demarcated box represent same DAB compared to season 2012/13. Vertical bars denote min-max values.

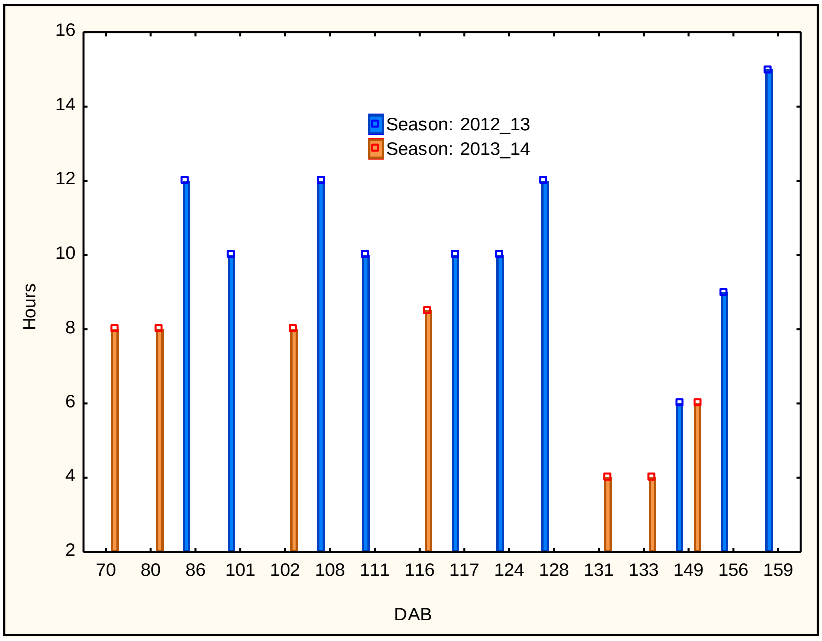


Figure 22 Hours irrigation relative to days after budburst (DAB) during season 2012/13 and 2013/14.

3.3.2.2 Plant water status

In 2012/13, the pattern of plant water status was similar between treatments (Figure 23). A large increase (more negative Ψ_{PD}) in Ψ_{PD} between 74-116 DAB was present during the 2013/14 season. This may be due to the high water demands from berry pea size up to véraison (Rogiers *et al.*, 2012) together with possible yield and growth increases compared to the previous season. The rapid increase in SWP after 116 and 149 DAB, for all the treatments, in the 2013/14 season was a response to irrigation application (Figure 22). However, the irrigation at 149 DAB only led to an immediate decline on GA and VSP grapevines, while the S grapevines first increased up to 165 DAB and rapidly declined.

It is interesting that the trend of soil moisture content (Figure 19-21) and plant water status (Figure 23) during season 2013/14 appear to be similar. Generally, when the soil water content is low it is expected that the grapevine will show signs of stress due to the expectation of predawn-soil equilibrium (Donovan *et al*., 2001). The SS, DS and VSP treatments in the 2012/13 season (Figure 23) responded similarly to this expectation. However, the GA grapevines growing in the driest soil showed no evidence of stressed conditions during either season 2012/13 and 2013/14. Despite the wettest soil conditions of the S grapevines, they seemed to be the most stressed in the 2013/14 season. Ourcival *et al*. (1994) stated that soil moisture heterogeneity can also contribute to predawn disequilibrium when a proportion of roots are situated in wetter soil and decreased plant hydraulic conductivity is present.

It is not easy to explain why this occurred, but it could be that the grapevine has reached a 'critical' potential restricting the rate of water loss in the case of the GA treatment; while the soil was wetter, the rate of water loss increased. This was in accordance to findings presented by Smart and Barrs (1973). It could also be, as mentioned by Collins and Loveys (2009), that the drying soil of the GA treatment led to reduced transpiration than grapevines growing in the wetter soils due to chemical signals produced by the roots, signalling to slow the water loss rate. Generally, *Vitis vinifera cv*. Shiraz is known to display near-anisohydric (less regulating, “optimistic”) behaviour (Schultz, 2003). However, the GA treatment appeared to contradict this behaviour with possibly regulating transpiration/stomatal conductance as a result of drying soil.

It's generally assumed that C3 plants close stomata at night, thereby preventing night-time transpiration and creating an equilibrium between soil water potential and Ψ_{PD} (Waring & Cleary, 1967). A theory with regards to the S treatment, response may be that increased night-time transpiration occurred, leading to more negative Ψ_{PD} values than that of the soil. This was comparable to the findings of Donovan *et al*. (2003). Still, it was expected for grapevines of the S treatment to experience more water constraints due to a more exposed microclimate. Signs of stress are clearly illustrated in Figure 24as well as sunburn damage which might also explain the more negative Ψ_{PD}. Similar findings on sprawling canopies were displayed by Stolk (2014). Nonetheless, grapevines of the S treatment only started to display more negative Ψ_{PD} after the high peak of -1800 KPa at about 116-123 DAB. This value can be classified as 'critical water stress' (Table 6) and it may be that the grapevines of the S treatment struggled to recover.

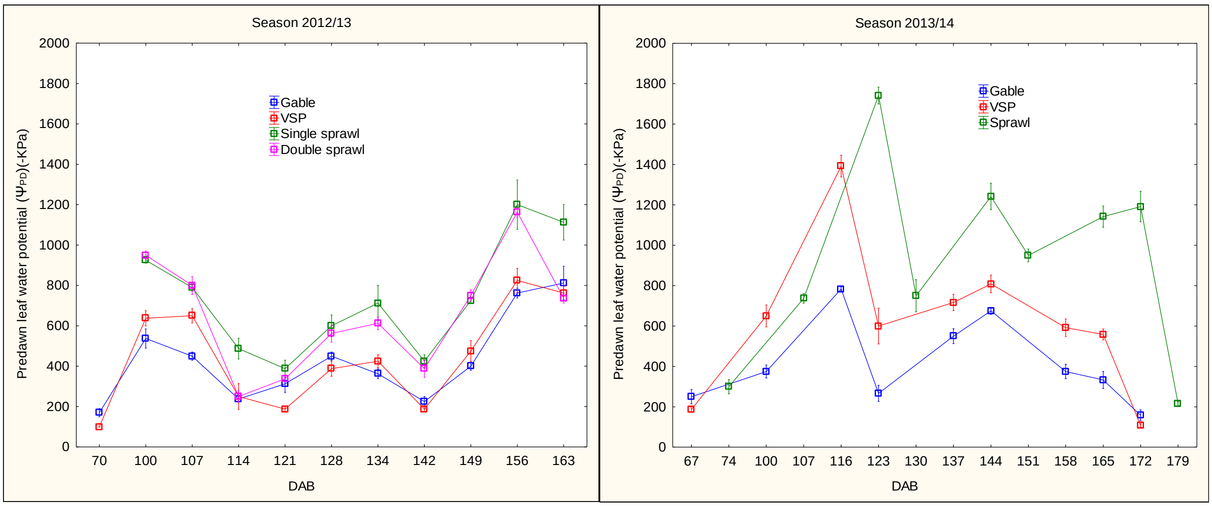


Figure 23 Predawn leaf water potential (Ψ_{PD}) relative to date of budburst (DAB) for the treatments in season 2012/13 and 2013/14 (means with ± standard errors shown).

Figure 24 Signs of a stressed sprawling canopy during the 2013/14 season.

3.3.3 Vegetative measurements

3.3.3.1 Shoot growth

Since shoot growth data was collected at such a late stage during the 2012/13 season, (Figure 25) no accurate assumptions can be made with regards to the cessation of shoot growth. From the 2013/14 season's data (Figure 26), however, shoot growth seemed to cease at about 71 DAB for the GA treatment, whereas the shoots of the VSP treatment were still growing at 110 DAB. Such growth late into the season usually occurs on vigorous grapevines, where the vegetative growth is a stronger sink than reproductive growth. On the other hand, it could also be that the grapevines of the VSP treatment did not bear many grapes; therefore the strength of the potential sinks was much lower than that of the growing shoots. This implied that grapevine balance could possibly have played a role. In addition to this, the S treatment was severely topped at about 58 DAB, which could explain the early plateau. This topping, while being industry practice in sprawling canopy systems, could have built in some artefacts with regards to grapevine balance and compensation, even though only non-topped shoots were measured.

Shoot growth was the highest on the VSP treatment compared to the sprawling and the GA treatments, the latter being the lowest, during both seasons (Figure 25 & Figure 26). Vertically trained shoots are known to be more vigorous and the conversion of a VSP canopy to a sprawling canopy can decrease shoot vigour (Iland *et al*., 2011). It has been stated that this vigour decrease is a result of hormone interaction, where auxin, gibberellins and cytokinins promotes shoot growth while ABA and ethylene reduces shoot growth (MacMillan 2003, Smart & MacMillan, 2003). Sap flow rates also appeared to be decreased in non-vertical shoots (Schubert *et. al*., 1996). Increased root temperature leads to increased shoot growth (Kliewer, 1975), which may be one of the reasons reduced shoot growth were present on the GA treatment, consisting of high foliage shadowing on the soil surface (Figure 6). The reduced shoot elongation of the GA and DS treatments (Figure 25) was most probably the result of the amount of buds retained, which leads to increased shoot production but at shorter lengths due to carbohydrate distribution as well as higher demand from increased crop loads (Smart, 1992). Buttrose and Mullins (1968) showed that increased root volume lead to increased shoot growth. As mentioned, the theory of increased root volume and -density which may have been altered through GA trellis conversion can somehow support the observation of increased GA shoot growth between the 2012/13 and 2013/14 seasons (Figure 25 & Figure 26). Shorter shoot lengths during 2012/13 relative to 2013/14 of all treatments can be due to stronger winds in the spring of 2012 (Figure 12).

Shoot growth has also been shown to be very sensitive to water stress (Smart, 1973). Water deficits will ultimately lead to reduced shoot vigour, shorter shoots and decreased leaf area per grapevine (McCarthy, 1997). As the soil dries out, stomatal aperture decreases, due to increased ABA synthesis in roots which is translocated into leaves (Stoll *et al*., 2000), thereby limiting transpiration. A dry soil can also limit photosynthesis, sugar assimilation and carbohydrate production when prolonged stomatal closure occurs (Chalmers, 2009). This could have occurred with regards to the GA trellis which displayed the driest soils (Figure 19-21) but not affecting leaf water potential (Figure 23). The possible near-isohydric behaviour of GA grapevines could also explain the overall decreased shoot growth. The conservation of water displayed by near-isohydric plants will limit carbon gain and thus decrease shoot growth (Kjelgren, 2010). Less shoot growth in the sprawling treatments may not only be due to severe topping, but also due to canopy light and temperature conditions ultimately leading to more stressed grapevines (Figure 23).

A very important aspect in any crop productivity study is to identify the reaction of the plant in limited conditions due to the sources and the sinks (Chaves, 1984). Removal of fruit from grapevines can provide an indication if photosynthesis is under the control of sink activity. The morphological responses associated with differences in crop load are linked to physiological responses (Edson *et al*., 1995).The indicator grapevines (100% fruit removal) displayed an interesting response between treatments (Figure 25&Figure 26). Indicator grapevines of the GA treatment produced longer shoots than GA grapevines, while the VSP and sprawling treatments showed the opposite trend for both seasons. The general expectation when the size of sources or sinks are altered by means of fruit removal, is that the photosynthetic rate increases as the relative source to sink ratio decrease and consequently vegetative growth increases (Hofäcker, 1978; Edson *et al*., 1995). The GA treatment displayed a response similar to this. However, it appeared that photosynthesis decreased with 100% bunch removal on the VSP, DS, SS and S treatments. The timing of bunch removal could also have played a role. Studies found that the presence of fruit as a strong sink stimulates the photosynthetic rate of individual leaves (Chaves, 1984; Downton *et al*., 1987; Kaps & Cahoon, 1989; Edson *et al*., 1993). The above mentioned authors found definite photosynthetic rate reduction for leaves on de-fruited grapevines, which may be due to less demand for photo assimilates when the sink is limited (Nabi *et al*., 2000). However, the nature of this response is not completely understood. Considering the conclusions in literature, it could possibly be that the grapevines from the VSP, DS, SS and S treatments were under a stronger control of sink activity, whereas the GA treatment indicated the opposite response. It may be that the leaf area (source size) of the GA treatment was limiting the photosynthetic activity when fruit was present (Petrie *et al*., 2000). As mentioned, the GA trellis was the only treatment displaying possible isohydric like behaviour (see paragraph 3.3.2.2 and 3.3.2.3). Isohydric-like behavioural plants alter their growth and physiology to conserve the resources present and manage their demand for resources in the future (Schultz, 2003). It could be that the GA treatment displayed this behaviour as a result of the crop present, whereas de-fruited GA shoots was not required to conserve resources resulting in elevated physiological function and stronger shoot growth. The GA treatment also did not experience the extent of plant water stress than the other treatments (Figure 23) and a very likely explanation may be that when stressed conditions are present together with crop removal; photosynthetic rate is decreased to a greater extent. Grapevine balance ratios between treatments may also play a role in the decreased shoot growth.

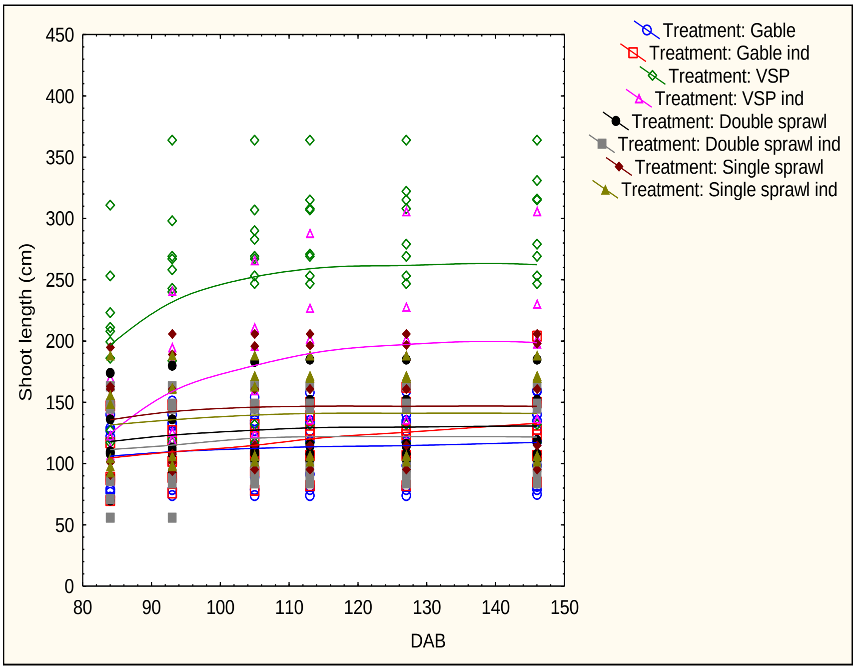


Figure 25 Shoot length (cm) relative to days after budburst (DAB) for the different treatments during season 2012/13 (distance weighed least squares fits are shown).

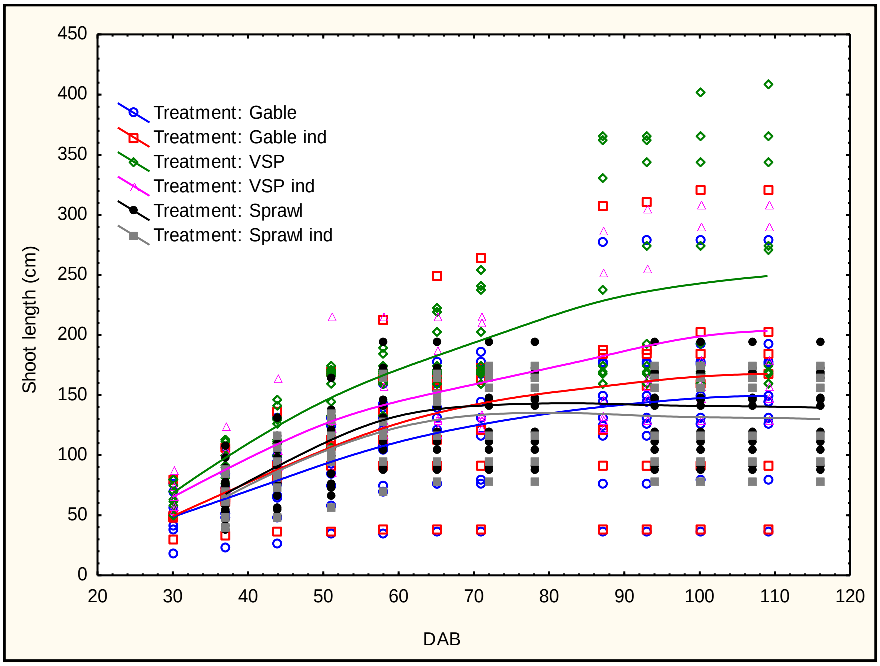


Figure 26 Shoot length (cm) relative to days after budburst (DAB) for the different treatments during season 2013/14 (distance weighed least square fits are shown).

3.3.3.2 Leaf age

Unfortunately leaf age could not be calculated for the 2012/13 season as plastochron measurements started at a stage that was too late to monitor active shoot growth (Figure 25).The date that shoot growth ceased in the second season can clearly be seen in Figure 27. The VSP treatment continued to produce new leaves throughout the growing season and its canopy consisted of leaves that were up to 170 days old. The mean canopy leaf age of the VSP treatment was not so much different than the S and GA treatments. However differences were present regarding leaf age distribution, with the VSP treatment containing a wider range of leaf ages, including the youngest leaves between treatments, which were a result of continued shoot growth (Figure 28). The canopies of the GA and S treatments also seemed to be similar when referring to mean leaf age values (Figure 28). However, perusal of the raw data indicated that grapevines of the S treatment did not contain leaves which were either younger than 58 days or older than 120 days. This was due to the topping action. The GA treatment was better in this regard with leaves as old as 140 days and as young as 40 days old. The wide variety of leaf age groups can be considered to be beneficial due to the different roles that the different leaf age groups play in the changing of import/export kinetics (Hunter, 2000). The GA treatment had younger leaves due to shoot growth ceasing on 71 DAB, rather than 58 DAB in comparison to the S treatment. As mentioned previously, the S treatment was severely topped at 58 DAB which explains this cessation of growth.

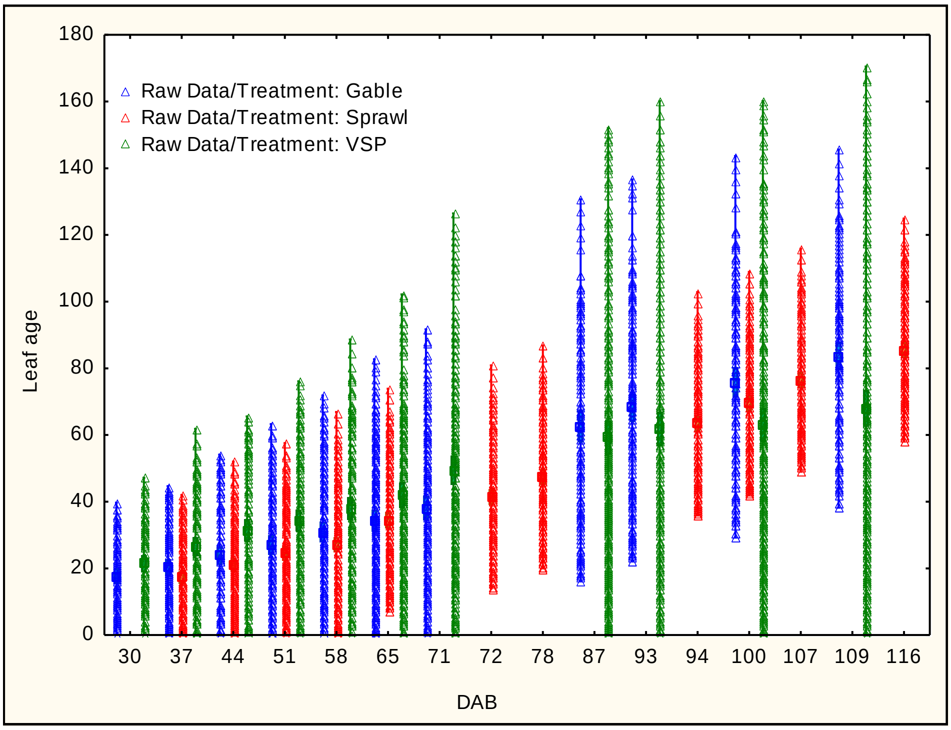


Figure 27 Leaf age relative to days after budburst (DAB) for the treatments of season 2013/14 (raw data shown).

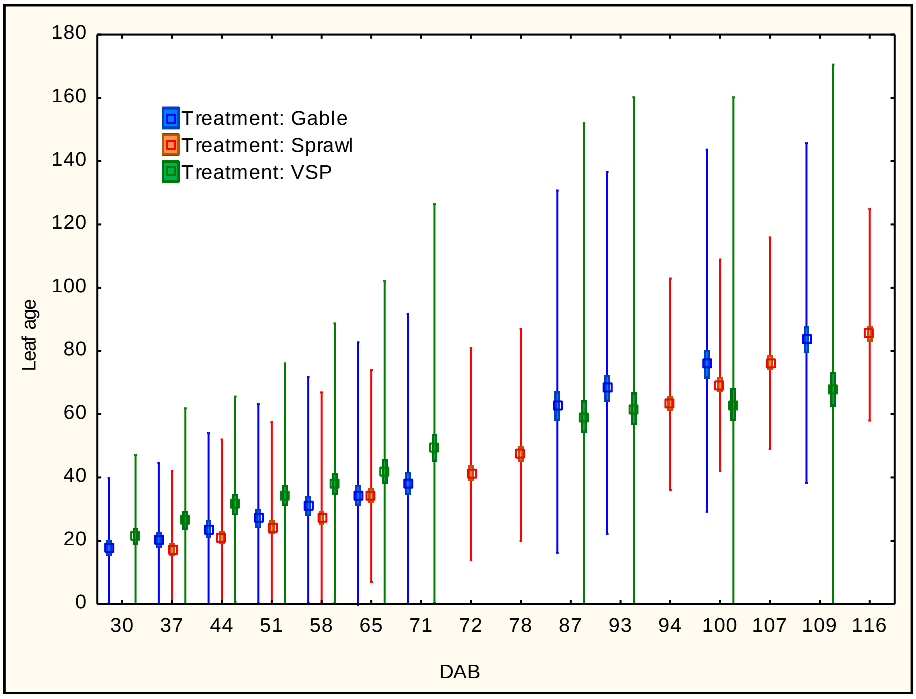


Figure 28 Mean leaf age relative to days after budburst (DAB) for the treatments during the 2013/14 season (whiskers display min-max values and the box plots 95% confidence intervals).

3.3.3.3 Shoot and leaf area assessment

In the 2012/13 season the GA treatment produced the least vigorous canopy in terms of leaf area, shoot length, laterals and internode length when compared to the other systems (Table 16).This is in accordance with the findings of Smart *et al*. (1989). Shorter shoot lengths could also be the result of strong winds (Figure 12) tipping the shoots against the canopy wires before they were positioned. Grapevines of the GA and DS treatments had the lowest leaf area per shoot and this seemed to be a function of shoot length or the number of leaves.

Differences between treatments did not occur regarding the number of laterals per shoot. However, differences in the lateral leaf area contribution occurred. The longest laterals were present on the VSP and DS treatments, contributing a third of the total shoot leaf area. It can be concluded that lateral leaf area was also a result of lateral length, with shorter laterals contributing less to the total leaf area per vine. Increased lateral lengths and its higher leaf area contribution may be the result of increased exposure to shoot tipping (Vasconcelos & Castagnoli, 2001). This may explain the response of the DS treatment. Lateral growth is more abundant during vigorous growth (Smart, 1992). This was the case for the VSP treatment. The main difference between the SS and DS treatments was shoot length and lateral contribution.

Similar internode lengths were present, but the longer shoot lengths of the SS treatment provided space for potentially more leaves. The SS treatment is a modified VSP training system and was expected to produce similar leaf area per shoot. The difference was due to shorter internodes and longer shoots on the VSP treatment providing more space for leaves as well as longer lateral growth. It could be that the more exposed microclimate of SS grapevines provided sufficient light in the canopy and more leaves was not necessary for growth. Longer internode lengths, among other factors, are signs of shoot vigour (Smart *et al*., 1989). The DS and SS treatments displayed longer internodes compared to the VSP treatment but shorter shoot lengths, the latter possibly a response of more stressed conditions during the season (Figure 23). The longer internodes of the DS and SS treatments can be considered a strange finding due to horizontal/downward growing shoots usually displaying shorter internodes. Furthermore, longer internodes may be due to increased shoot topping as a result of higher canopy wind exposure of the sprawled canopies. Another reason may be that the two sprawling systems initially experienced strong shoot growth. More stressed conditions can also be due to increased canopy exposure. It does not appear that leaf area/vine had an effect on Ψ_{PD} where VSP grapevines had a high leaf area but less negative leaf water potential and *vice versa* for SS grapevines.

In the second season of the study, a different response of the GA and S treatments was visible when compared to 2012/13 (Table 17). The S treatment displayed signs of decreased vigour in terms of leaf area/shoot (-23%) and shoot length (-8%) compared to season 2012/13 (Table 16). The S treatment was heavily topped during berry pea size, which explains the shorter shoot lengths and increased lateral compensation as described by Vasconcelos and Castagnoli (2001). The GA treatment seemed to respond better to the trellis conversion in the second season, displaying a 15% and 30% increase in leaf area/shoot and shoot length, respectively. This may be a function of the high angle of the GA trellis due to narrow rows, as well as longer term compensation reactions coming into play. The total leaf area per grapevine also did not correlate with plant water status (Figure 23). It is expected that the larger leaf area of GA grapevines should display lower plant water potentials, but the same results were obtained by numerous studies where the 'larger' grapevine displayed better drought resistance (Van der Westhuizen, 1974; Safran, 1978; Van Zyl & Van Huyssteen, 1980). It can be that the grapevines from the GA treatment already produced more and deeper roots in the second season which improved root colonisation and therefore access to more soil water. The S system produced the highest leaf area/vine, which, together with its exposure may explain the severe stressed conditions (Figure 23). The VSP treatment produced 14% longer shoots than the previous season and also the longest shoots between the treatments. Increase rainfall during 2013/14 (Table 16) may have had an effect on the increased vegetative growth. The lateral leaf area contribution to the total leaf area/shoot overall were decreased during the 2013/14 season, but lateral lengths increased concluding that either smaller lateral leaves or longer lateral internodes were produced. The S treatment produced shorter laterals but higher lateral leaf area contribution than the VSP treatment, suggesting possible lateral leaf enlargement or decreased lateral internode production on S grapevines.

It was clear during both seasons that the grapevines with higher crop loads, namely the GA, DS, and S grapevines, had less leaf area per shoot. This may be similar to the findings of Nabi *et al*. (2000), where the partitioning of more carbon to the fruit resulted in reduced leaf area. This can be confirmed when considering the mean cane mass. Generally it can be concluded that the total leaf area per grapevine was a function of the number of shoots present. Shoot length dominated leaf area/shoot. Leaf water potential seemed to correspond to shoot length in the case of the VSP and sprawl treatments but not with leaf area/vine. Furthermore, growth in terms of shoot length, increased considerably from season 2012/13 to season 2013/14, possibly due to increased rainfall in 2013/14 (Table 16).

Table 16 Shoot and leaf area characteristics present for each trellis system recorded during ripening in the 2012/13 season (CV: Coefficient of variance, SD-standard deviation).

	Gable			**VSP**			**Single sprawl**			**Double sprawl**		
	***Means**	**SD**	**CV (%)**	***Means**	**SD**	**CV (%)**	****Means**	**SD**	**CV (%)**	****Means**	**SD**	**CV (%)**
Main shoot length (cm)	117.2	31.8	27.2	205.9	84.6	41.1	159.7	58.4	36.6	136.3	33.9	24.9
Lateral length (cm)	39.7	0.7	15.8	71.2	1.4	19.9	46.6	1.9	23.4	59.4	1.9	24.2
Lateral number/shoot (no.)	7.0	2.6	37.1	7.0	2.6	38.5	6.0	4.8	61.1	7.0	3.4	50.3
Internode length of main shoots (cm)	4.5	0.7	15.8	6.9	1.4	19.9	8.2	1.9	23.4	8.0	1.9	24.2
Total Leaf area/ shoot (lateral + main shoots) (cm^2)	1632.0	561.5	33.7	3211.9	1226.2	45.2	2336.0	2086.1	63.2	2180.1	566.9	25.8
Total leaf area/vine (lateral + main shoots)(cm^2)	37535.1	12775.9	33.7	51389.8	19642.8	45.2	39711.9	35535.1	63.2	58863.3	15207.2	25.8
Proportion of lateral leaf area/shoot (%)	25.0	14.5	58.2	34.0	17.4	47.4	29.0	22.4	66.4	35.0	16.3	45.1

* Means calculated from 20 shoots per treatment.
** Means calculated from 11 shoots per treatment.

Table 17 Shoot and leaf area characteristics present for each trellis system recorded during ripening in season 2013/14 (CV- Coefficient of variance, SD- standard deviation).

	Gable			**VSP**			**Sprawl**		
	***Means**	**SD**	**CV (%)**	***Means**	**SD**	**CV (%)**	***Means**	**SD**	**CV (%)**
Main shoot length (cm)	165.0	58.1	35.2	238.8	83.1	34.8	136.2	49.5	36.4
Lateral length (cm)	40.4	39.1	99.4	109.9	108.3	98.5	75.5	64.4	85.3
Lateral number/shoot (no.)	5.0	3.5	76.9	7.0	4.3	62.9	6.0	2.6	47.9
Internode length of main shoots (cm)	7.2	0.2	2.7	8.4	0.2	2.6	8.0	0.2	3.6
Total Leaf area/shoot (lateral + main shoots) (cm^2)	1930.2	632.1	30.3	2906.6	541.0	19.6	1728.3	706.9	43.4
Total leaf area/vine (lateral + main shoots) (cm^2)	61766.5	20308.7	30.3	52319.1	9925.1	19.6	67404.7	27723.5	43.4
Proportion of lateral leaf area/shoot (%)	11.0	9.2	115.1	15.0	16.6	108.4	18.0	12.7	67.3

* Means calculated from 20 shoots (combined data from destructive and plastochron shoot measurements due to high variability).

3.3.3.4 Pruning

The 2012/13 season displayed substantial differences between the treatments subjected to 100% more bearer positions than normal bearer numbers (Table 18). As expected, definite vigour decrease occurred with the GA and DS treatments, with mean cane mass being 50 to 60% lower than the VSP and SS treatments. The lowest cane mass was recorded for the GA treatment, while the SS treatment produced the highest cane mass and it appeared to be a function of the number of shoots present and mean mass per cane. The high cane mass of the SS treatment relative to the VSP treatment was peculiar when considering the lower leaf area/shoot and shorter shoot lengths present on the SS treatment (Table 16). A possible explanation can be that the SS treatment produced a smaller yield, storing more reserves at the end of the season on thicker, but shorter shoots, the latter being a result of larger water deficits and topping in these grapevines (Table 20). The ideal would have been for the double bearer systems to have the same mass per cane as the normal systems with the compensation reaction occurring only in terms of mean mass per cane due to increased number of shoots. Although there was this response, the supply from leaves did not seem to be sufficient enough to sustain the grapevines' above ground biomass (Table 16). It could be that the lower cane mass was due to a response of the high crop level present with most of the carbon translocated to the growing grapes. Furthermore, 2012/13 was the first year of trellis conversion and there was not enough reserves present for initial shoot growth leading to reduced canopies. The subterranean growth is normally in balance with the growth above soil level (Richards, 1983; Southey & Archer, 1988), and any modification of the above-ground growth could also potentially have an impact on the root system. It could be that GA trellis compensated mainly in subterranean growth as a result of trellis conversion leading to stimulated root growth. This was evident with the GA treatment containing the wettest soils of all the treatments (Figure 19-21) with no signs of stress (Figure 23), a low leaf area per vine (Table 16) and low cane mass (Table 18). The SS treatment produced more non count shoots than the rest of the treatments (data not shown). This is in accordance with the findings of Kurtural *et al*. (2006) explaining that the occurrence of more non count shoots can possibly be the result of increased pruning severity on a very vigorous grapevine.

During the 2013/14 season, improved adaption of grapevines to the GA trellis system were evident with a 41%, 8% and 28% increase in cane mass, mass per cane and canes per vine, respectively (Table 19). This may have been due to recovery of reserves and expansion of the root system better supporting growth in the second season. The large leaf areas per grapevine (Table 17) support this, which can also contribute to the higher cane mass (Table 19). The 2013/14 season appeared to be more beneficial in terms of growing conditions, especially with regards to the VSP treatment which displayed a 37% increase in average cane mass. The high November rainfall during season 2013/14 (Table 15) might have contributed a great deal regarding the increased growth displayed by the GA and VSP treatments. The effect of increased bearer numbers on the S treatment cannot be compared to the previous season due to the application of a different pruning system (Table 4). The greatest effect of lighter pruning seemed to be the mean cane mass, displaying a 61% decrease compared to the first season (DS & SS value means). It can be concluded that the capacity of the different pruning methods were expressed in the number of shoots per grapevine in both seasons. Archer and Van Schalkwyk (2007) found similar results regarding alternative pruning methods. No substantial differences occurred between the treatments regarding the number of bearing canes, non-bearing canes and non-count shoots per grapevine (data not shown). However, the relationship of bearing cane mass to non-bearing cane mass differed, with 1.7, 2.4, and 0.9 for the GA, VSP and S treatments, respectively. It was clear that the S treatment produced thin, light shoots regardless of the presence of grapes. In contrast, grapevines of both the VSP and GA treatments produced stronger shoots when they had grapes. The demand from bearing canes seemed to be greater within VSP grapevines.

The reduced cane mass of the GA, DS and S treatments correlates with the lower leaf area per shoot (Table 16 & Table 17). It is important to take into account the severe topping of the S treatment which also contributed to the loss of cane mass and therefore leaf area, which was not supplemented by lateral compensation. It was too late for compensation reactions to take place due to the timing of the topping action. Considering vigour differences from an assessment of cane mass (Table 20), the GA (both seasons) and DS treatments showed moderate vigour conditions, whereas the VSP and SS treatments could be classified as highly vigorous during 2012/13. In 2013/14, vigour conditions shifted for S grapevines to low vigour. This may be the result of severe topping and water deficits (Figure 23). The total leaf area per grapevine (Table 16 & Table 17) corresponded to the amount of canes per vine (Table 18 & Table 19) with the DS and S treatments containing low leaf area/shoot but high number of canes/vine, thereby increasing leaf area per grapevine.

Table 18 Pruning data for the different treatments in the 2012/13 season (CV- Coefficient of variance, SD- Standard deviation).

Season	**Vegetative components**	**Gable**			**VSP**			**Single sprawl**			**Double sprawl**		
		Means	**SD**	**CV (%)**	**Means**	**SD**	**CV (%)**	**Means**	**SD**	**CV (%)**	**Means**	**SD**	**CV (%)**
2012/13	Cane mass/vine (g)	742.5	225.5	30.4	1076.6	504.6	45.9	1115.9	360.3	36.1	820.3	308.0	37.6
	Cane Mass (g)	32.9	10.1	30.6	68.7	31.2	44.1	67.1	16.9	29.5	31.1	11.9	38.2
	Spurs/vine (no.)	19.0	2.3	12.3	8.0	1.2	14.0	8.0	0.9	11.5	16.0	2.2	14.0
	Canes/vine - count shoots (no.)	23.0	3.3	14.5	16.0	2.4	15.3	17.0	3.7	21.3	27.0	5.1	18.9

Table 19 Pruning data for the different treatments in the 2013/14 season (Coefficient of variance, SD- Standard deviation)

Season	**Vegetative components**	**Gable**			**VSP**			**Sprawl**		
		Means	**SD**	**CV (%)**	**Means**	**SD**	**CV (%)**	**Means**	**SD**	**CV (%)**
2013/14	Cane mass/vine (g)	1258.1	480.0	38.2	1938.2	638.0	32.9	698.5	216.1	31.2
	Cane Mass (g)	40.0	17.2	42.7	109.8	40.3	36.6	18.9	7.2	37.9
	Bearing cane mass (g)	40.5	0.5	41.8	123.0	0.7	39.1	23.1	0.2	28.6
	Non-bearing cane mass(g)	23.4	0.1	51.9	51.5	0.1	63.9	25.3	0.1	46.7
	Spurs/vine (no.)	19.0	2.7	14.0	8.0	1.1	13.7	19.0	6.8	34.7
	Canes/vine - count shoots (no.)	32.0	4.1	12.9	18.0	4.1	22.5	39.0	10.2	25.9
	Bearing canes/vine (no.)	27.0	4.5	16.5	15.0	3.5	23.4	34.0	6.4	22.9
	Non-bearing canes/vine (no.)	4.0	2.5	66.7	4.0	2.9	52.4	5.0	2.7	65.7

Table 20 Representative values for vigour classification according to mean cane mass (g) (Smart & Robinson, 1992).

	Vigour		
	Low	Moderate	High
Mean cane mass (g)	<10	20-40	>60

3.3.4 Yield

2012/13 season: Much better linear relationships were observed between yield and the number of bunches per grapevine for the VSP and SS treatments compared to the DS and GA treatments (Figure 29). The GA and DS treatments, which had double the number of bearing buds, showed weaker correlations for the above-mentioned. This was most likely due to a stronger influence of other yield components rather than the bunch numbers. The DS treatment, compared to the rest of the treatments, also seemed to display the least linear correlation and the highest variation between yield and bunches per vine (Figure 29). The GA and DS treatments produced 240% and 210% more bunches together with 240% and 190% heavier yields, respectively, compared to the normal systems. It was expected for the GA and DS treatments to produce double the number of bunches due to increased shoot numbers (Table 18). Although grapevines of the GA treatment had less shoots/vine than the DS ones, yield of GA grapevines was 36% higher. This can be explained by better shoot efficiency, in terms of photosynthetic activity, bud differentiation and fertility, as well as improved utilization of sunlight energy from the soil surface due to better grapevine balance and microclimate (Volschenk & Hunter, 2001). A slightly higher cane mass for the SS treatment relative to the VSP treatment (Table 18) may have been the result of 20% less yield in the SS system. The DS treatment, relative to the GA treatment, and the SS treatment, relative to the VSP treatment, produced less bunches and lower yields per vine, which may be due to more stressed conditions during the season (Figure 23).

2013/14 season: The same response between yield and bunches per grapevine were present for the VSP treatment (Figure 30), but the high bunch numbers of the S and GA treatments did not correlate to yield as well as expected, mainly due to high variability in the bunch numbers on these grapevines.

Although the GA treatment produced 200% more bunches than the VSP, yields did not increase concomitantly and was only 130% higher than the VSP treatments. The S treatment produced the highest number of bunches/vine at 1.3 and 2.7 times more than the GA and VSP treatments, respectively. Yet, the number of bunches compensated with regards to bunch mass, producing yields that were 10% less than the GA treatment (Figure 31 & Figure 32). Considering both seasons, the GA treatment appeared to achieve optimal potential with slight differences between the two seasons. The VSP treatment struggled during the 2012/13 season but displayed a much better growing season in 2013/14 with an increase of 20% and 47% in bunches/vine and yield/vine, respectively. Lighter pruning in the S treatment led to an increase of 20% bunches accompanied by only 3% yield increase, and the expression of yield was possibly a function of the number of canes per grapevine (Table 19). As expected, cane mass decreased with an increased number of bunches per vine.

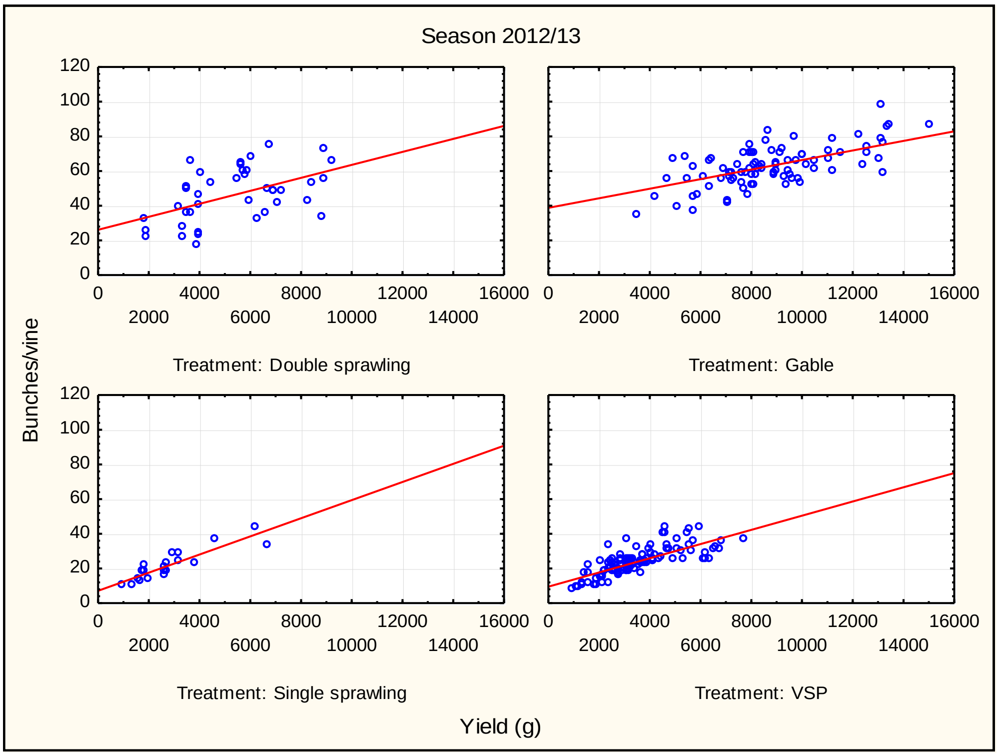


Figure 29 Relationship between the number of bunches per vine and yield per vine for the treatments during season 2012/13 (DS: y=26.1+0.0037x; r^2=0.25; SS: y=7.1+0.0052x; r^2=0.79; GA: y=44.8+0.0021x; r^2=0.26; VSP: y=9.5+0.0041x; r^2=0.57).

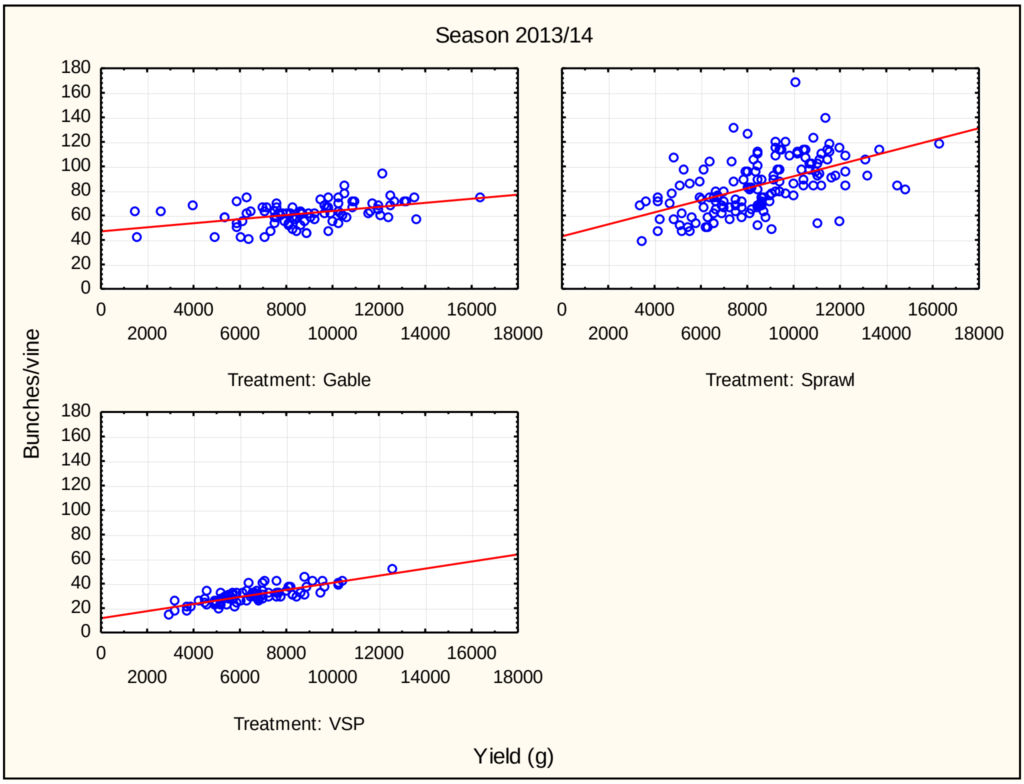


Figure 30 Relationship between the number of bunches per vine and yield per vine for the treatments during season 2013/14 (GA: y=46.9+0.0017x; r^2=0.20; S: y=42.9+0.0049x; r^2=0.30 VSP: y=11.7+0.0029x; r^2=0.63).

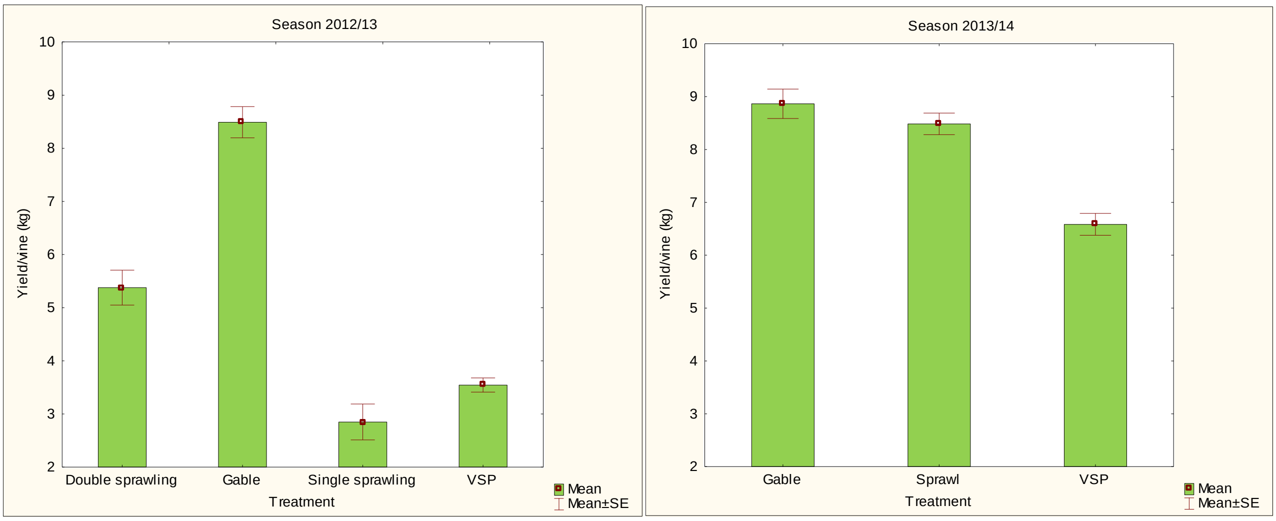


Figure 31 Yield per vine for the treatments during season 2012/13 and 2013/14 (means with ± standard errors shown).

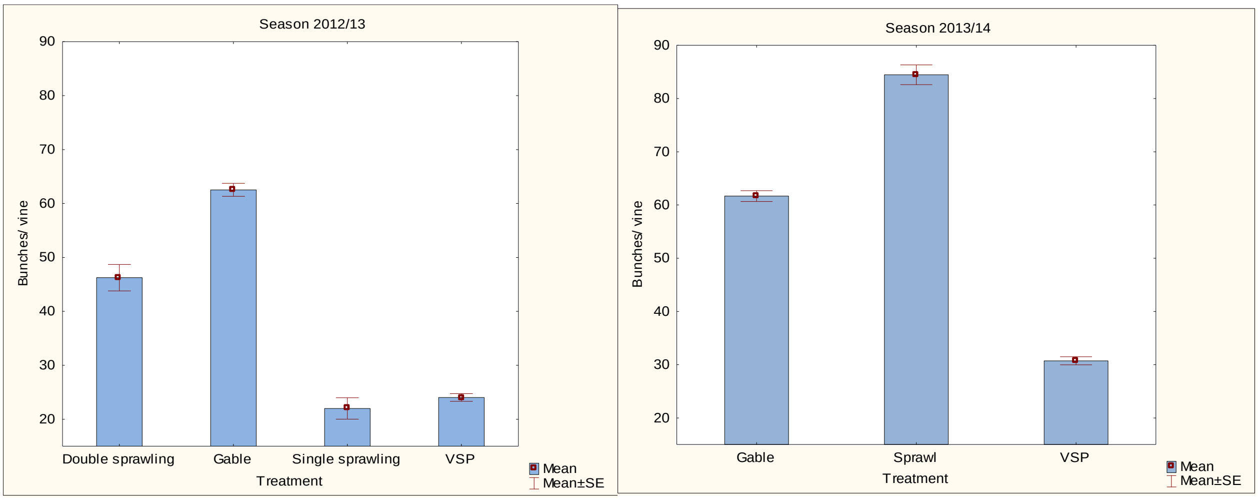


Figure 32Number of bunches per vine for the treatments in season 2012/13 and 2013/14 at harvest (means with ± standard errors shown).

3.3.5 Yield components

2012/13 season: The GA and DS treatments had double the number of buds (Table 21), which explains higher shoot numbers (Table 18). Yet, the GA treatment produced less than the expected double amount of shoots. A budburst percentage of only 60% can explain the small shoot number increase (Table 16). It is expected for larger trellis systems to improve budding percentage due to better accommodation of vegetative growth and improving the canopy light environment (Swanepoel, *et al*., 1990), but it can be that an imbalance of yield and growth was present the previous season, leading to lower budburst percentages (Hunter & Visser, 1990). It should also be taken into consideration that grapevines on the GA treatment was still being developed and therefore two bud spurs could not be pruned at all bearer positions. Overall, it can be concluded that the bud load has a definite effect on the number of shoots present. As expected, an increased bud load was associated with a decrease in budburst percentage (Archer & Van Schalkwyk, 2007). In some cases, more than 100% budburst occurred on the SS treatment (Table 21). A budburst percentage of more than 100% can be due to shoots emerging from buds other than allocated on bearer positions, of which the SS treatment clearly had the most (Table 18). According to Archer (2011), the budburst percentage can determine the number of bunches. However, the opposite occurred with regards to the GA treatment which had an estimated budburst percentage of 60% (Table 21) and approximately 60 bunches per vine (Figure 32). Thus, the number of bunches per vine was not a function of the number of shoots present, but a function of fertility, which was very high at 2.7 bunches per shoot.

The most dominant yield component responsible for the expression of yield in the GA treatment seemed to be its fertility (Table 21). The GA treatment produced 180%, 150% and 200% more bunches than the VSP, DS and SS treatments, respectively. This high fertility impacted bunch mass negatively, producing bunches 8% lighter than the VSP bunches. It was expected that the GA treatment should produce only twice as many bunches than the VSP treatment due to double the number of buds allocated, but it had three times as many bunches compared to the VSP treatment (Figure 32). When considering that the 2012/13 season was the first stable year after trellis conversion started in 2011/12, and that fruitfulness is determined in the previous season, the expectation would have been for the GA treatment to obtain similar fertility than the VSP treatment. The GA treatment was, however, initially formed by retaining its VSP cordons in order to reduce vigour of shoots used to form new cordons. The canopy on the newly formed cordons was therefore less dense, which could have stimulated fertility on these canes and spurs. It is important to note that the yield/vine was not exactly three times higher than the VSP treatment, which can explain the effect of yield component compensation. This compensation was due to an 8% lower average bunch mass than the VSP treatment (Table 21).

The main difference between the SS and DS treatments appeared to be only the increased number of bunches per shoot (Table 21) and per vine (Figure 32), in favour of the latter. This was expected due to double the amount of shoots present as a result of a high budburst percentage and increased bud load. The low fertility with regards to the SS treatment compared to the VSP treatment was peculiar, due to it being a VSP system the previous season. Fertility was 17% lower than the VSP treatment as well as 20% lower yield and 14% lower bunch mass. This can be a consequence of more stressed conditions during the growing season (Figure 23) or a denser VSP canopy in the previous season.

2013/14 season: The bud load of the lightly pruned S treatment was estimated according to the bud load present on mechanical pruned grapevines in literature. The reason for this was that the S treatment was not pruned to an exact number of buds and it was impossible to count the large number of buds per grapevine. According to Bodor *et al*. (2013), mechanical pruned grapevines have a bud load of 63 to 76 buds/vine. Archer and Van Schalkwyk (2007) retained 72 buds with mechanical pruning where 14 spurs per grapevine were present. Therefore approximately five buds per spur were retained. With regards to this study the average number of buds retained per spur regarding simulated mechanical pruning will be according to the bud load presented by Archer and Van Schalkwyk (2007) of five buds per spur (Table 22).

Similar trends with regards to yield component expression occurred in the 2013/14 season (Table 21 & Table 22). It can be concluded that the GA treatment had reached its optimal productivity. Although an increased budburst percentage (24%) were present, the GA treatment compensated by decreasing fertility (30%) and increasing bunch mass (6%) and berry mass (4%), whereas the amount of berries/bunch were unaffected. It seemed that the higher yield/vine of the GA treatment (Figure 31) was mainly due to the fertility and bunch numbers with an increase of 44% and 62% respectively in relation to the VSP treatment (Table 22). According to Archer (2011), the yield performance of a grapevine is determined by the number of effective buds allocated, where the effectiveness of a bud is achieved when sufficient fertility is induced. The development of the anlagen (undifferentiated primordia) is affected by light and temperature. The study states that about a third of full sunlight and more than 20°C ambient temperature is required for optimal development of anlagen. Unfortunately no micro-climatic data exists for the 2012/13 season. The S treatment had the highest fertility between treatments and this can be due to less dense canopies in the previous season leading to better a light environment in the bunch zone (Swanepoel *et al*., 1990).

Improved budburst occurred with the VSP treatment as well, which may have been caused by better environmental conditions, in terms of temperature, during the time of budburst in season 2013/14 (Figure 9). Budburst percentage was above 100% for the VSP treatment and can be due to the same reasons as discussed for the SS treatment in the 2012/13 season. Generally, the VSP treatment displayed an improved season with increased bunch mass (30%) and the number of berries per bunch (26%), which can explain the yield increase (Figure 31). Lighter pruning of the S treatment clearly had an enormous effect on bud load, containing 2.5 and 5.5 times more buds compared to the GA and VSP treatments, respectively (Table 22). The enormous bud load resulted in a 55%, 26% and 24% decrease in budburst, bunch mass and berries per bunch respectively, compared to the 2012/13 season. Yet, the S treatment displayed the highest fertility between treatments and this, together with the number of shoots produced (Table 19) were responsible for the higher yields (Figure 31).

It is important to note the difference in mean berry mass between the treatments with the GA treatment having the smallest berries in both seasons (Table 21 & Table 22) and the highest number of berries per bunch in the 2012/13 season (Table 21). Considering grape-and wine quality, the skin to flesh ratio is altered when smaller berries are present, thus modifying the concentration of soluble solids (Barbagallo *et al*., 2011). However, a study by Walker *et al*. (2005) stated that berry size does not affect wine quality. This can therefore only be concluded from sensory data. The vigour differences between treatments may have affected berry size. Cortell *et al.* (2007) concluded that smaller berries were consistently produced by low-vigour grapevines. During both seasons, the high-vigour VSP grapevines produced the largest berries, yet the S treatment during 2013/14, classified as low-vigour, still produced larger berries than the GA treatment.

The actual expression of yield components was tested by using the formula developed by Zeeman and Archer (1981). Each yield component (shown as A, B, D, E, and X) was made 'unknown' and the actual values were used to calculate the expected yield component value ('unknown' letter). The 'unknown' yield components is referred to as 'formula' values and the yield component values obtained for this study is referred to as 'actual' values. During the 2012/13 season the DS treatment seemed to be the only treatment not displaying similar formula values (Table 23). It appeared that the main reason for the higher 'X' value from the formula was budburst percentage and average bunch mass. Results showed that that the DS treatment displayed higher variation with regards to both bunch mass and budburst percentage (with the latter the most dominant) (Table 21) and can explain the different formula values (Table 23). The actual values of the S treatment varied the most relative to the formula-derived values in season 2013/14, also containing a far higher 'X' formula value. Yield components such as bud load and bunch mass seemed to be the reason for this expression and the higher variation in bud load (Table 22) supports the reason for different formula values (Table 23). The C factor of the formula i.e. non-count buds/collar buds (as mentioned in Chapter 2) is not included due to it being unknown how many fruit and shoots will originate from the buds. It may be that the C factor of the S treatment contributed more to the formula and the role of collar buds should be taken into consideration. The S treatment might have produced more fertile shoots from positions not situated on the allocated spurs, which does not reflect in the formula.

Table 21 Yield components for the different treatments in the 2012/13 season (CV- Coefficient of variance, SD- standard deviation).

Season	**Yield components**	**Gable**			**VSP**			**Single sprawl**			**Double sprawl**		
		Means	**SD**	**CV (%)**	**Means**	**SD**	**CV (%)**	**Means**	**SD**	**CV (%)**	**Means**	**SD**	**CV (%)**
2012/13	Average estimated bud load (no.)	38.0	4.7	12.3	17.0	2.3	14.0	16.0	1.8	11.5	31.0	15.6	28.1
	Estimated budburst percentage (%)	60.0	7.3	12.1	96.0	8.2	8.7	107.0	23.8	21.1	87.0	26.2	48.2
	Fertility	2.7	0.3	11.3	1.5	0.5	31.1	1.3	0.5	38.2	1.8	0.6	36.6
	Average bunch mass (g)	136.0	40.0	29.4	148.0	35.0	23.7	127.0	27.7	21.8	123.0	48.0	39.1
	Average berry mass at harvest (g)	1.6	0.1	2.9	1.7	0.0	1.9	1.6	0.0	2.8	1.6	0.1	6.5
	Berries/ bunch (no.)	88.0	26.5	30.1	87.0	19.6	22.7	79.0	18.0	22.8	77.0	33.5	43.3

Table 22 Yield components for the different treatments in the 2013/14 season (CV- Coefficient of variance, SD- standard deviation).

Season	**Yield components**	**Gable**			**VSP**			**Sprawl**		
		Means	**SD**	**CV (%)**	**Means**	**SD**	**CV (%)**	**Means**	**SD**	**CV (%)**
2013/14	Average estimated bud load (no.)	39.0	5.4	14.0	17.0	2.3	13.7	97.0*	33.9	34.7
	Estimated budburst percentage (%)	84.0	11.6	13.9	110.0	21.3	19.3	42.0	23.4	22.2
	Fertility	2.0	0.4	18.9	1.7	0.4	22.9	2.2	0.6	25.4
	Fertile shoot percentage (%)	88.0	8.1	9.2	80.0	11.8	14.8	84.0	7.8	9.3
	Average bunch mass (g)	144.3	38.5	26.7	214.0	35.7	16.7	103.0	28.2	27.3
	Average berry mass at harvest (g)	1.6	0.01	0.3	1.8	0.0	0.2	1.7	0.1	6.2
	Berries/bunch (no.)	89.0	23.9	26.7	118.0	19.7	16.7	60.0	16.0	26.5

Table 23 Comparison of actual yield components relative to formula derived yield components for the different treatments during season 2012/13 and 2013/14. X= yield/vine (g); A= bud load/vine; B= budburst/vine; D= fertility/shoot; E= average bunch mass (g).

		Actual values					**Values derived from formula**				
Season	**Treatment**	**X**	**A**	**B**	**D**	**E**	**X**	**A**	**B**	**D**	**E**
2012/13	Gable	8490	38	0.60	2.7	136.21	8404	38	0.61	2.7	137.60
	VSP	3546	17	0.96	1.5	147.60	3541	17	0.96	1.5	147.79
	Single sprawl	2851	16	1.07	1.3	126.90	2824	16	1.08	1.3	128.10
	Double sprawl	5379	31	0.87	1.8	122.58	6028	28	0.78	1.6	109.39
2013/14	Gable	8864	39	0.84	2.0	144.00	9435	37	0.79	1.9	135.29
	VSP	6584	17	1.10	1.7	213.86	6799	16	1.07	1.6	207.11
	Sprawl	8485	97	0.42	2.2	103.23	9252	89	0.39	2.0	94.67

3.3.6 Grapevine balance ratios

The Ravaz index defined grapevine balance as a post-harvest measurement, where the yield of the current harvest is used against the pruning mass following the current harvest (Ravaz, 1911). This only indicates how close the grapevine came to be optimally balanced. The growth-yield relationship is calculated by using the pruning mass of the current season against the yield of the following season. Partridge (1925) investigated the methods to use the yield/pruning mass ratio to estimate how the grapevine would perform in the future. The highest Ravaz value was reached by the GA treatment during the 2012/13 season (Table 24). This is expected due to the high yield (Figure 31) and low cane mass (Table 18). According to norms found in literature, the GA treatment in 2012/13 can be classified as over cropped, while the VSP and SS treatments were under cropped (Table 12), but to effectively classify the balance of the grapevine is to determine if grapes were ripened optimally. The substantial difference between the GA and VSP treatment regarding the Ravaz index (Table 24) was expected due to the higher yields obtained from the GA treatment displaying a 58% increase in relation to the VSP treatment (Figure 31). Regarding the GA and DS treatments in 2012/13 and the S treatment in 2013/14, an increased number of buds retained during pruning (Table 21 & Table 22) resulted in decreased pruning mass, meaning compensation took place with regards to the increased shoot number (Table 18 & Table 19). Decreased cane mass displayed by the S treatment might be the combined effect of water deficits (Figure 23) increased clusters per vine (Figure 32) and severe topping. These findings are comparable to the findings of Goodwin and Jerie (1992). The low cane mass of the GA treatment may be due to the effect of the increased yield. An overall increase in the growth-yield relationship occurred for all treatments, especially for the VSP and sprawling treatments (Table 24), confirming the improved environmental conditions during the following season. The values of the growth-yield index correlated to the values obtained from the various treatments seemed to be more in favour for the VSP and SS treatments. Therefore, suggesting that the vegetative growth will be sufficient to effectively support an increase in yield. The treatments containing double the number of buds are required to increase vegetative growth and improve its balance to support the crop while sustaining future grapevine function. Fortunately, the GA treatment produced adequate vegetative growth (Table 19) to support the crop during the 2013/14 season, with a more beneficial Ravaz index value (Table 25) indicating satisfactory grapevine balance according to literature (Table 12). Normally Ravaz values also provide information about the growth in the next season, with high values indicating that there may not be enough reserves to sustain early growth. The role of cytokinins, produced by active root tips, is also essential for the induction of anlagen (Shrinivasan & Mullins, 1978). Although the GA treatment struggled with aerial growth due to trellis conversion, it can be that the root system was still vigorous enough to produce sufficient cytokinin. Less severe water stress occurred in relation to other treatments making roots more metabolically active and more upward flow of sap in the xylem (containing cytokinin) (Figure 23) (Archer, 2011). There were no difference in Ravaz values for the VSP treatment between seasons (Table 24 & Table 25), indicating that although the yield increased significantly during season 2013/14 (Figure 31), vegetative growth also increased. The S treatment displayed signs of grapevine imbalance in season 2013/14 (Table 25). This was expected due to the high yield, number of bunches (Figure 31 & Figure 32) and very low cane mass (Table 19) which was a response of increased bud load (Table 22). Vegetative growth accommodation of the GA treatment was not the deciding factor for the increased budburst percentage, but rather the source to sink balance of the grapevine, with an improved Y/CM ratio during the 2013/14 season and thereby increased budding percentage (Table 22).

Based on the work of Kliewer and Dokoozlian (2005), it seems that sufficient leaf area was obtained for most of the treatments during both seasons, except for the GA treatment in the 2012/13 season (Table 24 & Table 25). The LA/Y ratio of the GA treatment was directed more to the lower threshold values (Table 24) with values being slightly less than the desired LA/Y. These low LA/Y values may have implications for grape ripening (Bindon, *et al*., 2008). A large decrease in LA/Y ratio for the VSP and sprawling treatments occurred (Table 25), which can be explained by the yield increase of both treatments during 2013/14 (Figure 31).

The low crop load of VSP compared to GA grapevines can explain why the shoot growth of the VSPI treatment decreased while the GAI treatment increased (Figure 25 & Figure 26). Grapevines already containing low yields relative to vegetative growth and then removing the crop will possibly have even less drive to produce and translocate carbohydrates to active sinks.

Table 24 Mean values of the different indices for the treatments of 2012/13 season (CV- Coefficient of variance, SD- Standard deviation).

Indices	Gable			VSP			Single sprawl			Double sprawl		
	Means	SD	CV (%)	Means	SD	CV (%)	Means	SD	CV (%)	Means	SD	CV (%)
Ravaz (yield:cane mass)	11.8	3.7	30.7	3.5	1.9	52.9	2.9	1.2	40.2	7.2	3.1	42.9
Growth-Yield (yield:cane mass)	12.4	3.6	29.2	8.2	6.3	76.7	8.6	2.2	25.9	11.0	4.4	39.7
*Leaf area/vine:yield/ vine (cm^2/g)	4.4	1.5	33.7	14.5	5.5	45.2	14.0	12.5	63.2	11.0	2.8	25.8

*Leaf area used to determine LA/Y ratio is the sum of main and lateral leaf area per vine present during ripening.

Table 25 Mean values of the different indices for the treatments of 2013/14 season (CV- Coefficient of variance, SD- Standard deviation).

Indices	Gable			VSP			Sprawl		
	Means	SD	CV (%)	Means	SD	CV (%)	Means	SD	CV (%)
Ravaz (yield:cane mass)	7.4	2.7	35.2	3.7	1.3	35.3	12.9	4.5	34.6
*Leaf area/vine:yield/vine (cm^2/g)	7.0	2.3	30.3	8.0	1.5	19.6	8.0	3.3	43.4

*Leaf area used to determine LA/Y ratio is the sum of main and lateral leaf area per vine present during ripening.

3.3.7 Spatial plot variability

The spatial plot layout displays the yield, cane mass and Ravaz index for each grapevine located within each treatment during the 2012/13 and 2013/14 season (refer to Figure 92 & Figure 93 in the Addendum). The indicator grapevine positions are indicated in Figure 89 and Figure 90 in the Addendum.

The goal with this section was to emphasise the difficulty in designing an experiment of this nature and effectively monitor treatment/trellis differences. It is clear that great variation existed not only between treatments but also between grapevines within each treatment. This could have impacted water status, shoot growth and ripening measurements severely and assumptions should be carefully considered. Of course, in retrospect, this data can be used to improve experiment design or shift measurement positions, but it can also be debated if a randomised block design would have been a benefit at all, considering the nature of variability in the trial.

The highest grapevine yield variability in the 2012/13 season seemed to be within both the sprawling and GA treatments (see Figure 92 in the Addendum). The GA treatment had a number of grapevines with very high yield, especially towards the end of the row and may be due to soil heterogeneity within the treatment. The DS and SS treatments could clearly be distinguished, with the DS treatment (containing double the number of buds) showing more grapevines with higher yield. The VSP treatment displayed the most constant yield, with only a few grapevines with higher yields in the beginning of the row. Pruning mass distinguished the normal trellis systems from the GA and DS systems. Grapevines of the GA treatment displayed little variability and also the lowest cane mass compared to the other treatments. Specific grapevines that displayed higher vigour also had higher yields. Higher variability occurred within the rest of the treatments. It appears that vigour decreased towards the end of the rows, especially row two and three (left to right), for the VSP treatment. The effect of yield on the Ravaz index could clearly be seen, with higher yields leading to higher Ravaz values. Very high Ravaz values were obtained from GA grapevines in row five and for VSP grapevines in rows two and three.

The following season produced overall higher yields in especially the VSP and S treatments (see Figure 93 in the Addendum). The higher yields of S grapevines were due to lighter pruning methods (as mentioned previously). Yield variability decreased slightly within the GA treatment, but row two still displayed higher yields. Highest variability was present for S grapevines, which was expected due to variability in bud numbers per grapevine (Table 22). The lighter pruning method severely impacted on pruning mass when compared to the previous season (see Figure 92 & Figure 93 in the Addendum) and can possibly be concluded that the vigour expressed in the area of the S treatment was not a function of soil variability. However, the VSP treatment showed definite decreased vigour towards the end of the treatment rows (more in season 2013/14, possibly due to improved growth) and may be a result of soil heterogeneity. The GA treatment also displayed a few grapevines with higher vigour in the same area. One of the neutron probes in the GA treatment area was positioned in the higher vigour area, which may explain drier soils. On the other hand, both the probes in the VSP treatment area were situated in the low vigour spots which make it risky to interpret this data effectively.

3.3.8 Light and photosynthetic measurements

3.3.8.1 Light quantity and quality

2012/13 season: High variation between ceptometer measurement replicates occurred for all treatments, especially in the morning (Figure 33). The highest canopy variation (sensor and replicate variation) was observed for the GA treatment, especially the east cordon (Figure 33 & Figure 35). The east cordon of GA trellis system was exposed to more radiation during the morning (Figure 33) and vice versa for the west cordon during midday (Figure 34) The higher % PAR for the GA east cordon in the afternoon may be due to the position of the sun aligning with the west cordon and causing the east cordon to intercept more sunlight at that angle. The DS treatment displayed higher canopy variation than the SS treatment, with two measurements showing almost no % PAR.

2013/14 season: Red light relative to far red light are highly absorbed by leaves and therefore lower R:FR values occur when shaded conditions are present, such as in dense canopies (Smart, 1988). Near the canopy surface the R:FR is near 1, while within a dense canopy the values drop to between 0.15 and 0.75 and, in very shaded conditions, can drop to even less than 0.1 (Dry, 2000).There was a linear correlation between the % ambient PAR and red to far red ratio (Figure

36). The same trend between treatments occurred throughout three phenological stages, measured at the same time (14:00), (Figure 37-39) with the S canopy displaying the highest R:FR ratio (close to 1 which is highly favourable) and % ambient PAR between the treatments, as well as higher canopy variation. The latter is expected as the canopy of the S is not vertically positioned such as in the VSP and GA treatments. The GA treatment had higher PAR and canopy variation relative to the VSP treatment. This was expected as the GA treatment intercepted more direct radiation and produced a less dense canopy causing less overshadowing than the VSP treatment, which could also explain the higher induced fertility (Table 21 & Table 22). Mellet (2010) displayed comparable results. What was not expected was the relatively low % PAR in the GA treatment. It has to be put in perspective with light requirements of the grapevine however. Although, the GA treatment's values ranged from 2.0 to 5.0%, while the VSP treatment's ranged from 0 to 1.5%, with an ambient PAR of 3500 $\mu E.m^{-2}.s^{-1}$on that specific day (data not shown), a % PAR of 3.0would equal 105 $\mu E.m^{-2}.s^{-1}$ compared to a % PAR of 1.0 which would equal 35 $\mu E.m^{-2}.s^{-1}$. The S canopy displayed roughly a % PAR of 40, indicating a PAR of 1400 $\mu E.m^{-2}.s^{-1}$ on a day with ambient values of 3500 $\mu E.m^{-2}.s^{-1}$. According to Archer (2011), optimal fertility can be reached at ± 800 $\mu E.m^{-2}.s^{-1}$, while PAR values of <15 $\mu E.m^{-2}.s^{-1}$ almost immediately induces infertility. This means that fertility should decrease from the S to GA to VSP treatments in the 2014/15 season. The fertility expressed in 2013/14 is a function of the light conditions in the 2012/13 season. The VSP clearly had the lowest % PAR, especially during midday and afternoon, during 2012/13, which may explain the lower fertility in 2013/14 (Table 22). The GA treatment reached values up to 70 % PAR of ambient during the 2012/13 season with an average ambient of 2000 $\mu E.m^{-2}.s^{-1}$, therefore a light intensity of 1400 $\mu E.m^{-2}.s^{-1}$. In comparison to 2013/14, it is clear that the GA treatment had far more beneficial light conditions in the first season. It will be interesting to see how the fertility is affected in the next season (2014/15) as a result of the enormous difference in light intensities. Note that the 70 % PAR is only the maximum value and the GA treatment displayed high canopy variability during the 2012/13 season meaning that the calculated value is not fixed.

The high radiation regime of the S treatment during the 2013/14 season could have had an effect on the water deficits experienced by S grapevines (Figure 23). The more exposed canopy produced by grapevines of the S treatment may have led to higher maximum bunch temperatures (Figure 17). Increased maximum bunch temperatures therefore resulted in increased transpiration, but the increased light may have led to a photosynthesis plateau (Iland *et al.*, 2011) and potentially reducing shoot growth (Figure 26). The R:FR ratio for the GA treatment increased as the season progressed (Figure 40) perhaps due to leaf abscission, considering that this measurement was done in the bunch zone, where older leaves are mainly found.

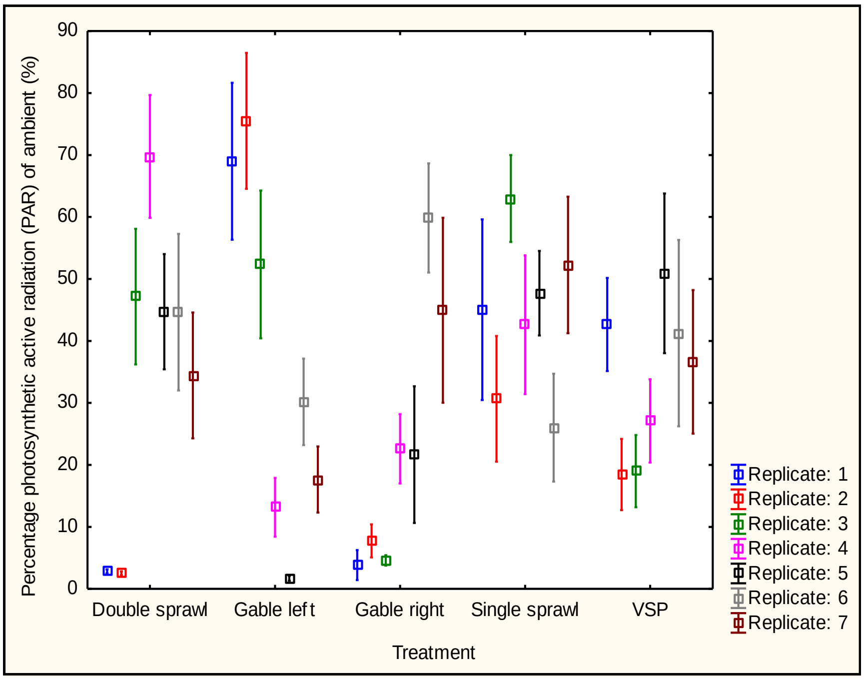


Figure 33 Percentage photosynthetic radiation (PAR) relative to ambient values for each replicate of the different treatments during ripening at 10:00 in season 2012/13 (Means with ± standard errors calculated from eight sensor positions and replicates represent ceptometer placements).

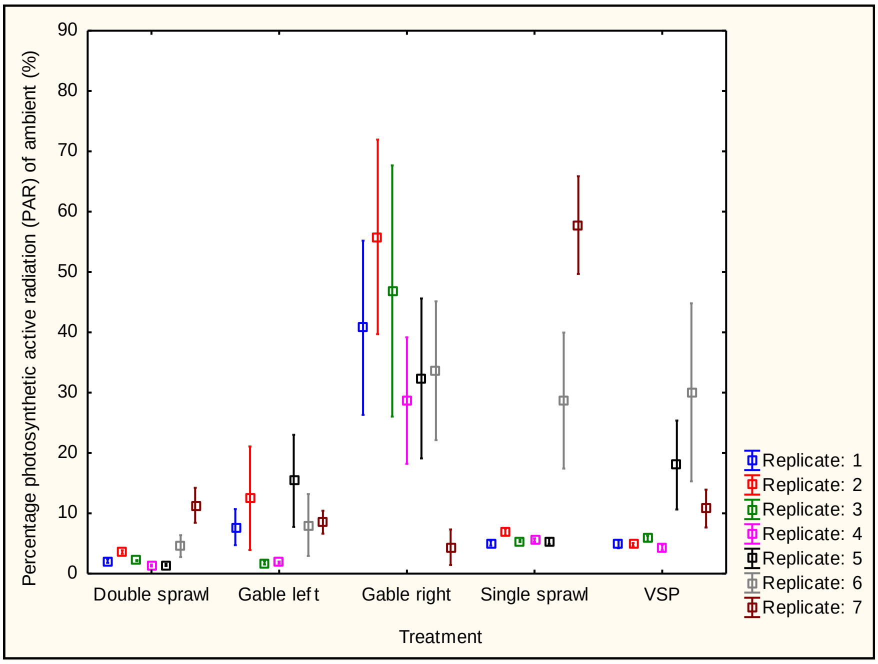


Figure 34 Percentage photosynthetic radiation (PAR) relative to ambient values for each replicate of the different treatments during ripening at 14:00 in season 2012/13 (Means with ± standard errors calculated from eight sensor positions and replicates represent ceptometer placements).

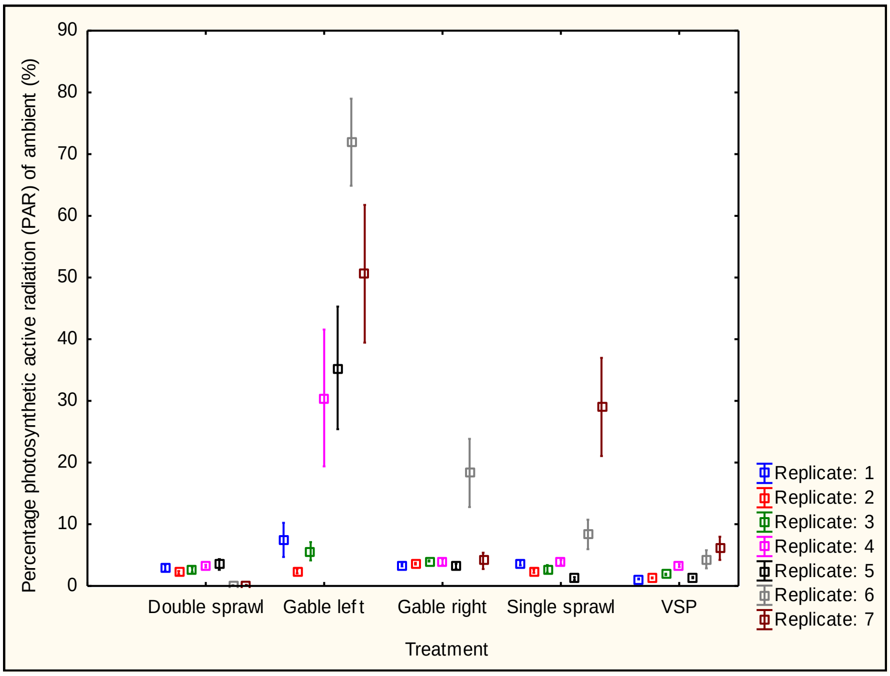


Figure 35 Percentage photosynthetic radiation (PAR) relative to ambient values for each replicate of the different treatments during ripening at 16:00 in season 2012/13 (Means with ± standard errors calculated from eight sensor positions and replicates represent ceptometer placements).

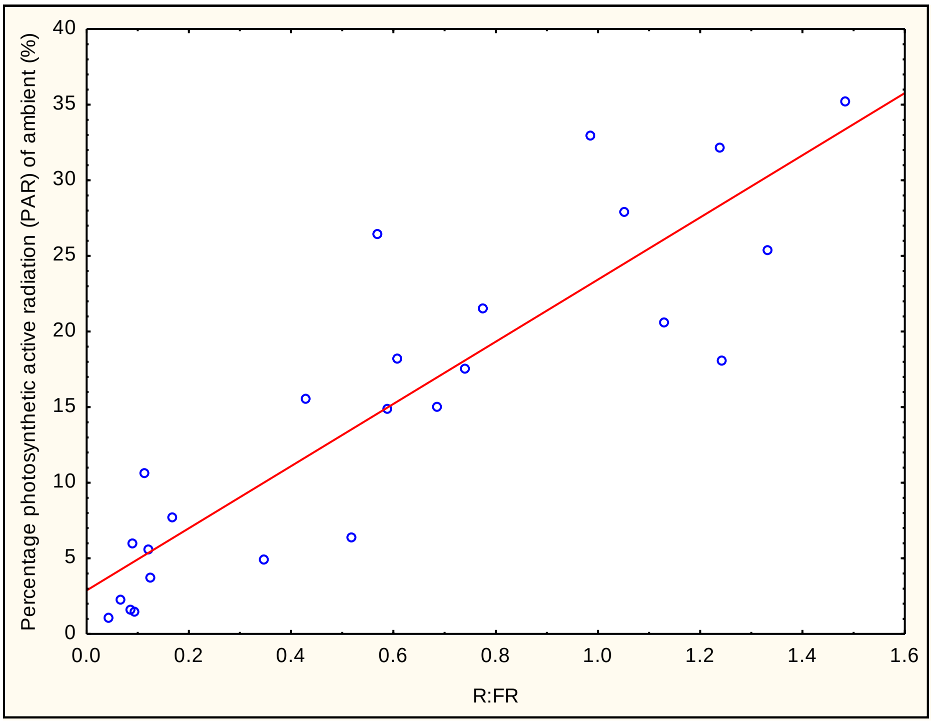


Figure 36 Relationship between the percentage photosynthetic radiation (PAR) of ambient and the ratio of red light to far-red light (R:FR) for all the treatments on three dates of measurements during season 2013/14 (y=2.886+20.5562x; r^2= 0.78). Data points represent means of sensor positions and ceptometer placements (replicates).

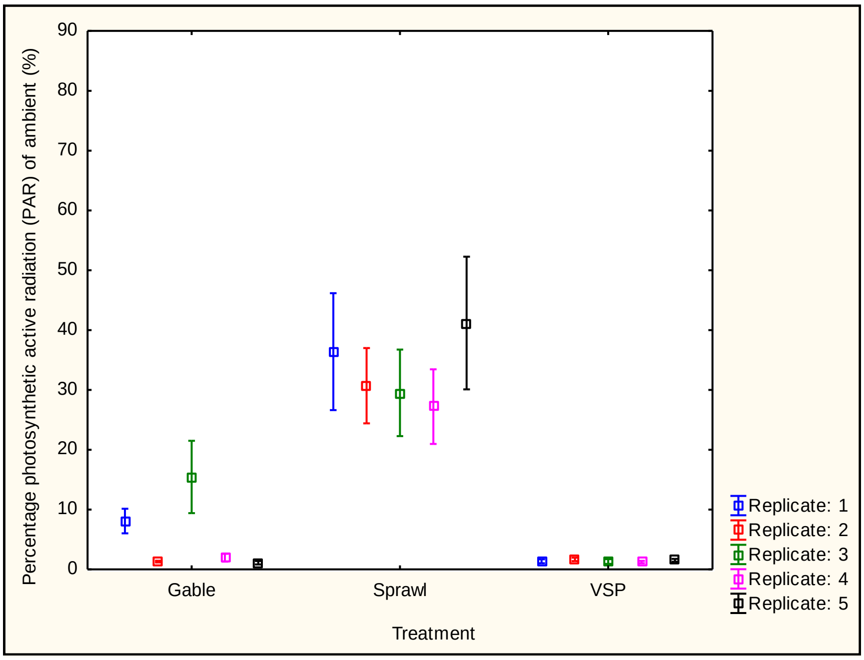


Figure 37 Percentage photosynthetic radiation (PAR) relative to ambient values for each replicate of the different treatments during berry pea size at 14:00 in season 2013/14 (Means with ± standard errors calculated from eight sensor positions and replicates represent ceptometer placements).

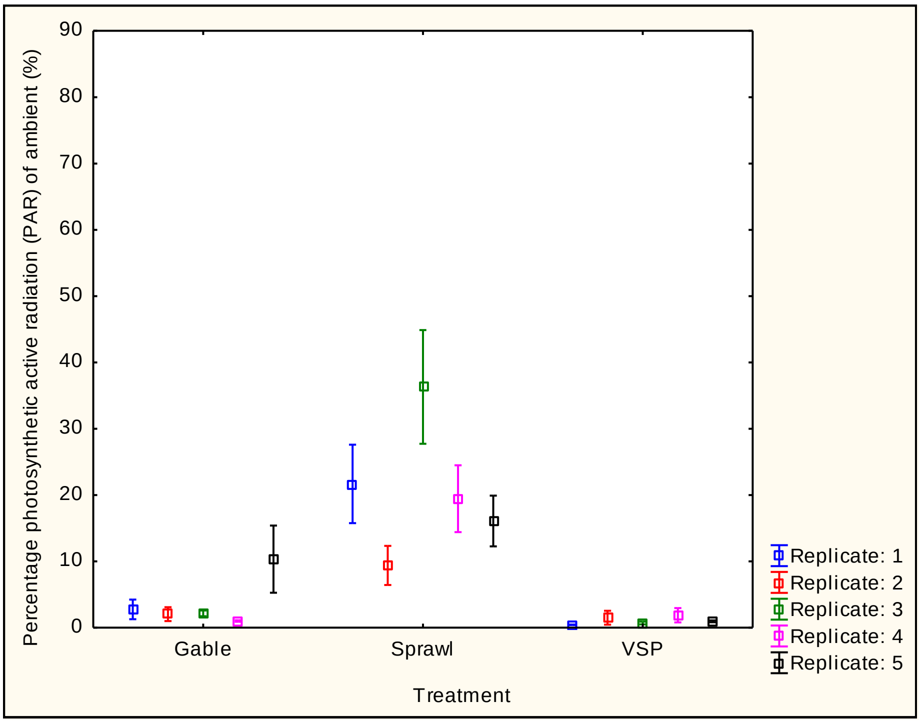
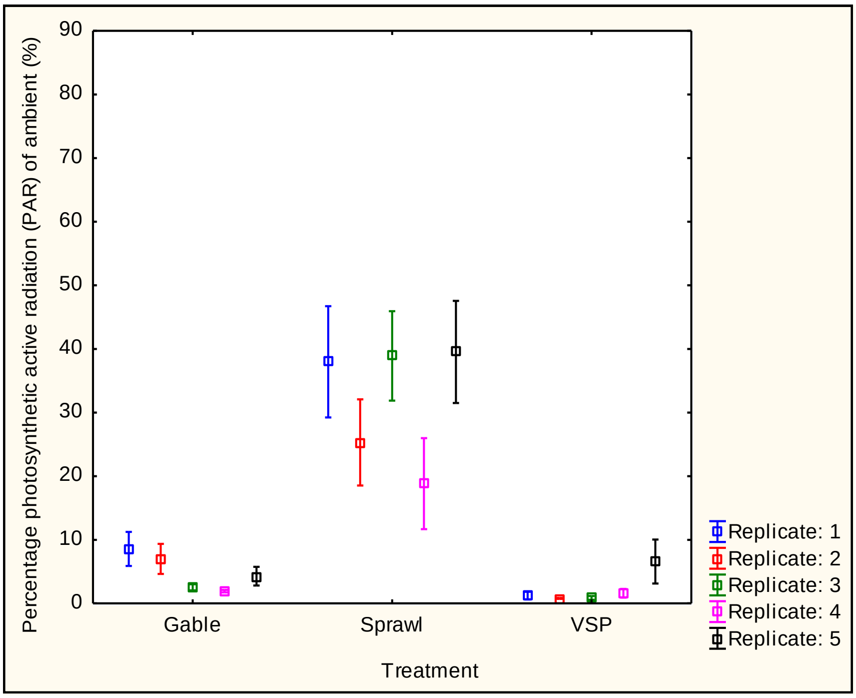


Figure 38 Percentage photosynthetic radiation (PAR) relative to ambient values for each replicate of the different treatments during véraison at 14:00 in season 2013/14 (Means with ± standard errors calculated from eight sensor positions and replicates represent ceptometer placements).



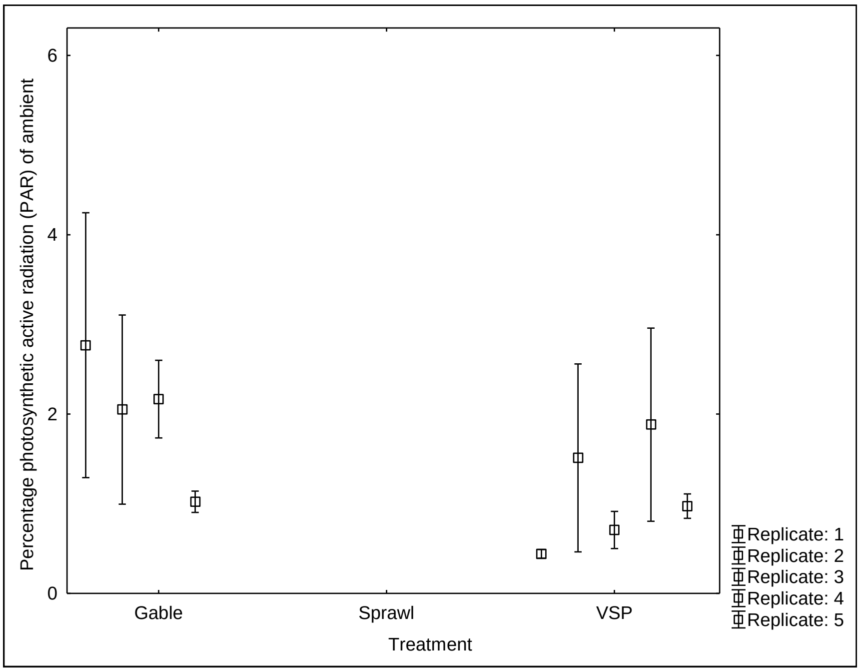


Figure 39 Percentage photosynthetic radiation (PAR) of ambient for each replicate of the different treatments at 14:00 during ripening in season 2013/14 (Means with ± standard errors calculated from eight sensor positions and points of each replicate represents ceptometer placement) (above). The plot below represents more detail on the lower values of the GA and VSP treatments.

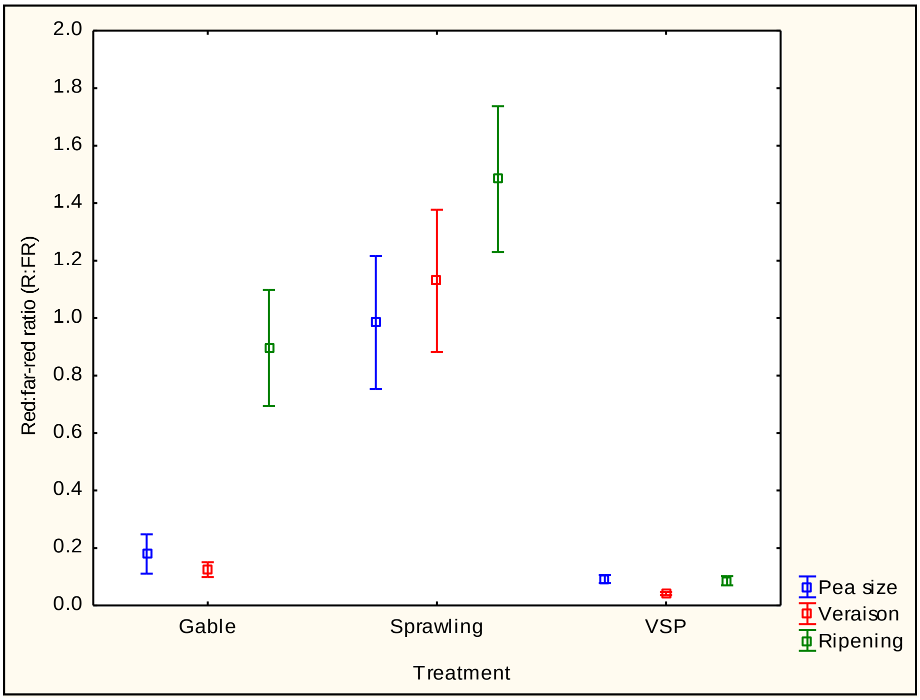


Figure 40 Red/far-red ratio (R:FR) for the different treatments during three phenological stages (pea size, véraison and ripening) at 14:00 in season 2013/14 (means with ± standard errors shown).

3.3.8.2 Sun fleck measurements

The amount of light on the soil surface displayed by the canopy shadow supports the findings in paragraph 3.2.4.1. The S treatment, especially during the afternoon, had the highest amount of canopy gaps, followed by the GA and the VSP treatments (Figure 41). The relative higher percentage sun flecks compared to bunch zone measurements, displayed by the VSP and GA treatments (especially the GA treatment), emphasises the importance of diffuse light which will be present at higher amounts on the soil surface.

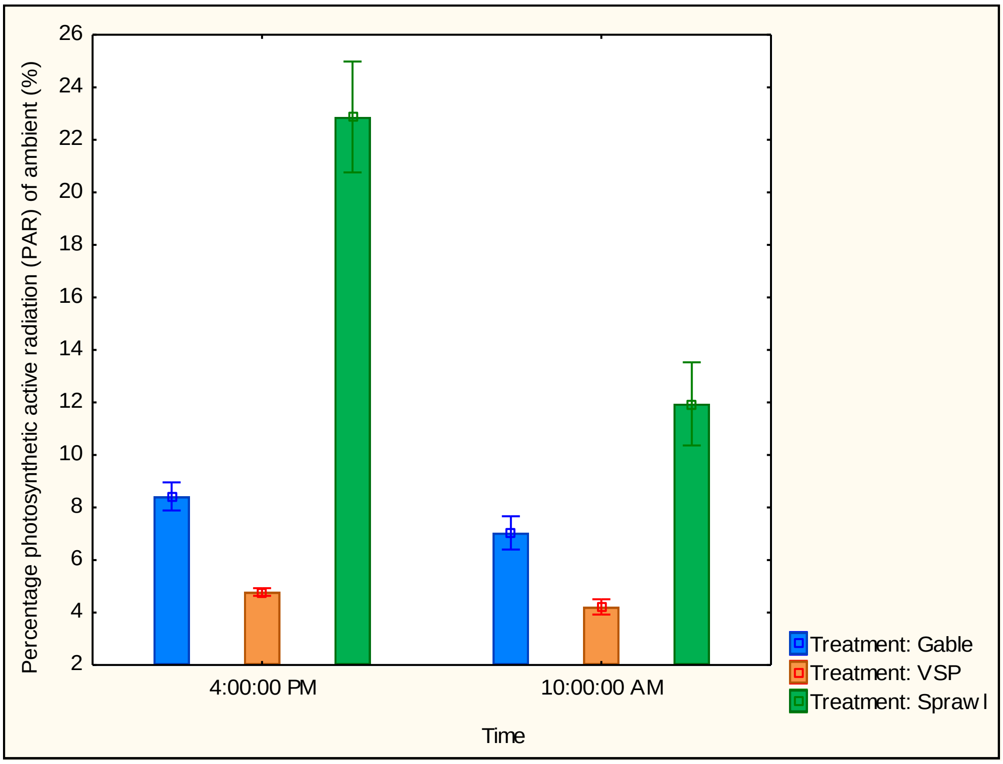


Figure 41The percentage photosynthetic active radiation (PAR) relative to ambient of the different ceptometer sensors on the soil sun fleck surface for the treatments during ripening in season 2013/14 (means ± standard errors).

3.3.8.3 Stomatal conductance

2012/13 season: There were no substantial differences between treatments with regards to stomatal conductance, regardless of leaf age (Figure 42-44). However, differences were evident regarding leaf exposure (Figure 43). The measurements took place during the late stages of ripening only. In general, as expected, the stomatal conductance decreased when stressed conditions increased from 142 to 166 DAB, regardless of leaf exposure and age. The stomatal conductance of all the treatments decreased after 172 DAB, possibly due to leaf degradation and the harvesting of the DS and SS treatments' grapes on 169 DAB (Table 10). This could be the reason why the SS and DS treatments did not display a peak during 172 DAB of older sun leaves compared to the VSP and GA treatments (Figure 42), as stomatal conductance decreases after grapes are removed. The application of irrigation (Figure 22) seemed to keep the stomatal conductance relatively constant. However, on the days where temperatures were above 30°C (DAB 142, 166 and 172) (Figure 9) the stomatal conductance of older sun leaves increased for all the treatments, except for the GA treatment on 142 DAB (Figure 42). A possible explanation may be that when sufficient water was present, due to rainfall in this case (Figure 13), the GA grapevines regulated stomatal aperture. However, when irrigation and rainfall did not occur for some time (DAB 166-172) and temperatures were also between 32-38°C, no regulation took place with GA grapevines exhibiting similar stomatal conductance than VSP grapevines (Figure 42). In contrary to the water status of GA grapevines displaying isohydric-like behaviour (see paragraph 3.3.2.1 and 3.3.2.2). According to Schultz (2003), this indicates typical behaviour of an anisohydric-like Shiraz. It might be that the night time recovery of the GA treatment was much better compared to the other treatments as stomatal regulation occurs during the day and night (Willmer & Fricker, 1996).

The SS and DS treatments displayed definite reduced stomatal conductance in shaded leaves, especially on 121 DAB, relative to the VSP and GA treatments (Figure 43). Denser canopies of the DS and SS treatments could explain this, due to stomata being stimulated by light (Iland *et al*., 2011). However, the % PAR of ambient did not display great differences compared to the VSP and GA canopies (slightly higher than VSP and lower than GA) in the morning when stomatal conductance measurements also took place (Figure 33). However, the shaded leaves of the SS and DS treatments were located beneath the canopy and the PAR measurements were performed in the bunch zone. The GA and VSP treatments displayed higher stomatal conductance than the DS and SS treatments and can be due to less stressed conditions (Figure 23) and, consequently, better stomatal recovery.

The young sun-exposed leaves of SS canopies indicated two irregular peaks during 131 and 142 DAB (Figure 44). Strong winds of ± 4 m/s occurred on 131 DAB (Figure 12) and it maybe that the SS grapevines was more exposed by wind than the rest of the treatments and led to concomitant partial stomatal closure. Temperatures of approximately 34°C occurred on 142 DAB and the young leaves of SS canopies might have been more exposed to the elements, resulting in increased stomatal aperture.

2013/14 season: A general decrease in stomatal conductance occurred as the season progressed. This was expected as stomatal responses become more sluggish and maximum apertures reached are smaller as the leaves age (Willmer & Ficker, 1996).The greatest difference between treatments, regardless of leaf age and exposure, occurred at berry pea size (Figure 45-47). Strong winds of *ca.* 4-5 m/s during that time (Figure 12) might have had a greater effect on the GA treatment resulting in lower stomatal conductance; or stomatal regulation occurred once more when sufficient water were present due to rain at 49 DAB (Figure 13) accompanied by high temperatures (>30°C)(Figure 9). Drier soils possibly experienced by the GA treatment (Figure 19-21) may have also played a role in the decreased conductance. The S treatment displayed a much higher conductance in older shaded leaves compared to the VSP and GA treatments (Figure 46) as well as similar conductance than older sun leaves during pea size (Figure 45). Similar or higher stomatal conductance of shaded leaves can occur when sufficient canopy gaps allows sun flecks and diffused light to reach leaves in the shade (Iland *et al*., 2011) and the higher percentage sun flecks supports this (Figure 41). It may also be that the higher conductance during the early growth stages of the S treatment was due to the presence of older leaves in the canopy as the S treatment displayed earlier budburst than VSP and GA grapevines (Table 29-33).The stomatal conductance remained relatively constant from véraison to ripening with little differences between treatments, except with regards to older sun leaves of S canopies which further decreased as the season progressed (Figure 45). This could be a result of the severe stressed conditions at approximately 116 DAB and failed recovery of S grapevines from there on (Figure

23), which resulted in earlier initiation of leaf degradation and senescence and therefore decreasing stomatal activity. Comparing the overall stomatal conductance during 2013/14 to plant water status (Figure 23), it seemed that higher stomatal conductance were present in the absence of stress and decreased conductance in the presence of stress. The maximum temperatures on the day of measurements were between 36°C and 40°C for véraison (106-113 DAB) and ripening (141-146 DAB)(Figure 9) and it might be that even in the absence of stress, stomatal conductance remained constant at these temperatures.

The 2012/13 season displayed overall higher stomatal conductance compared to season 2013/14. The plant water status during 2012/13 also displayed overall lower values (less negative Ψ_{PD}). This can be due to more irrigation applied (Figure 22) and higher rainfall during 2013/14 (Table 15). It was not necessarily the effect of the climate, with both the 2012/13 and 2013/14 seasons displaying similar GDD (Figure 10).However, the high November rainfall in the 2013/14 season (Table 15) may have led to increased grapevine vigour and therefore resulted in the development of more dense canopies. More dense canopies will transpire more rapidly and increase soil water extraction which was evident regarding soil moisture content at the end of the second season, especially in the deeper soil layers (Figure 20 & Figure 21). Increased stress conditions (more negative Ψ_{PD}) and therefore lower stomatal conductance in the 2013/14 season could have been the result.

During ripening, shaded leaves could not be found for the GA treatment and this is supported by the increased red to far red values during the end of the season (Figure 40) as a result of a decrease in canopy density possibly due to leaf degradation/abscission. The S treatment displayed the same response but shaded leaves were abundant being beneath the canopy. Perhaps the leaves exposed to sun experienced too high exposure leading to increased leaf senescing and leaf abscission. Variability of the data during both seasons for all treatments could be due to the impact of the environment on stomata. The stomatal conductance values were measured during three phenological stages in 2013/14 at three different times of day in the order of the GA, VSP and S treatments (the measurement of each treatment lasting ± 40 min), which could also have contributed to the high variation (Figure 48). Clearly the temperatures differed with regards to time of day. Unfortunately the mesoclimatic data for the 2012/13 season could not be retrieved due to technical difficulties with the data loggers.

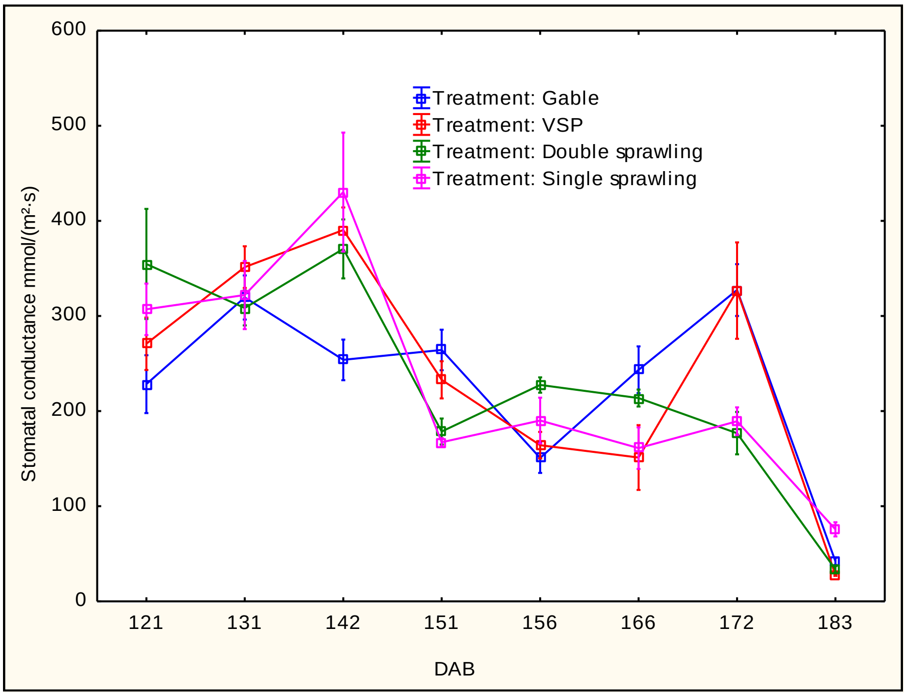


Figure 42 Stomatal conductance relative to days after budburst (DAB) of older sun-exposed leaves for the treatments during season 2012/13 (means ± standard errors).

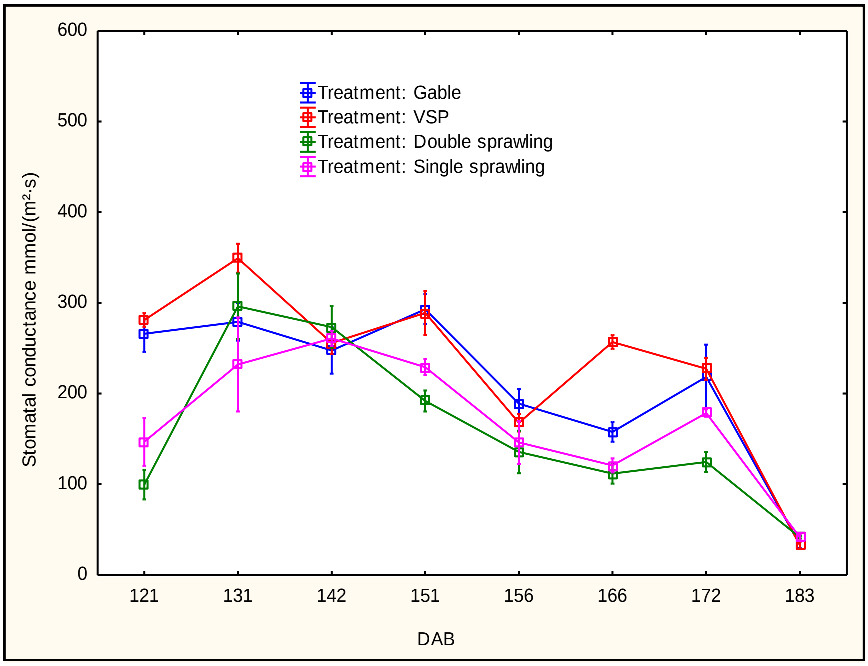


Figure 43 Stomatal conductance relative to days after budburst (DAB) of older shaded leaves for the treatments during season 2012/13 (means ± standard errors).

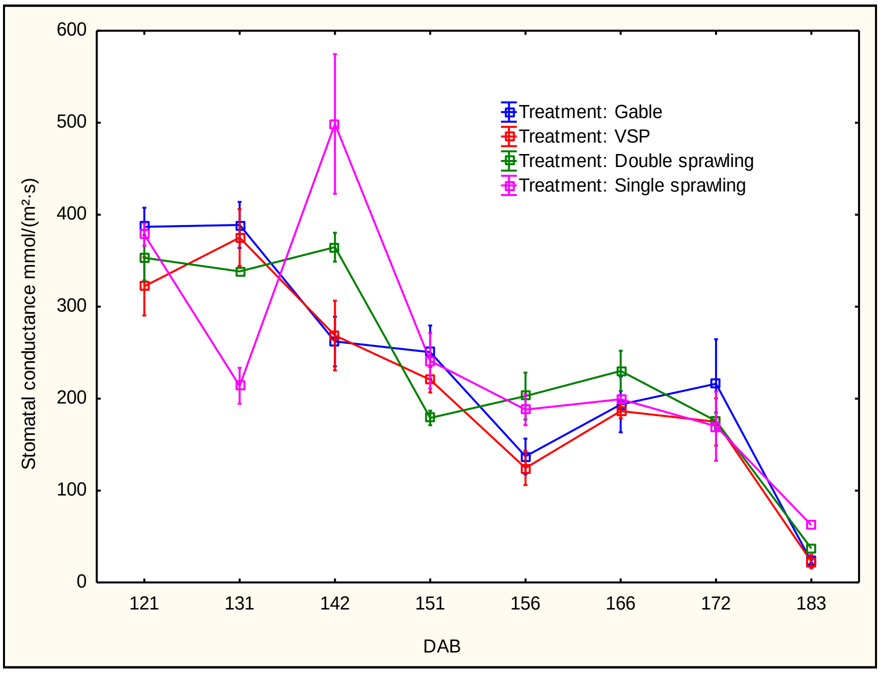


Figure 44 Stomatal conductance relative to days after budburst (DAB) of young sun-exposed leaves for the treatments during season 2012/13 (means ± standard errors).

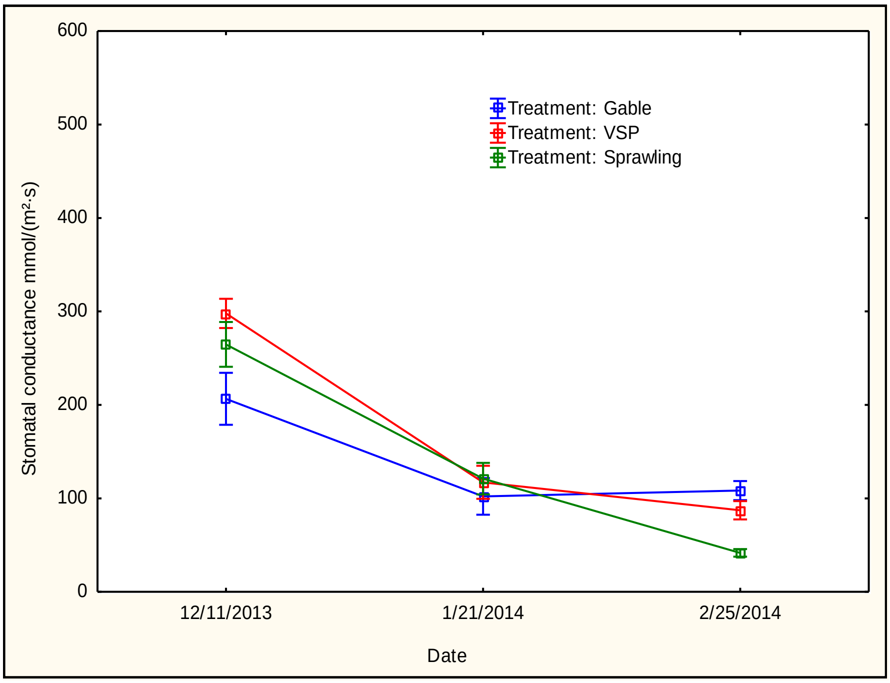


Figure 45 Stomatal conductance relative to date (pea size, véraison and ripening) of older sun-exposed leaves for the treatments during season 2013/14 (means ± standard errors).

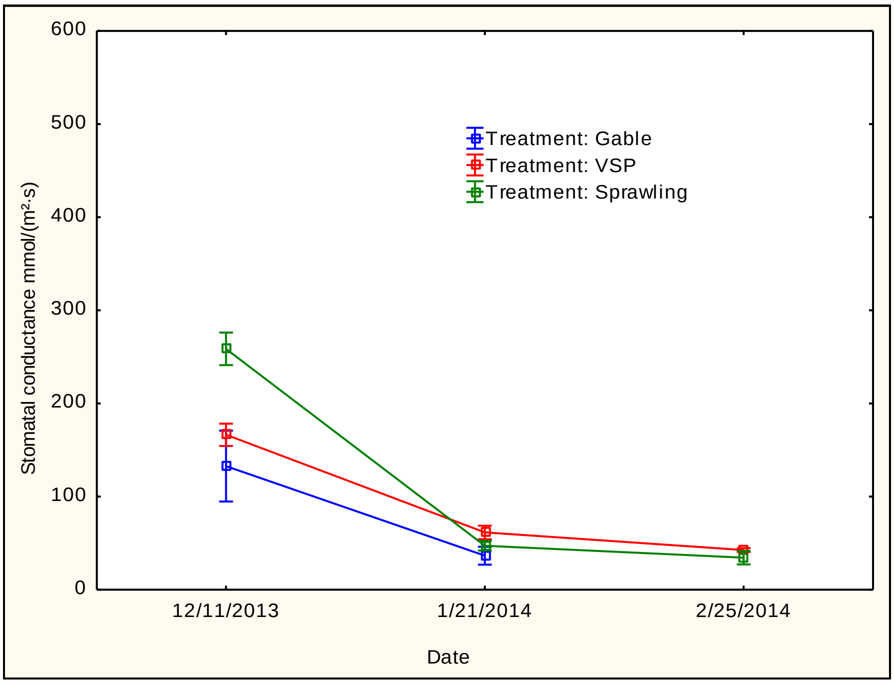


Figure 46 Stomatal conductance relative to date (pea size, véraison and ripening) of older shaded leaves for the treatments during season 2013/14 (means ± standard errors).

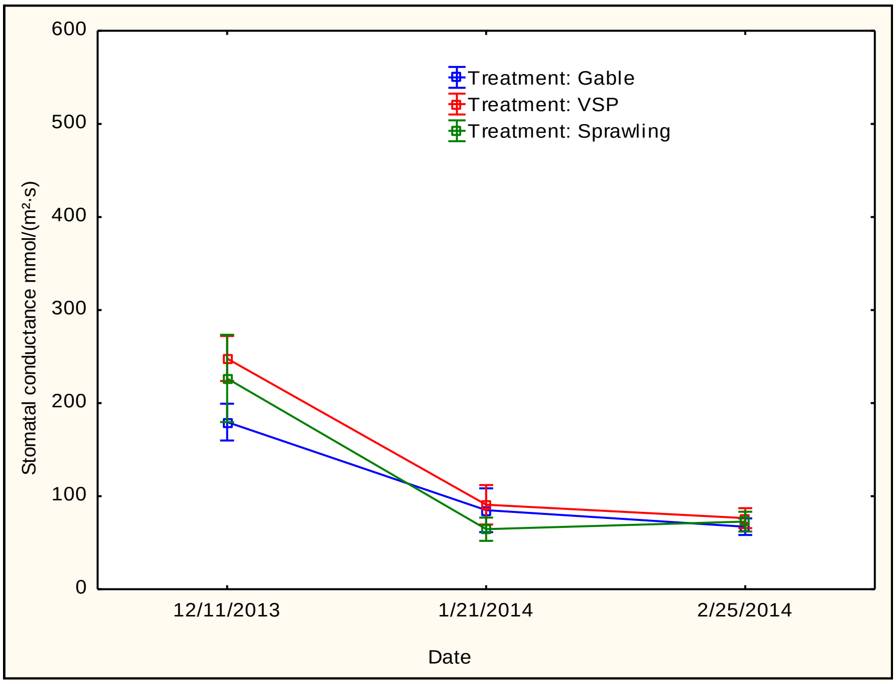


Figure 47 Stomatal conductance relative to date (pea size, véraison and ripening) of young sun-exposed leaves for the treatments during season 2013/14 (means ± standard errors).

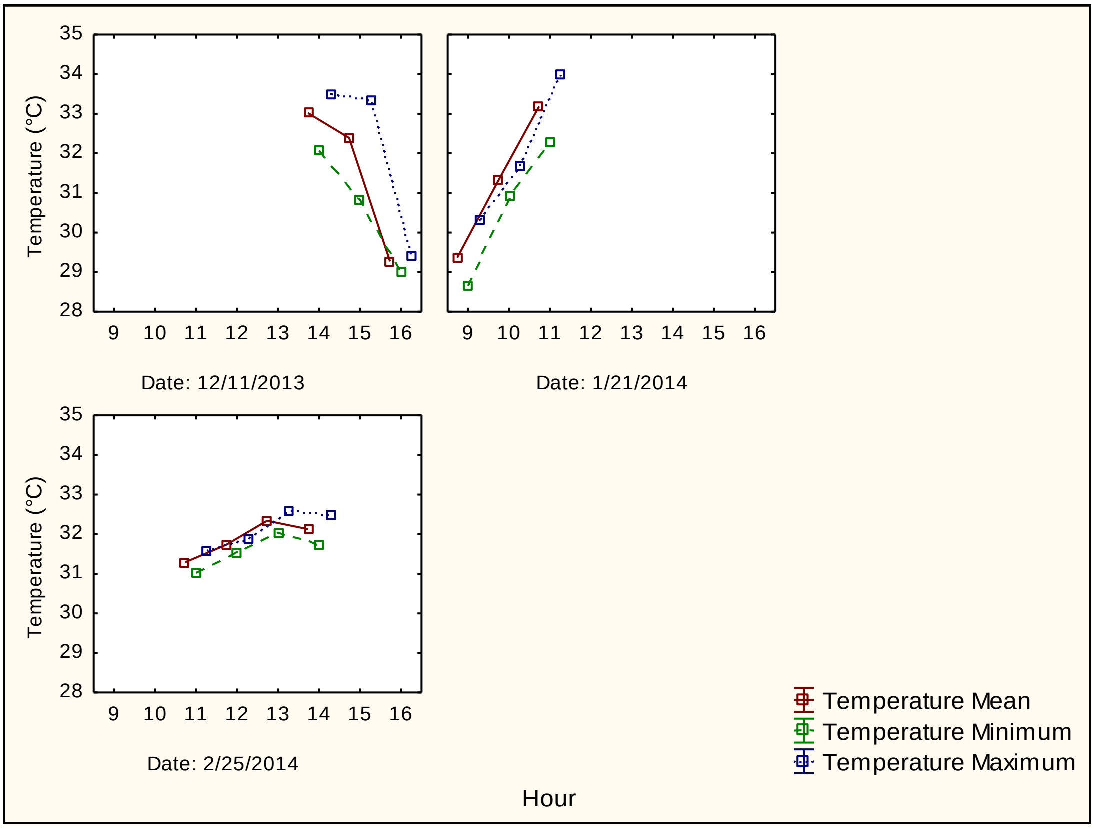


Figure 48 Minimum, mean and maximum temperatures relative to hour of day during three phenological stages in season 2013/14 (means ± standard errors).

3.3.8.4 Chlorophyll content index (CCI)

2012/13 season: The chlorophyll content was measured at a late stage during the season (Figure 49-51). In general it can be concluded that the leaves sustained chlorophyll late during the season - up to 166-172 DAB, which was prior to harvest (Table 10). Stressed conditions and failed recovery of the SS treatment at 163 DAB (Figure 23) may explain the rapid decreases of CCI after 156 DAB.

2013/14 season: The CCI for older leaves reached maximum levels at véraison after which it decreased considerably (Figure 52 & Figure 53). This only occurred for the VSP and S treatments while the CCI of the GA treatment stayed constant after maximum levels were reached. It might be that the high sink demand (crop) of GA grapevines delayed chlorophyll degradation, as Hofäcker (1978) explained that higher sink activity lead to increased chlorophyll concentrations due to sustained photosynthesis. The greatest differences between treatments also occurred during véraison. Hunter and Visser (1989) reported higher chlorophyll contents of leaves located in the interior of the canopy. This was seen only for the S treatment, while the chlorophyll content of the GA treatment was similar between leaf exposures and higher for the older sun leaves of the VSP treatment during véraison (Figure 52 & Figure 53). The S and VSP treatments displayed similar CCI for old shaded leaves up until after véraison where the shaded leaves of S canopies underwent immense degradation possibly due to severe water stress during that time (116 DAB) (Figure 23) and higher canopy exposure (Figure 38) stimulating chlorophyll degradation. The yellow leaves are clearly illustrated in Figure 24. The higher chlorophyll content of older VSP leaves can be attributed to the lower % PAR of ambient (Figure 37-39) and red to far red ratios (Figure 40). Kappel and Flore (1983), as well as Marini and Marini (1983), also found similar results where chlorophyll concentrations in sun-exposed leaves were higher than ones in more shaded conditions. However, the GA canopies displayed lower light levels than S canopies but contained overall lower chlorophyll concentrations. Lower chlorophyll accumulation may be a result of the lower vigour of the GA treatment, where an increased number of sinks from increased number of shoots probably led to the distribution of nitrogenous compounds such as chlorophyll.

The differences between treatments might also be due to the effect of leaf age. The S treatment had the oldest leaves in the canopy at about the time of véraison (Figure 28) which may explain the higher CCI of young leaves (Figure 54). The VSP treatment in contrast had the youngest canopy at véraison, therefore a lower CCI for young leaves. The VSP treatment also had the oldest leaves, ranging up to 170 days old (Figure 27), which may explain the high CCI values of older leaves (Figure 52 & Figure 53).

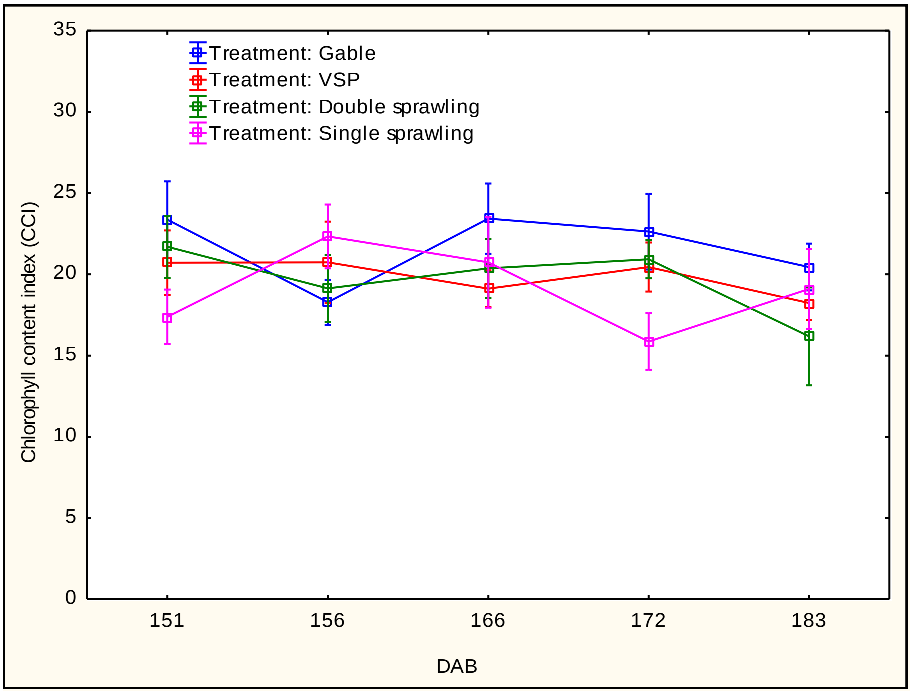


Figure 49 Chlorophyll content index (CCI) relative to days after budburst (DAB) of older sun-exposed for the different treatments during season 2012/13 (means ± standard errors).

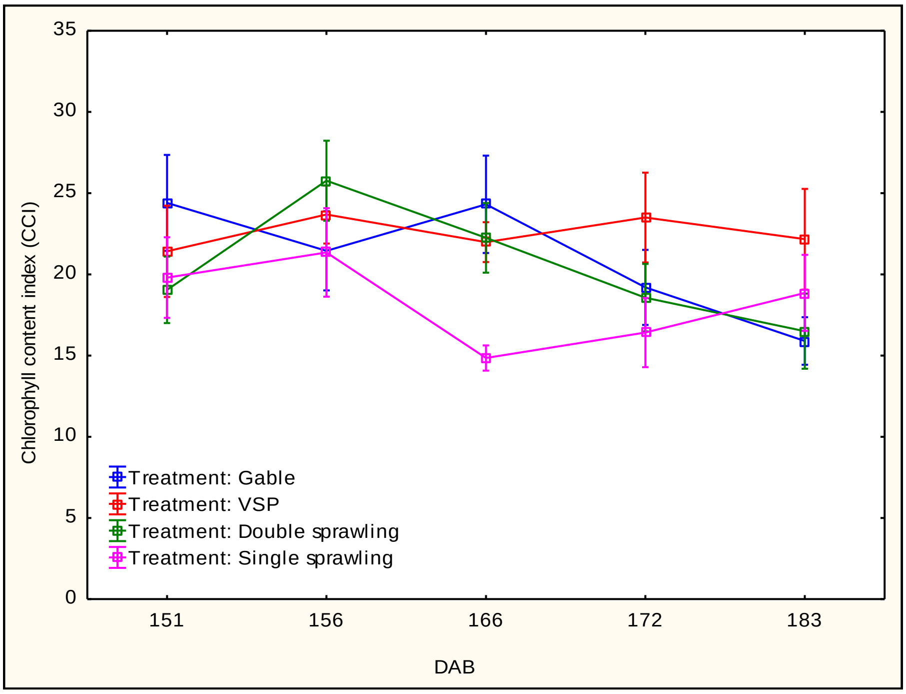


Figure 50 Chlorophyll content index (CCI) relative to days after budburst (DAB) of older shaded leaves for the different treatments during season 2012/13 (means ± standard errors).

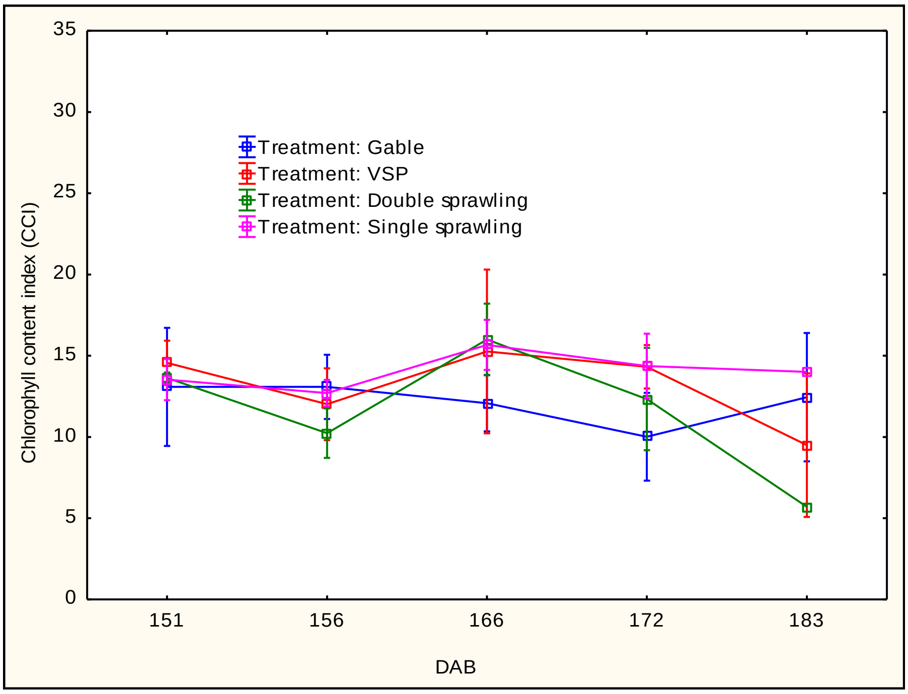


Figure 51 Chlorophyll content index (CCI) relative to days after budburst (DAB) of younger sun-exposed for the different treatments during season 2012/13 (means ± standard errors).

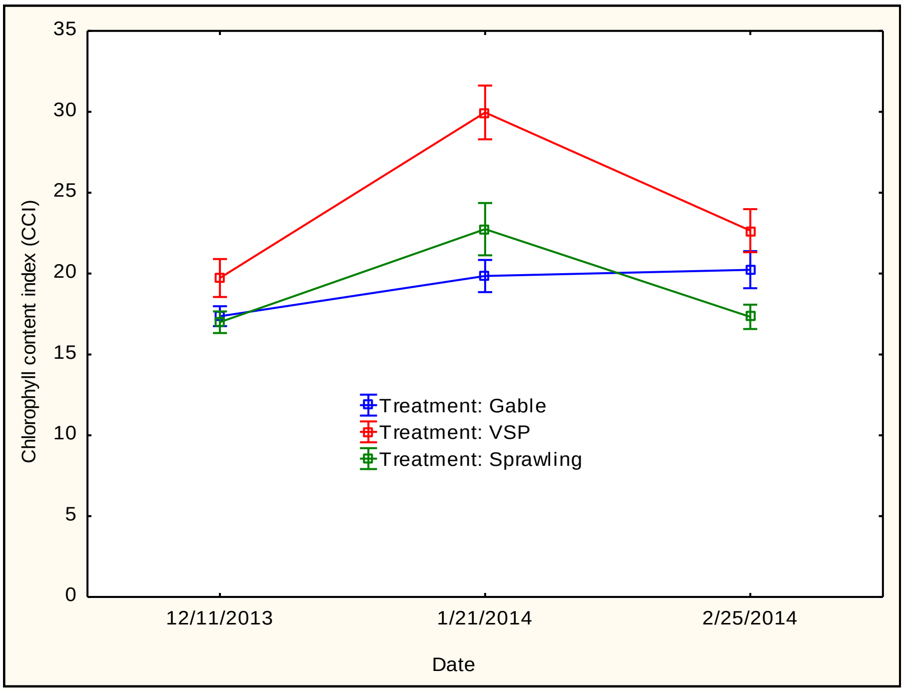


Figure 52 Chlorophyll content index (CCI) relative to date (pea size, véraison and ripening) of older sun-exposed leaves for the different treatments during season 2013/14 (means ± standard errors).

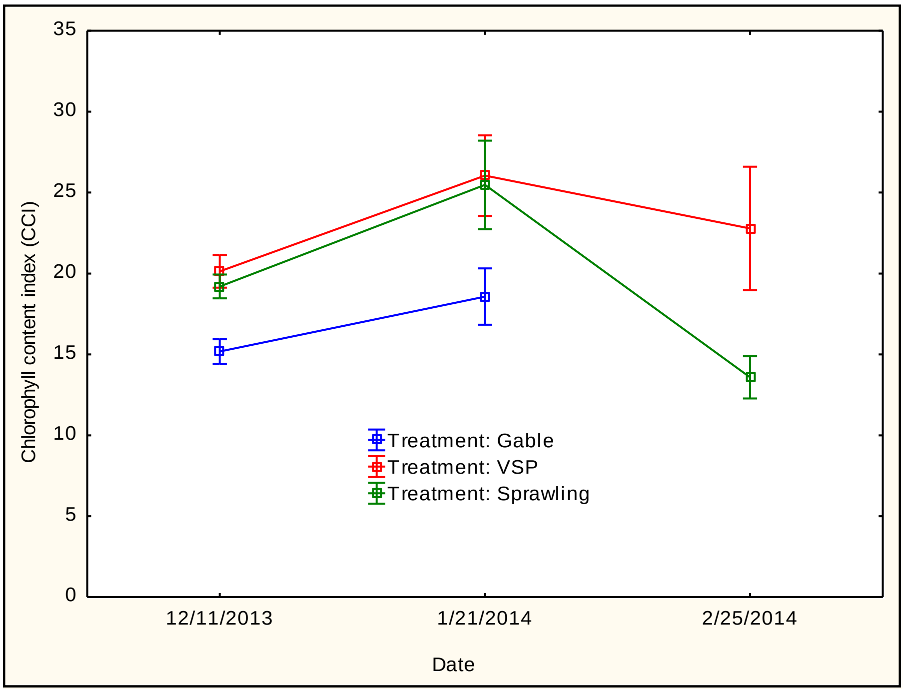


Figure 53 Chlorophyll content index (CCI) relative to date (pea size, véraison and ripening) of older shaded leaves for the different treatments during season 2013/14 (means ± standard errors) (note that no shaded leaves could be found for GA treatment during ripening).

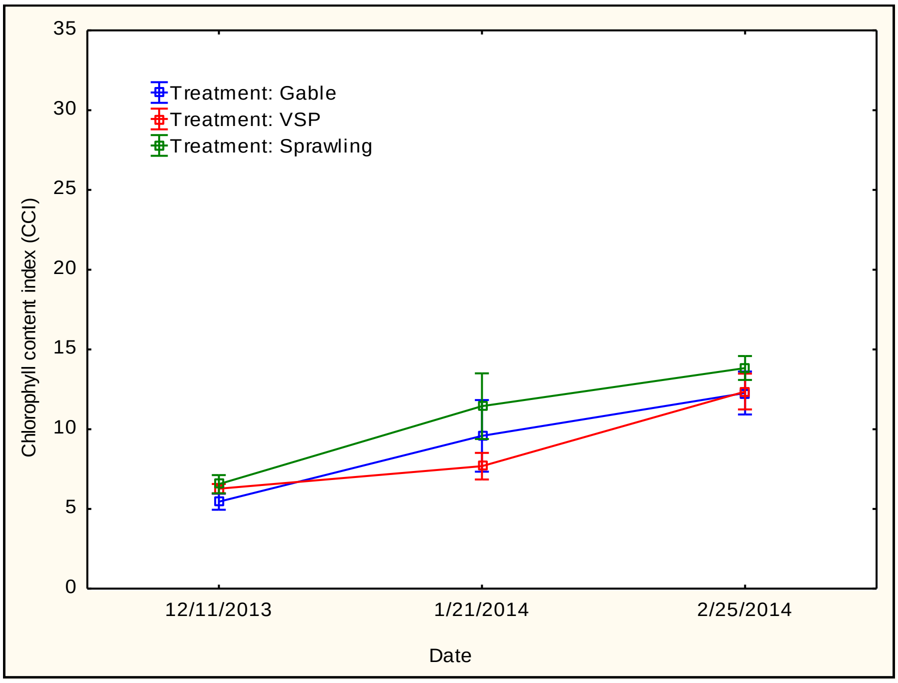


Figure 54 Chlorophyll content index (CCI) relative to date (pea size, véraison and ripening) of young sun-exposed leaves for the different treatments during season 2013/14 (means ± standard errors).

3.3.9 Ripening

The evolution of sugar per berry (mg/berry) was lower for the GA treatment compared to the rest of the treatments during season 2012/13 (Figure 55). During 2013/14, the lowest sugar loading seemed to occur with the S treatment (Figure 56). Delayed phenology might be the cause when looking at the berry volume evolution, with the GA (Figure 59) and S (Figure 60) treatments displaying lower berry volumes in the beginning of ripening. Berry mass was not displayed due to a high correlation of higher than r^2=90 (data not shown) to berry volume. Delayed phenology could be a response of grapevine imbalance with the GA treatment containing a low LA/Y ratio and both the GA and S treatments with high Y/CM ratios (Table 24 & Table 25). A low LA/Y ratio, as a result of high bunch numbers and low leaf area/vine, could possibly result in carbon allocation restriction to bunches, which slows ripening and prevents the ripening of bunches to desirable levels (Edson *et al*., 1993; Miller & Howell, 1998). This was definitely the case for the GA treatment during 2012/13 (Table 24) and can explain the delayed sugar accumulation (Figure 55 & Figure 57). The same might have occurred regarding the presence of high Y/CM ratios (as result of increased yields) in the case of GA (Table 24) and S (Table 25) grapevines. Lower berry volumes, in the case of the S treatments, can be the result of severe stressed conditions during the onset of ripening (DAB 113) (Figure 23) and an inability to recover from stress even though irrigation was applied as discussed previously (Bindon *et al*., 2011). Reduced sugar unloading from the phloem to the grape berry is also a response of water deficits (Esteban, *et al*., 2002) and can also explain the delayed sugar loading. Bindon *et al*. (2008) concluded that high bud loads had a definite decreasing effect on sugar accumulation. This supports the sugar loading response of the S treatment, with higher bud loads (Table 22). The GA treatment had the smallest berries at harvest during both seasons (Table 21 & Table 22). During the 2012/13 season, the berries from the GA grapevines were smaller from the beginning of the season (Figure 59). However, smaller berries during 2013/14 was due to a decrease in berry volume from 164 DAB (Figure 60), which can be related to higher mean bunch temperatures than the other systems during that time (Figure 16).

According to Miller and Howell (1998), increased crop load can also be associated with lower pH and higher titratable acidity (TA). The GA treatment clearly displayed this response during 2012/13 (Figure 61 & Figure 63). The pH levels of the S and GA treatments, consisting of higher yields, were similar which were together lower than the VSP treatment (Figure 64). However, little differences were seen with regards to TA during 2013/14, with S berries showing only slightly lower TA values (Figure 62). Smart (1982) stated that juice pH is the most affected by microclimate. Higher pH values of VSP berries during 2013/14 could be the result of more shaded canopy conditions relative to the open canopies of S and GA grapevines (Figure 37-39) (Smart, 1991; Archer & Van Schalkwyk, 2007).

It can be concluded that delayed ripening, in terms of sugar evolution, is the effect of source to sink balances within the grapevine. This was evident when referring to the GA treatment during both seasons, where high Y/CM and low LA/Y ratios during 2012/13 restricted sugar loading, while adequate ratios in 2013/14 had no effect on sugar accumulation. The ripening of the S treatment was a combined effect of water deficit and yield to cane mass relationship. Adequate LA/Y yield ratios occurred, but also increased Y/CM ratios, indicating sufficient foliage to effectively ripen grapes but decreased pruning mass, as result of either water stress or pruning level, together with high crops, possibly restricting carbon allocation and sugar accumulation.

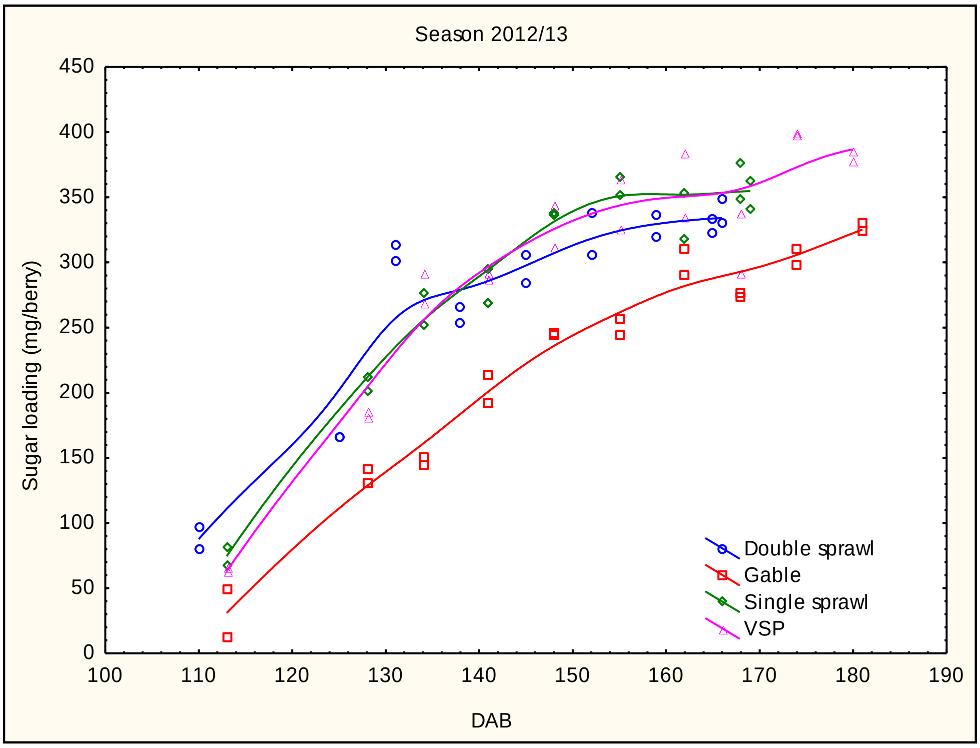


Figure 55 The evolution of berry sugar content relative to days after budburst (DAB) from ±10°B up to harvest for the treatments in season 2012/13 (distance- weighed least- square fits are shown).

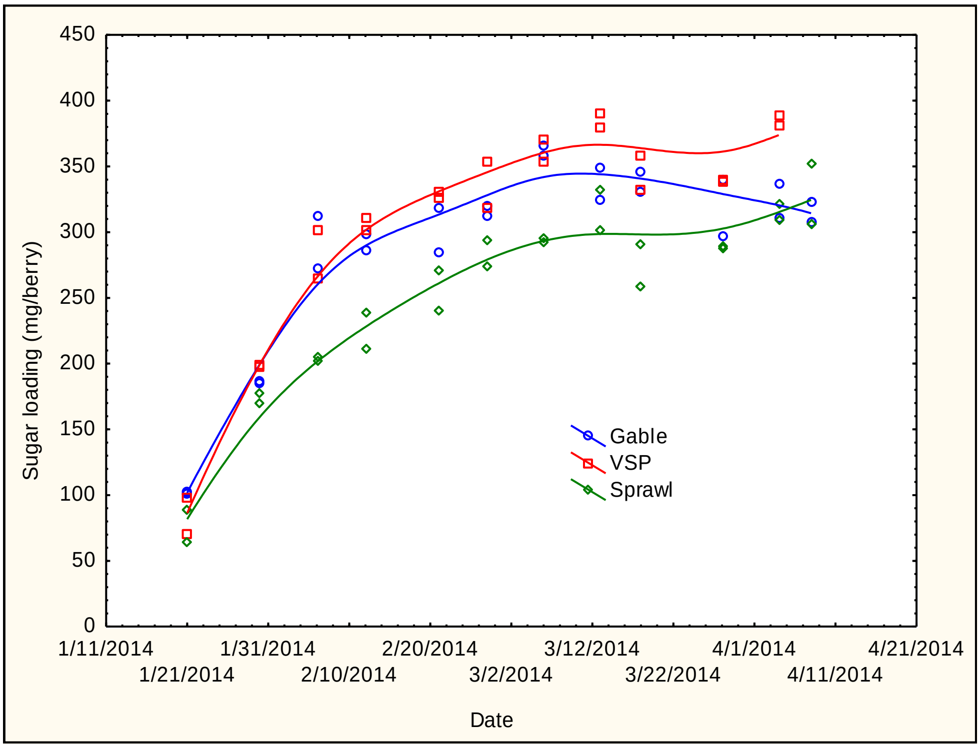


Figure 56 The evolution of berry sugar content relative to date from ±10°B up to harvest for the treatments in season 2013/14 (distance- weighed least- square fits are shown).

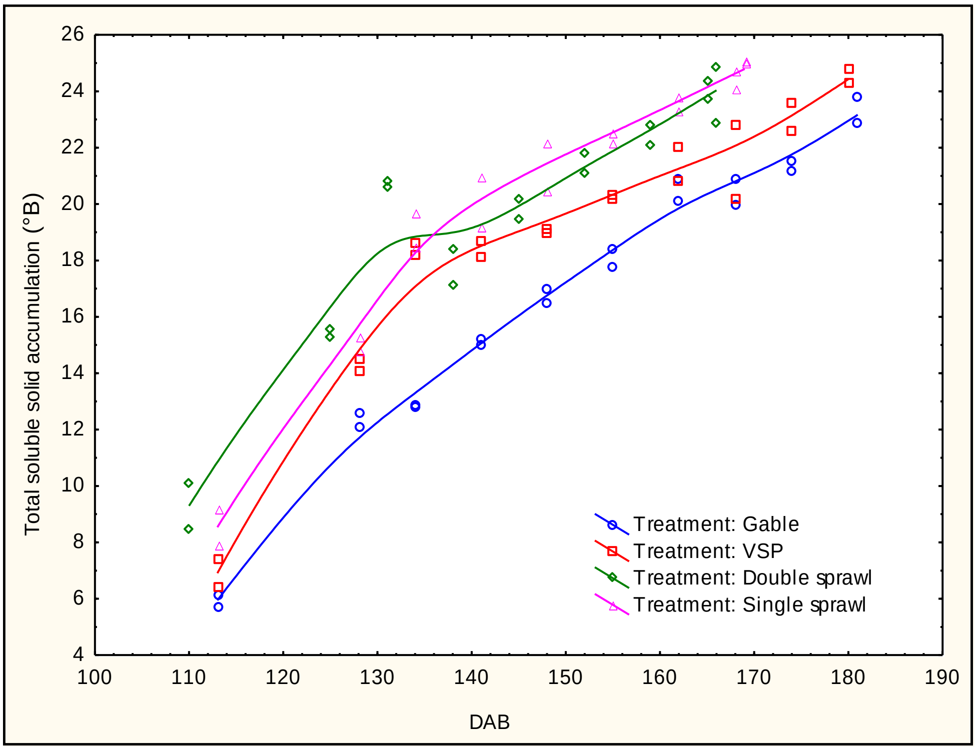


Figure 57 Total soluble solids accumulation relative to days after budburst (DAB) for the treatments during season 2012/13 (distance- weighed least- square fits are shown).

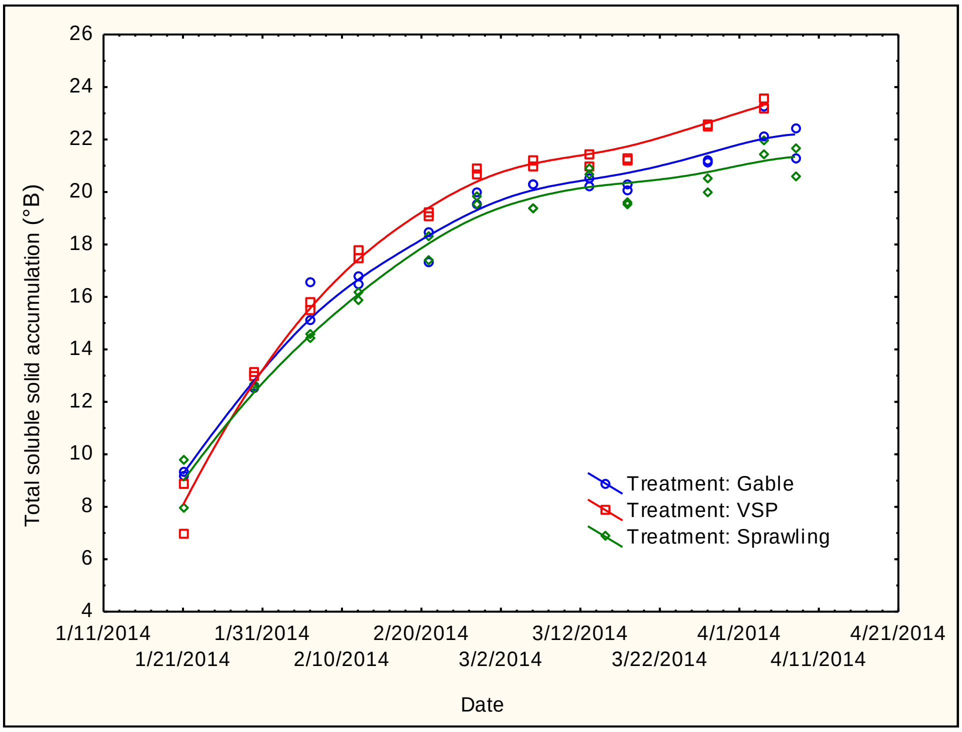


Figure 58 Total soluble solids accumulation relative to date for the treatments during season 2013/14 (distance- weighed least- square fits are shown).

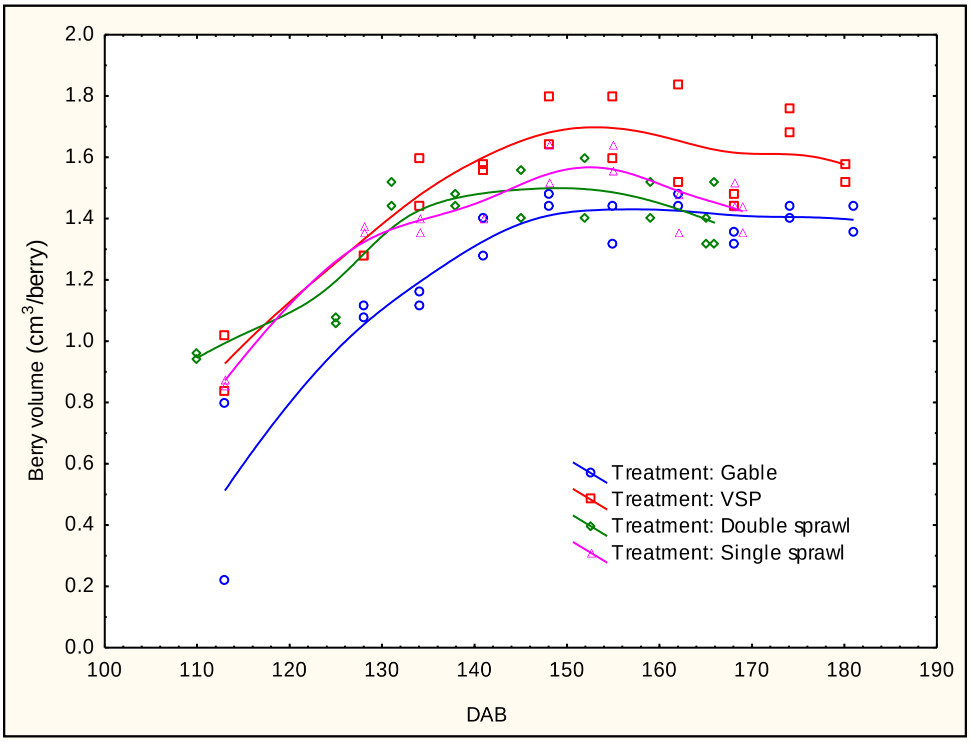


Figure 59 Berry volume relative to days after budburst (DAB) for the treatments during season 2012/13 (distance- weighed least- square fits are shown).

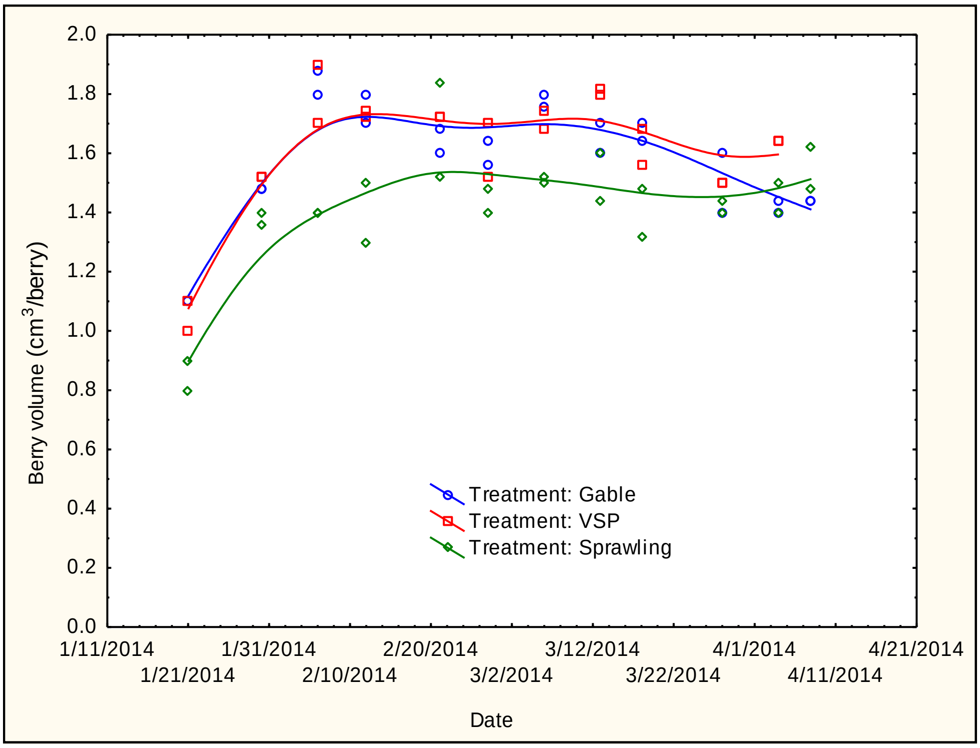


Figure 60 Berry volume relative to date for the treatments during season 2013/14 (distance- weighed least- square fits are shown).

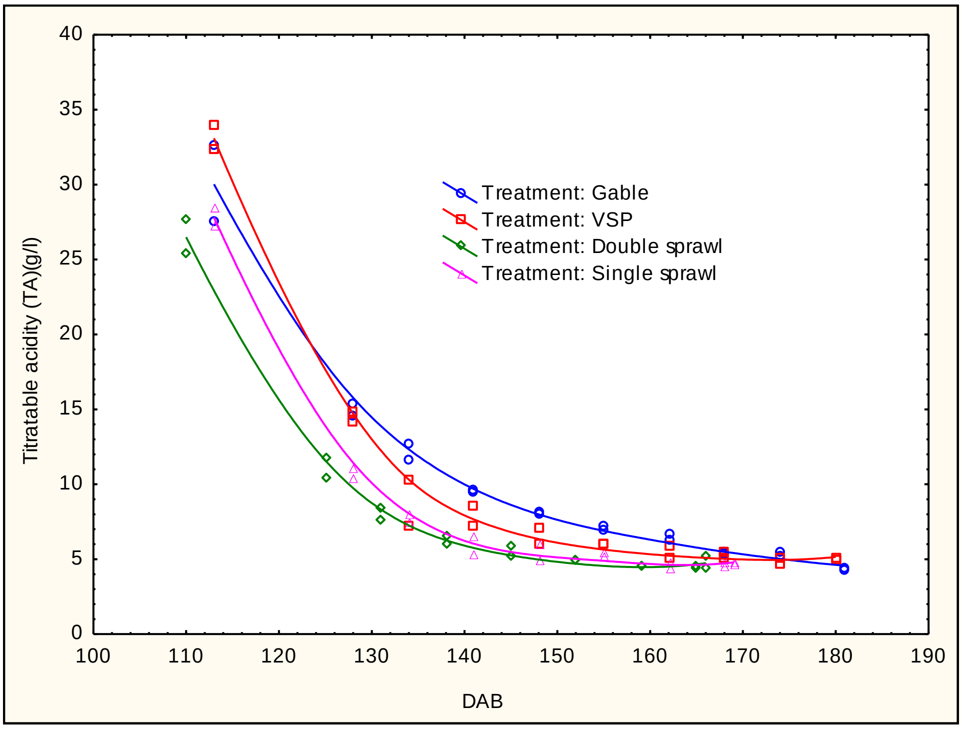


Figure 61 Titratable acidity (TA) relative to days after budburst (DAB) for the treatments from ±10°B up to harvest in season 2012/13 (distance- weighed least- square fits are shown)

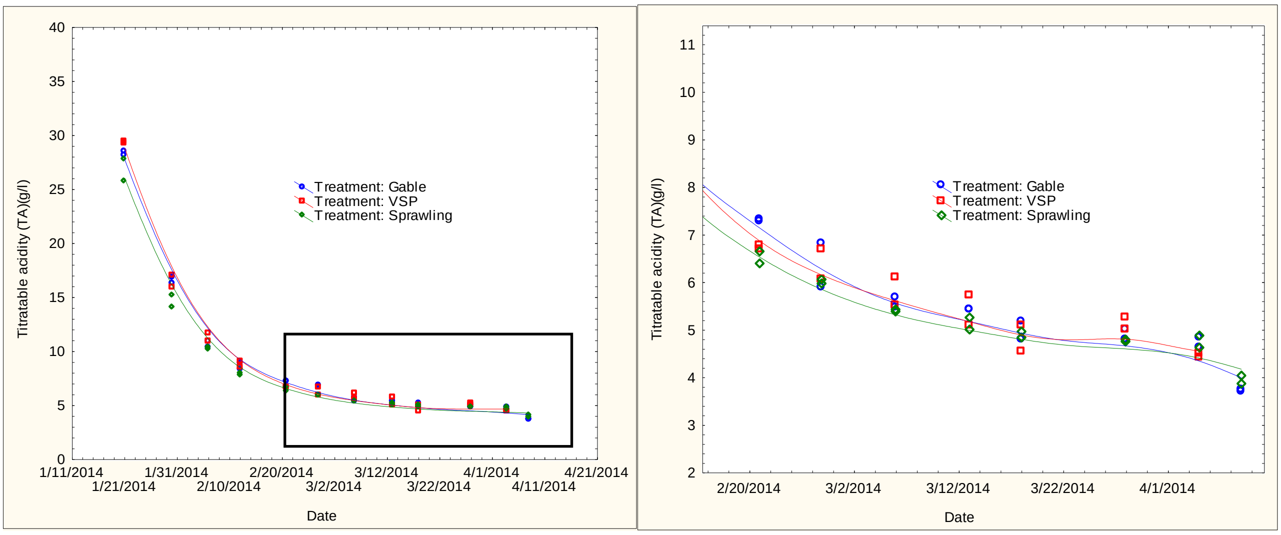


Figure 62 Titratable acidity (TA) relative to date for the treatments from ±10°B up to harvest in season 2013/14 (distance- weighed least- square fits are shown). Demarcated area shown on the figure on the right.

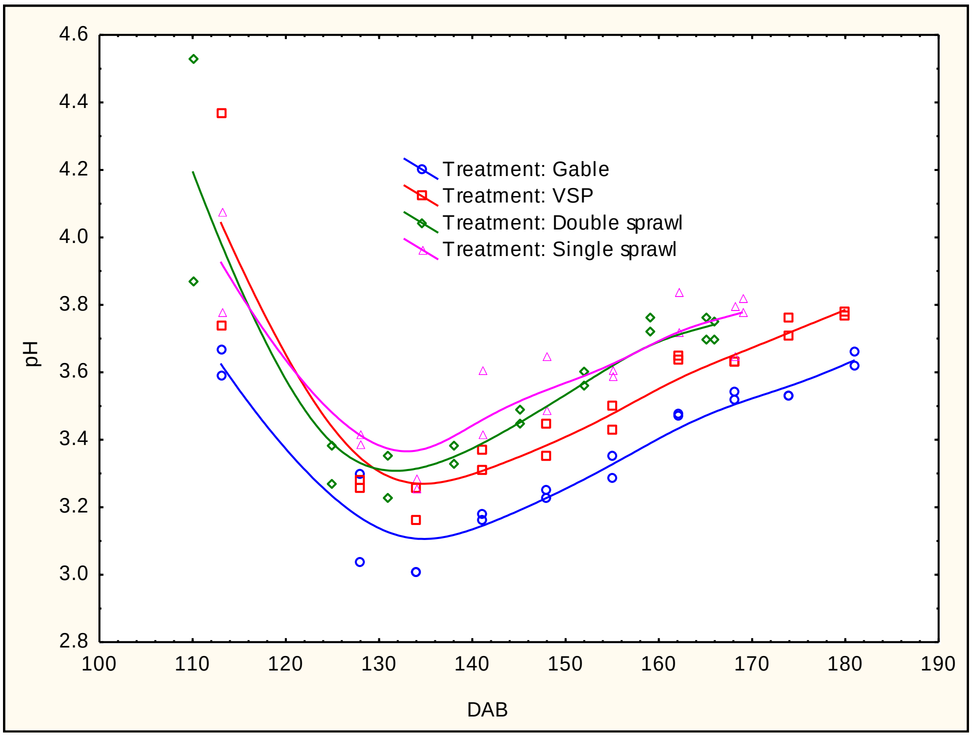


Figure 63 Berry pH values relative to days after budburst (DAB) for the treatments from ±10°B up to harvest in season 2012/13 (distance- weighed least- square fits are shown).

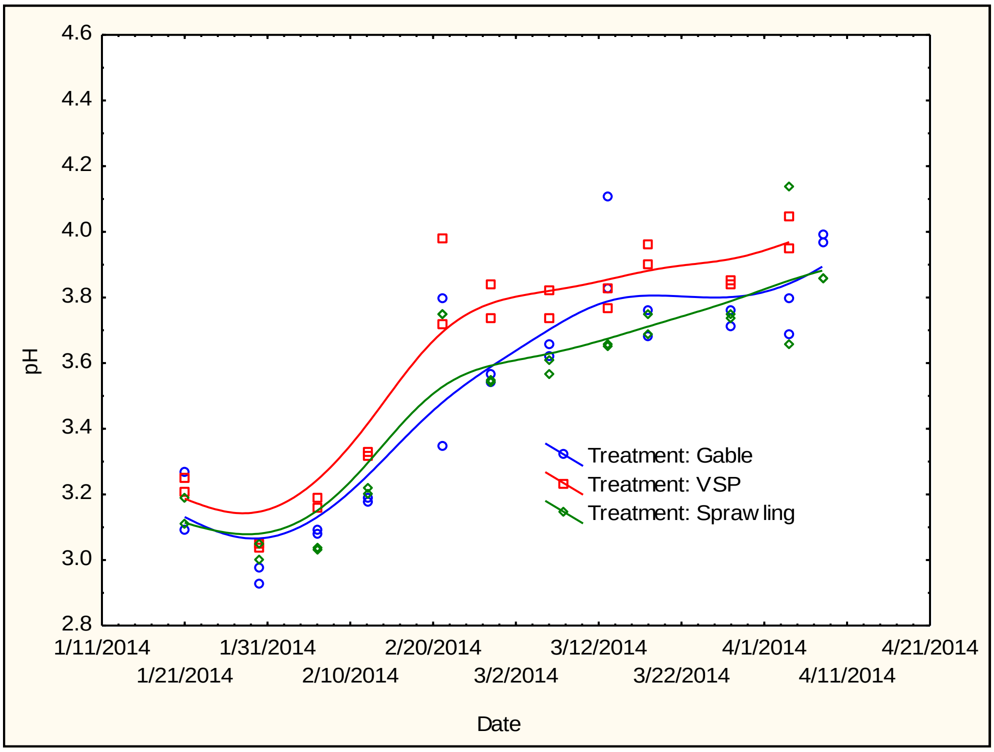


Figure 64 Berry pH values relative to date for the treatments from ±10°B up to harvest in season 2013/14 (distance- weighed least- square fits are shown).

3.3.10 Phenolic measurements

3.3.10.1 Grape juice analyses

Without the consideration of berry size (expressed as per gram berry mass), the highest colour and total phenolics per berry were obtained with the VSP trellis system (Figure 65 & Figure 67). In contrast, when berry size was considered, the GA treatment produced the highest colour (Figure 66). The improved colour per gram berry mass of GA berries relative to VSP berries can be ascribed to better sunlight penetration in the bunch zone (Figure 38)(Clingeleffer, 1988; Clingeleffer, 1993) and the smaller berries produced by GA grapevines (Table 22). The VSP treatment's grape juice contained the highest phenolics regardless of berry size (Figure 67 & Figure 68). In contrast to findings reported by Bindon *et al.* (2011), in the current study the reduced berry volume as a consequence of water deficits on S grapevines did not seem to lead to increased anthocyanin concentrations. Grape berries from S bunches, overall displayed the lowest colour and phenolics compared to the other treatments. It might be that the prolonged higher light intensities (Figure 37-39) and increased maximum temperatures (Figure 17) in the bunch zone of the S treatment, reached the threshold over which anthocyanin concentration declines (Mabrouk & Sinoquet, 1998).

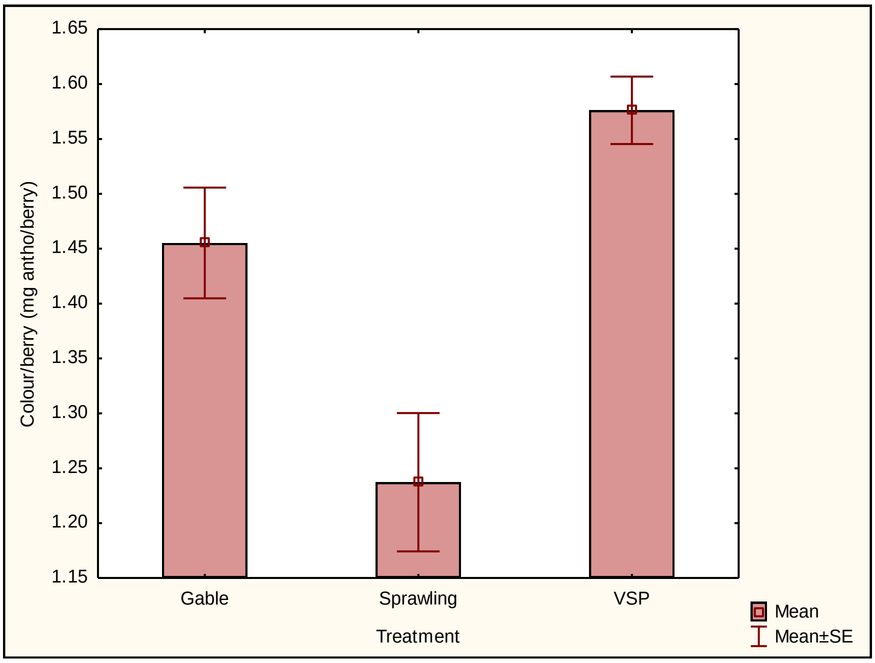


Figure 65 Colour per berry for the treatments evaluated at harvest during season 2013/14 (means ± standard errors).

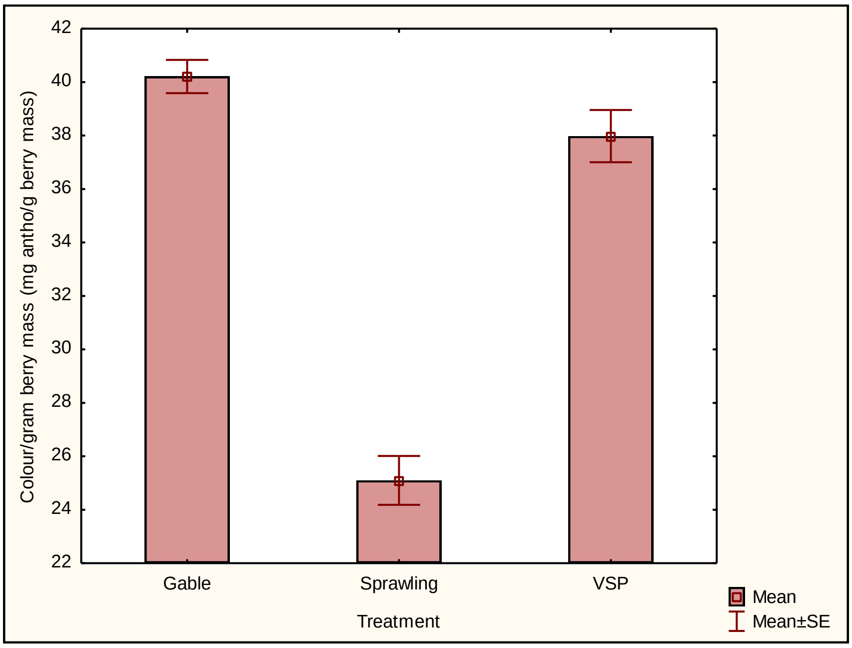


Figure 66 Colour per gram berry mass for the treatments evaluated at harvest during season 2013/14 (means ± standard errors).

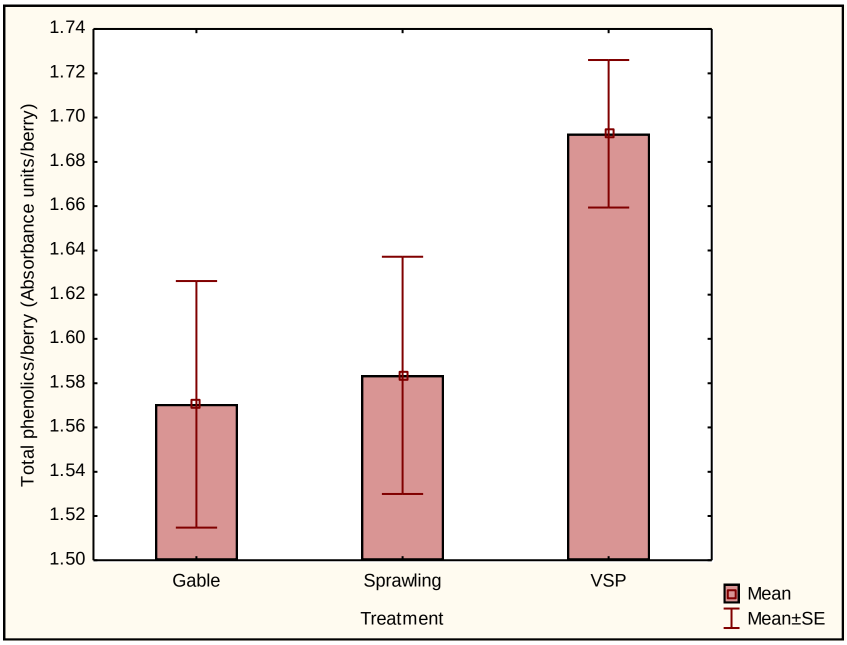


Figure 67 Total phenolics per berry for the treatments evaluated at harvest during season 2013/14 (means ± standard errors).

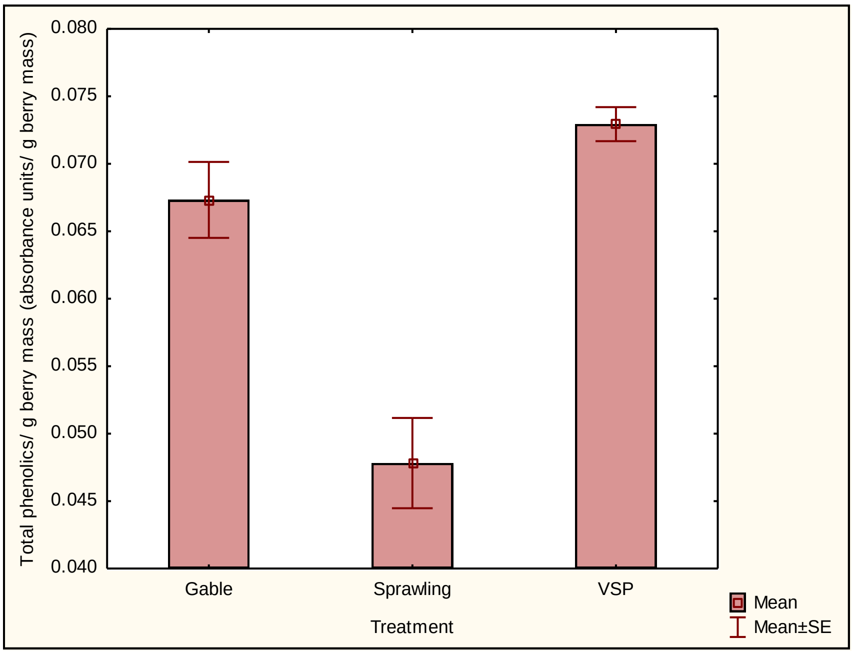


Figure 68 Total phenolics per gram berry mass for the treatments evaluated at harvest during season 2013/14 (means ± standard errors).

3.3.10.2 Wine analyses

The highest colour density at actual wine pH and SO_2 levels was obtained for the S treatment (Figure 69). Under uniform conditions where the wine pH was the same and the discolouring effect of SO_2 removed, the GA treatment produced the highest colour density (Figure 73). The colour per gram berry mass (Figure 66) determined the colour density in the wine rather than the colour per berry without consideration of berry size. The GA and S treatments displayed different wine colour shade compared to the VSP system (Figure 70). The GA treatment had higher hue values than the S treatment under natural wine conditions (Figure 70) but this changed at uniform pH, without the influence of SO_2, where the S treatment had a higher hue than the GA treatment (Figure 71). Wines produced from S grapes also contained the highest concentration of total red pigments (Figure 72), while the lowest concentration of phenolics was present (Figure 74). Wine colour and -density are decreased when shaded conditions are present (Smart, 1982). This was evident with the VSP treatment containing the most shaded conditions between treatments (Figure 38-40) and producing the lowest wine colour density (Figure 69 & Figure 73) and total red pigments (Figure 72). The total phenolics in the wines were related to berry size, where the trend between treatments corresponded with the total phenolics per gram berry mass (Figure 68), rather than total phenolics per berry (Figure 67).

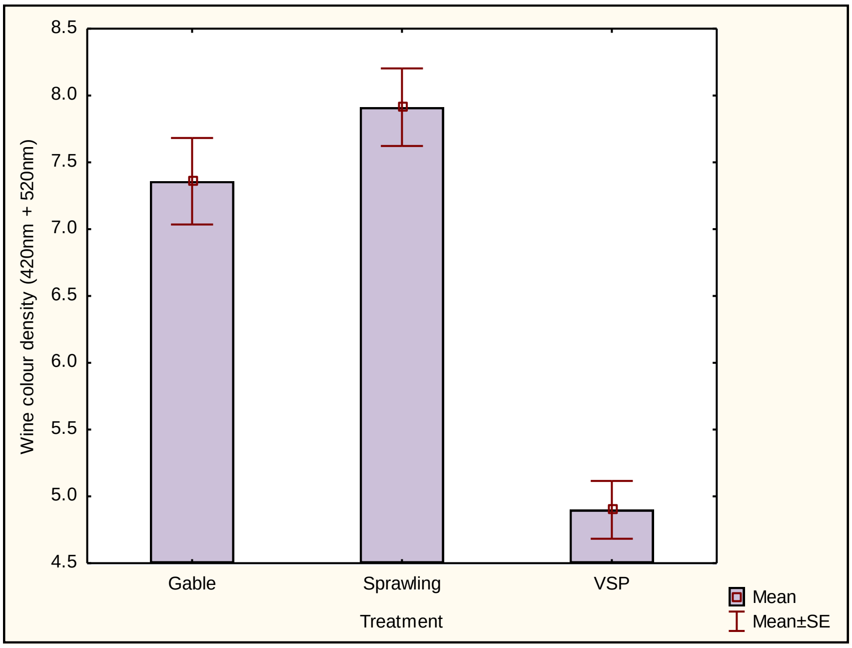


Figure 69 Wine colour density for the treatments from season 2013/14 (means ± standard errors).

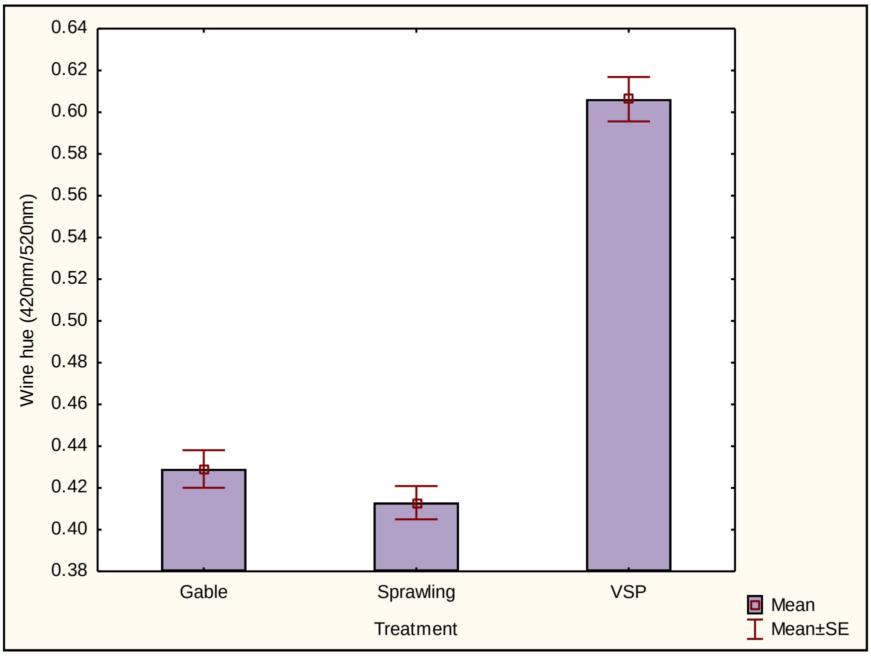


Figure 70 Wine colour hue for the treatments from season 2013/14 (means ± standard errors).

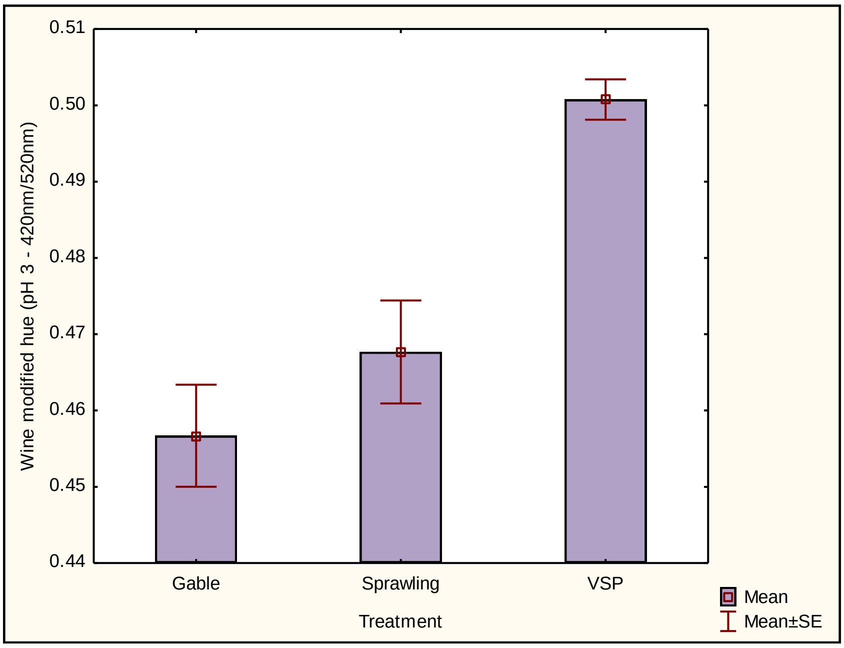


Figure 71 Wine modified hue for the treatments from season 2013/14 (means ± standard errors).

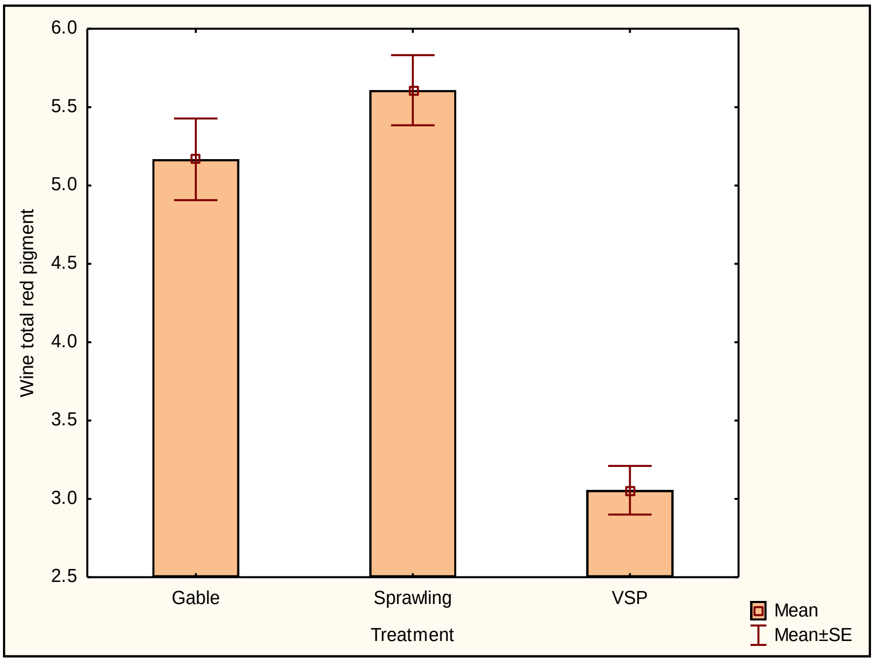


Figure 72 Wine total red pigment for the treatments from season 2013/14 (means ± standard errors).

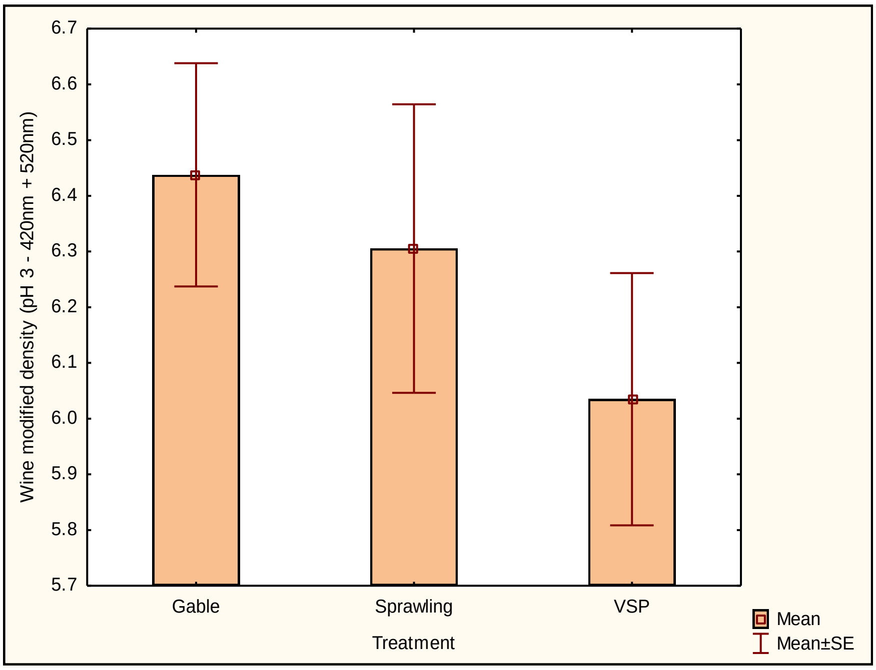


Figure 73 Wine modified density for the treatments from season 2013/14 (means ± standard errors).

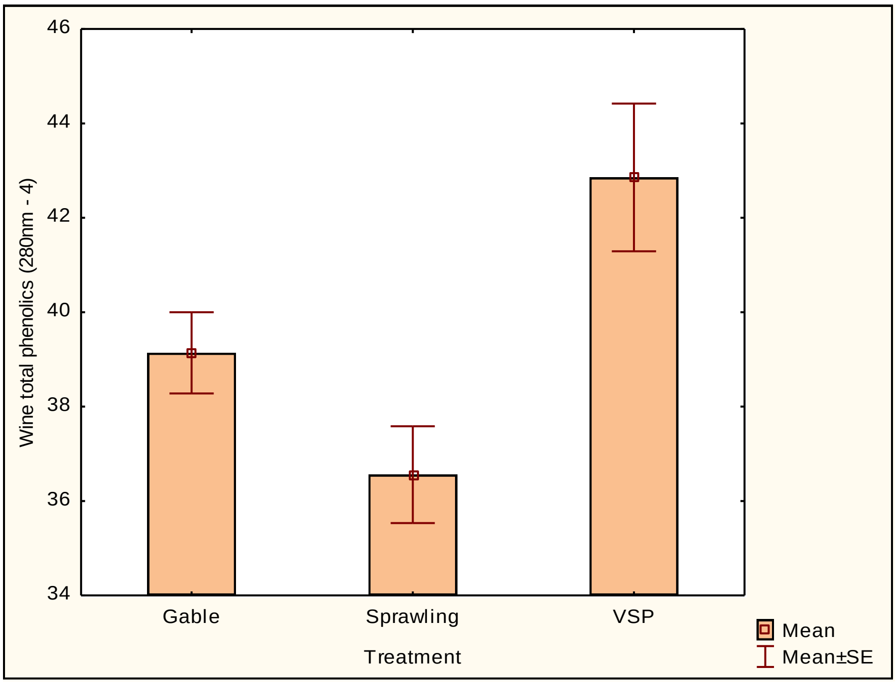


Figure 74 Wine total phenolics for the treatments from season 2013/14 (means ± standard errors).

3.3.11 Sensory evaluation

Panel performance was evaluated according to the workflow by Tomic *et al*. (2010). All panellists were repeatable and consensus was reached (data not shown). Attribute significance is displayed in (Figure 75). A correlation matrix shows that some grape- and wine measurements and significant sensory attributes display significant correlations (refer to Table 32 in the Addendum). A principle component analysis (PCA), which was generated from sensory QDA, was drafted to only display these significant sensory attributes and significant grape- and wine measurements (Figure 76).

The difference between the S and VSP treatments (F1 [81.5%]) was greater than the difference between the S and GA treatments (F2 [9.81%]). The GA treatment shifted more to the green attributes (cooked vegetables, gherkin, and jalapeno) than the S treatment, and the S treatment displaying overall more berry-like attributes (prune, blackberry and blackcurrant) compared to the VSP and GA treatments. The primary attributes describing the VSP treatment and also distinguishing it from the S (mostly) and GA treatments, were vegetal (most dominant), tarry and horsey characters. However, the second field replicate of the VSP wine was the only treatment displaying tarry and smoky characters. The spatial plot variability displayed vigour differences for the grapevines within the VSP treatment, especially in the beginning of the treatment, which could possibly be linked to the wine replicate variation. The GA treatment produced wines with vegetal and berry attributes, with the latter probably being more dominant.

Individual scatterplots were drafted to indicate the nature of correlations between sensory attributes and grape- and wine measurements. Valid correlations were not always found due to grouping of treatment data points (Figure 77) in effect “forcing” the correlation. The S treatment’s replicates separated when bud load was correlated (Figure 78) with the blackcurrant attribute, which may be due to carry over effects from the previous year's 'double and single' sprawling treatments, with the double sprawl having double the amount of buds. It also shows that replicates can have an effect within treatments. For some attributes, the treatment points were evenly distributed and grouped together (Figure 79). This indicates a clear treatment effect. It will therefore be better to compare trends using mean error plots.

Sensory attributes were standardised to vegetal aroma and vegetal flavour as well as berry aroma and berry flavour to simplify the discussion. Sensory attributes such as cooked vegetable (Figure 82), blackberry (Figure 83), berry taste (Figure 84) and cooked vegetable taste (Figure 85) were used to represent vegetal aroma, berry aroma, berry flavour and vegetable flavour, respectively, due to similar correspondence to other vegetal and berry attributes (Table 32).

Pruning level and physiological fruit maturity could have played a role in the sensory characteristics of the different treatments (Bogart & Bisson, 2006). Very few studies focused on the sensory attributes of Shiraz as a result of different crop loads. Studies of the effects of varied yield on sensory attributes by means of descriptive analysis were done on Riesling (Reynolds *et al*., 1994), Pinot noir (Reynolds *et al*., 1996b) and Cabernet Sauvignon (Chapman *et al*., 2004) and concluded similar findings. The study by Chapman *et al*. (2004) concluded that when yields were altered by pruning, the lower crop load grapevines (severe pruning) produced wines that were more bitter, vegetal and less fruity (and vice versa for lighter pruned grapevines). No significant effect on wine aromas was obtained by manipulating yields with bunch thinning. The authors suggested that this was possibly related to grapevine balance (LA/Y & Y/CM). When yield was increased by pruning, the leaf area and shoot growth decreased. But with bunch thinning the canopy remained unchanged. The vegetal character from severe pruning might have been due to increased vigour and therefore canopy shading, increasing the expression of methoxypyrazines (Bogart & Bisson, 2006).

Similar responses were found in this study with regards to the VSP, GA and S treatments (Figure 76). As bud load increased (Figure 80), vegetal aromas decreased (Figure 82) and berry aromas increased (Figure 83). The S treatment with a bud load of 2.5 times and 5.5 times higher than the GA and VSP treatments (Table 22) respectively was the farthest from vegetal wine attributes and the fruitiest. The GA treatment was also more fruity than vegetal, but more vegetal than wines from the S treatment, maybe due to lower bud numbers than S grapevines. The VSP treatment, which was pruned most severely, produced wines which were the highest in vegetal characters.

Canopy or bunch light exposure may have also played a role, with the VSP treatment being the most vigorous, in terms of shoot growth (Figure 26) and cane mass (Table 19), with the lowest Y/CM ratio (Table 25), the lowest bunch exposure (Figure 37-39) and the highest canopy density (Figure 41) at véraison. Literature suggests that increased methoxypyrazine accumulation can occur when bunches are shaded after pre-véraison (Scheiner *et al*., 2009).High vigour can cause shaded conditions and excessive growth may result in fruit with higher methoxypyrazine content, regardless of bunch exposure (Lakso, 2009). The S treatment, on the other hand, were the least vigorous with the highest Y/CM ratio, the highest bunch exposure and the lowest canopy density between treatments, which could have resulted in decreased vegetative aromas (Lakso, 2009). The trend between % PAR (Figure 38) and vegetal (Figure 82 & Figure 85) and berry (Figure 83 & Figure 84) attributes supports this. It is suggested that crop load (expressed as Y/CM) is more related to methoxypyrazines than grapevine growth and vigour where grapevines containing lower yields generally have higher vigour (Scheiner *et al*., 2009). Correlations and trends were found between Y/CM ratios and vegetal and fruity aromas and flavours (Table 32). The higher the Y/CM ratio (Figure 81), the higher the intensity of berry aromas (Figure 83) and berry taste (Figure 84). While, the inverse occurred with regards to vegetable aromas (Figure 82) and taste (Figure 85). It seems that the wine taste together with aroma was affected by grapevine balance, while mostly aromas were correlated with regards to bud load (Table 32). Wine bitterness trends also correlated to the Y/CM ratio and bud load (Table 32), with increased bitterness perceived with decreased Y/CM and higher bud load. This supports the findings in literature mentioned above.

Vegetal characters and undesirable colour development can also be associated with incomplete fruit ripening (Bogart & Bisson, 2006). Sugar accumulation (Figure 56 & Figure 58) and TA (Figure 62) were not negatively affected by the VSP treatment, although pH was higher (Figure 64). The vegetal characters could therefore rather be a result of bunch exposure (higher pH in shaded conditions) than incomplete ripening. Increased yield (S & GA treatments) was correlated with increased grape TA (data not shown) which probably concludes that higher yields may have resulted in delayed berry ripening. Berry colour and total phenolics, correlated negatively with berry aromas (Table 32) and seemed to be related to the VSP treatment (Figure 76) which supports the theory that berry ripening possibly did not play a role. Wine colour density, wine red pigment and fruitfulness, correlated with berry taste and where related to the S and GA treatments, rather than the VSP treatment. This may perhaps be due to improved bunch light environments, rather than ripening, which is also known to produce more fruitful shoots (Ristic *et al*., 2007). The trend of smoky and tarry taste (Figure 87) and horsey, plaster aromas (Table 32) was indirectly proportional to yield (Figure 31) and directly proportional to wine hue (Figure 70) and volatile acidity (data not shown). The high VA may indicate that the VSP wines were not fully microbial stable or oxygen contact occurred. Furthermore, it could possibly be that the VSP wines (especially the second replicate) contained traces of *Brettanomyces* which is known to produce horsey, smoky, plaster and tarry aromas (Du Toit & Pretorius, 2000). The higher hue may therefore perhaps be a result of some oxidation that took place (Fell *et al*., 2007).

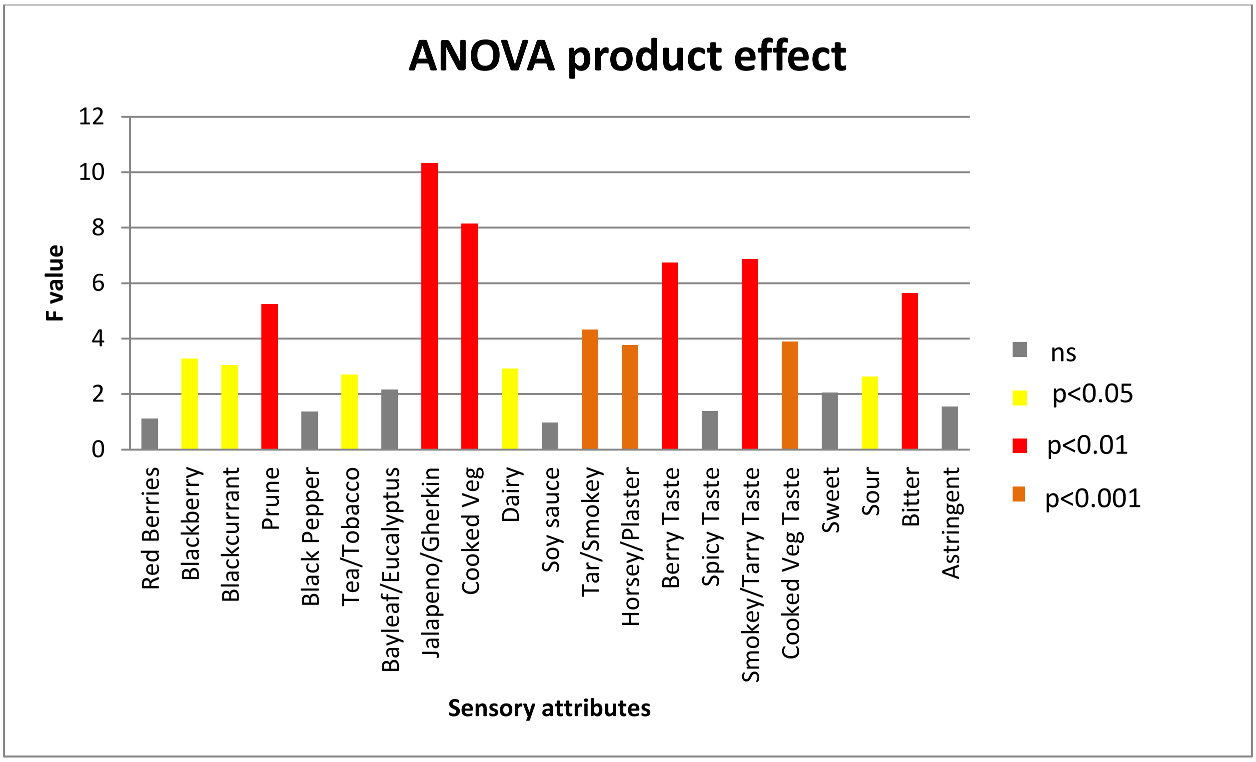


Figure 75 ANOVA product effect displaying significance among the different sensory attributes.

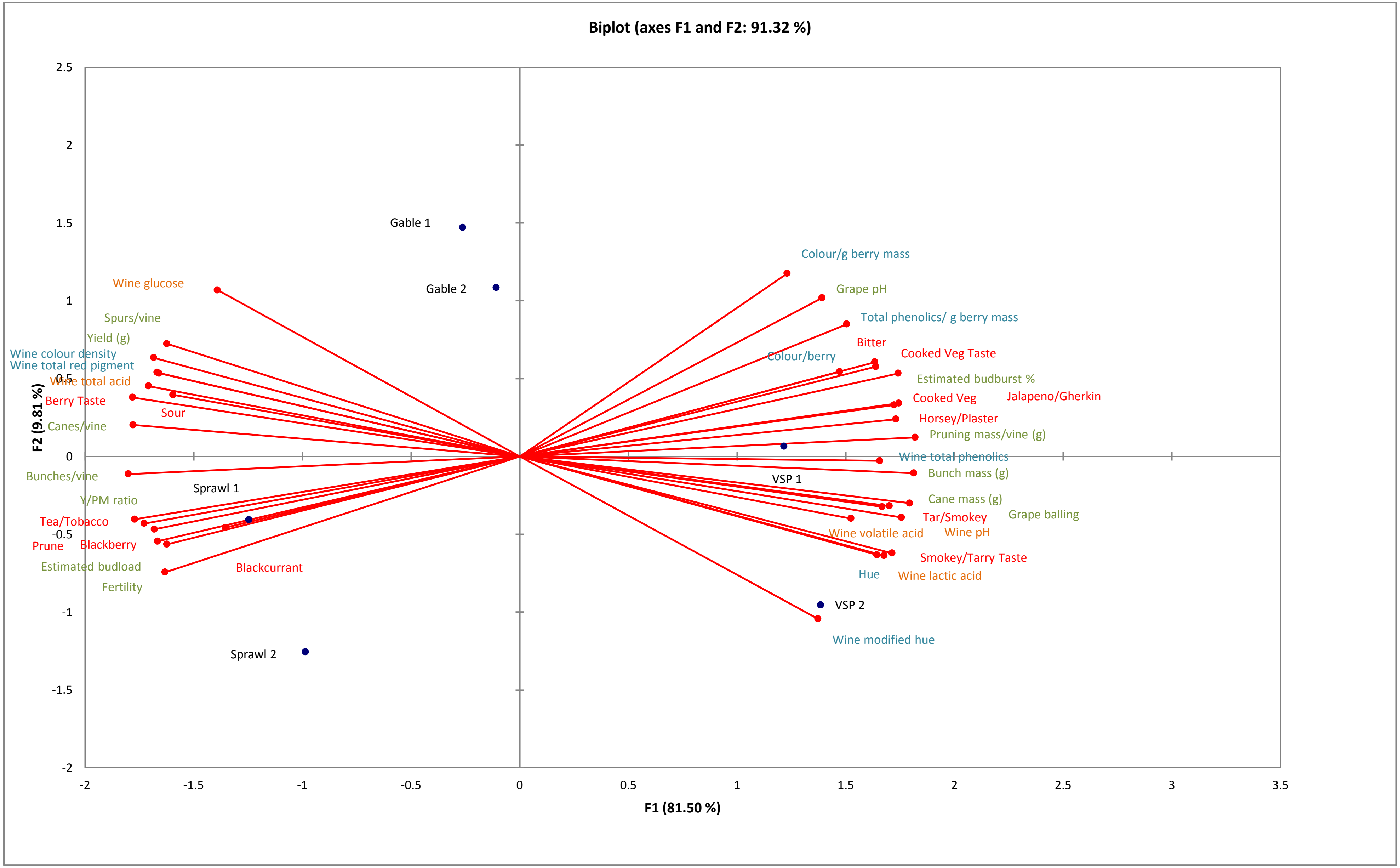


Figure 76 Principle component analysis (PCA) of the sensory wine attributes together with vegetative, colour and harvest measurements for the different treatments during season 2013/14.

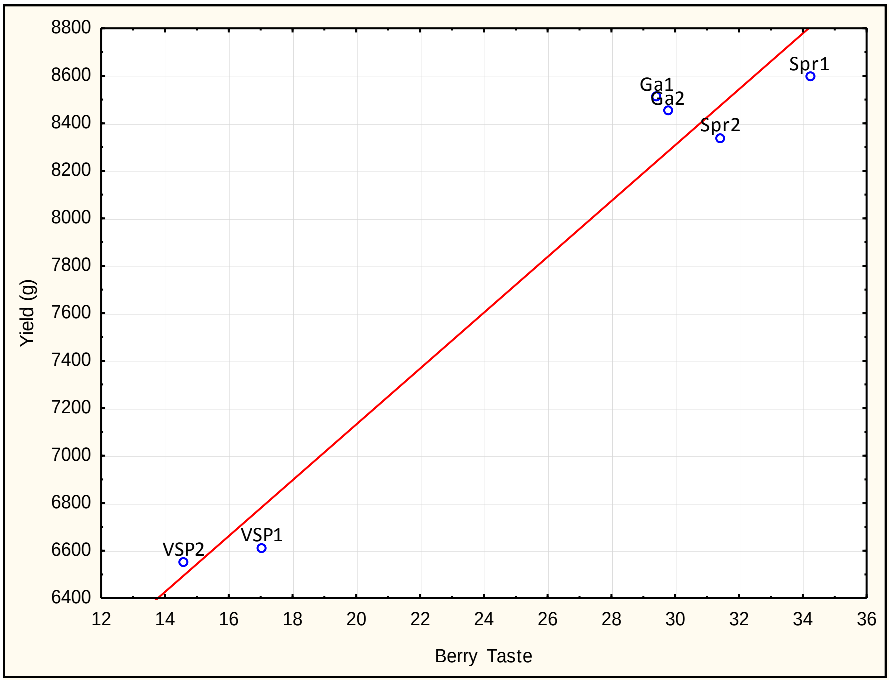


Figure 77 Relationship between yield and berry taste/flavour for the treatments and their replicates during season 2013/14 (y=4779.47+117.61x; r^2=0.96)

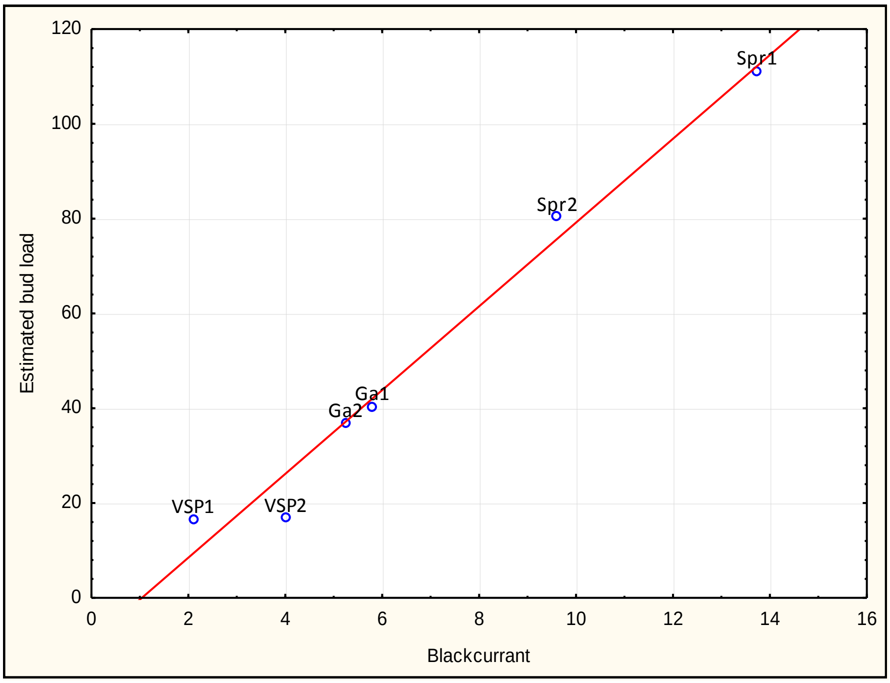


Figure 78 Relationship between the estimated bud load and blackcurrant wine attribute for the treatments and their replicates during season 2013/14 (y=-9.21+8.83x; r^2=0.98)

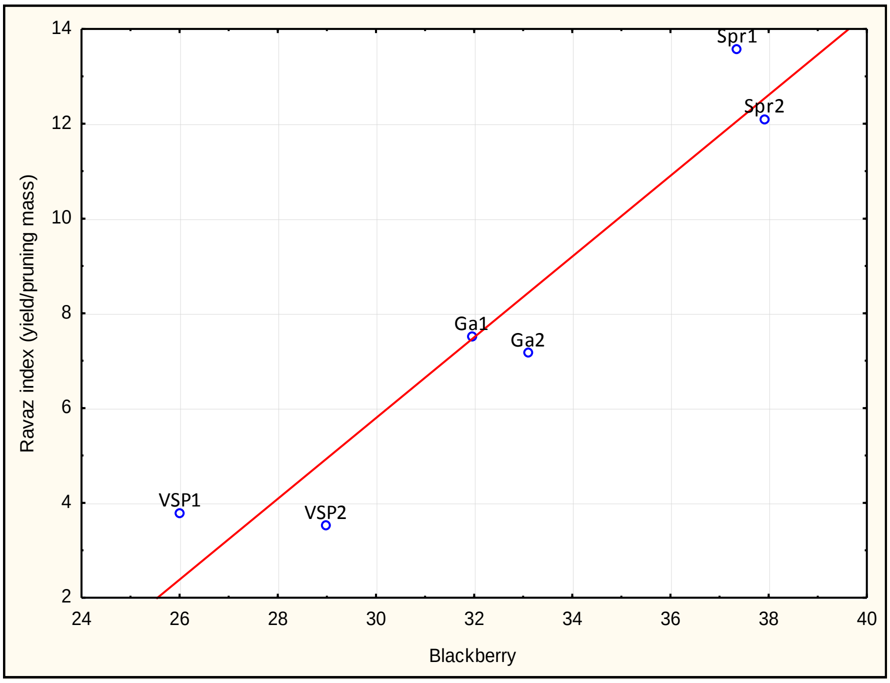


Figure 79 Relationship between the Ravaz index (yield to cane mass ratio) and blackberry wine attribute for the treatments and their replicates during season 2013/14 (y=-19.76+0.85x; r^2=0.91)

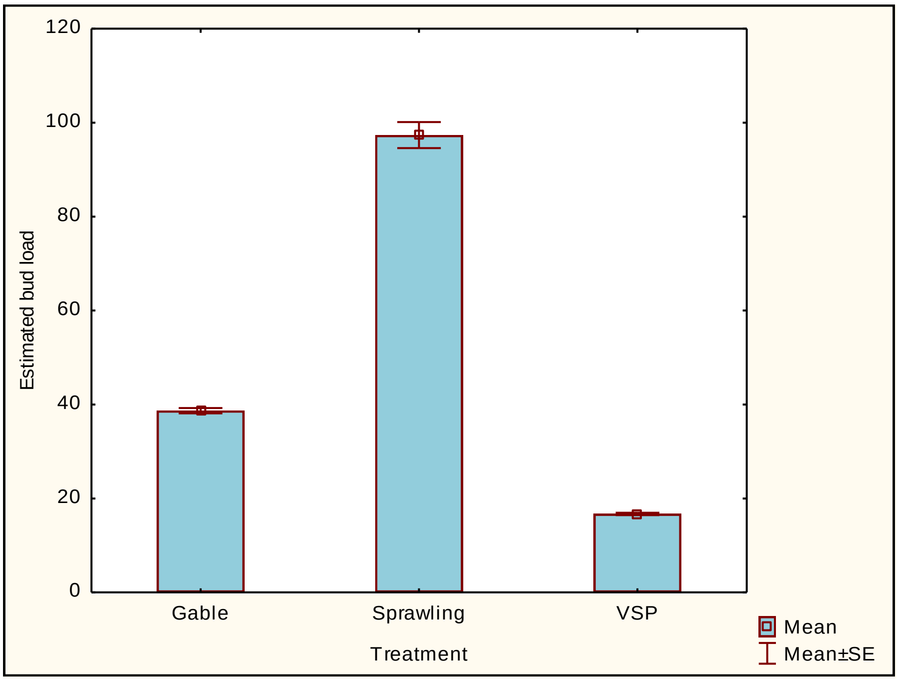


Figure 80 Estimated bud load for the different treatments during season 2013/14 (means ± standard errors).

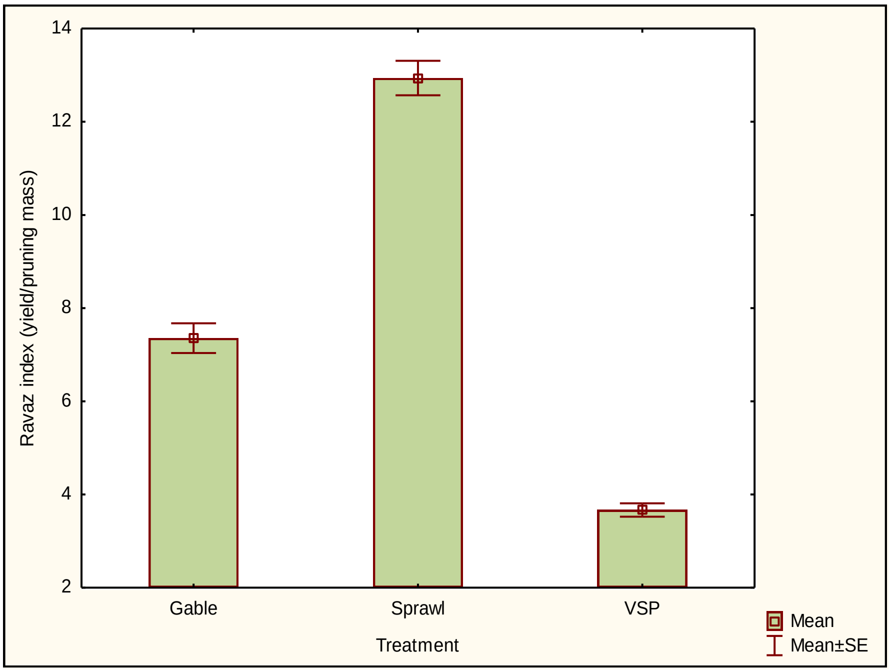


Figure 81 Yield/cane mass ratio (Y/CM) for the different treatments during season 2013/14 (means ± standard errors).

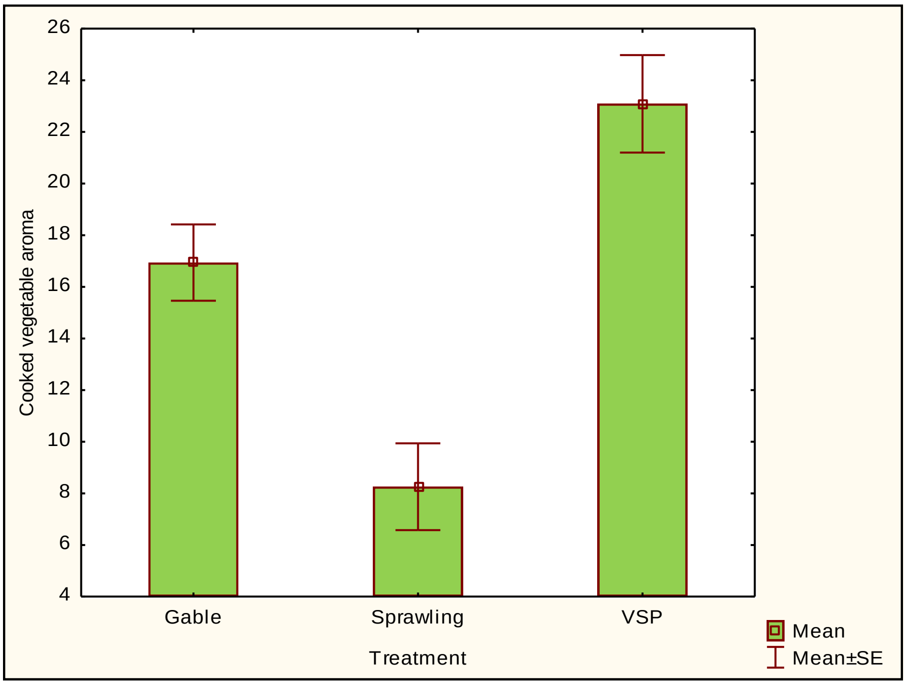


Figure 82 Cooked vegetable aromaof the experiment wines of the different treatments (means ± standard errors).

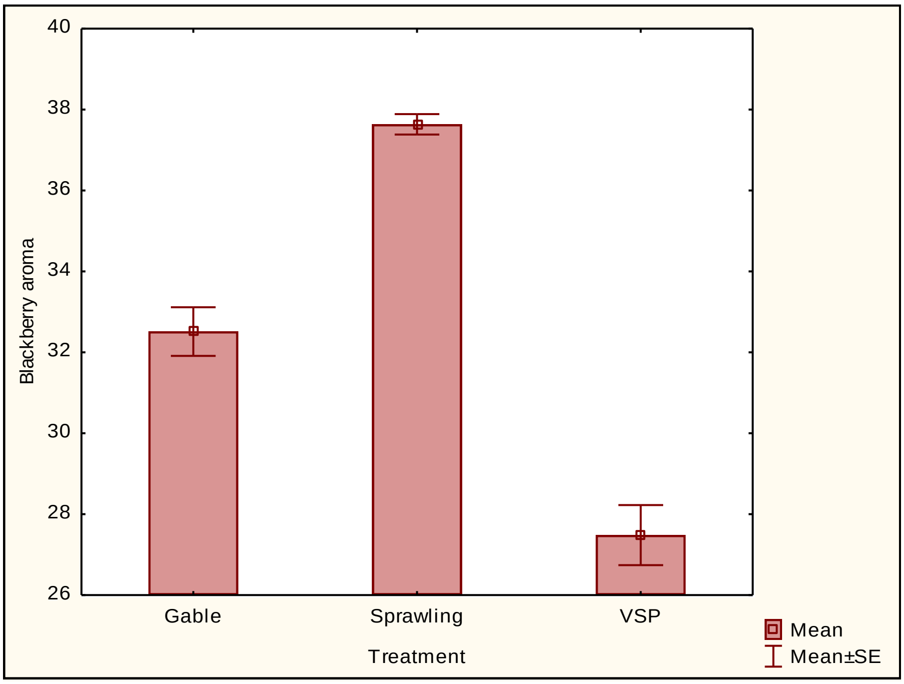


Figure 83 Blackberry aromaof the experiment wines of the different treatments (means ± standard errors).

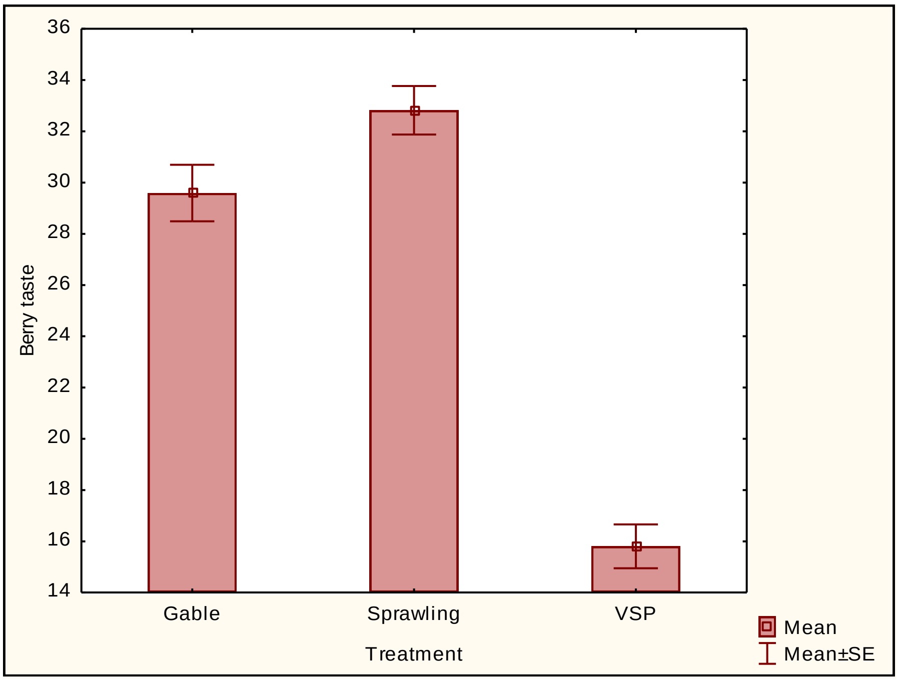


Figure 84 Berry taste of the experiment wines of the different treatments (means ± standard errors).

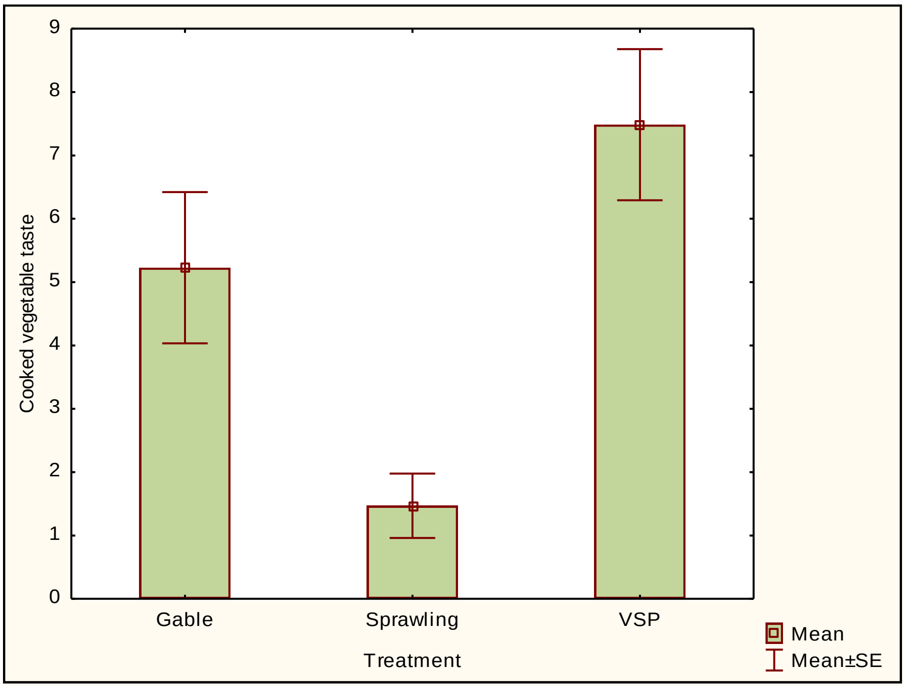


Figure 85 Cooked vegetable taste of the experiment wines of the different treatments (means ± standard errors).

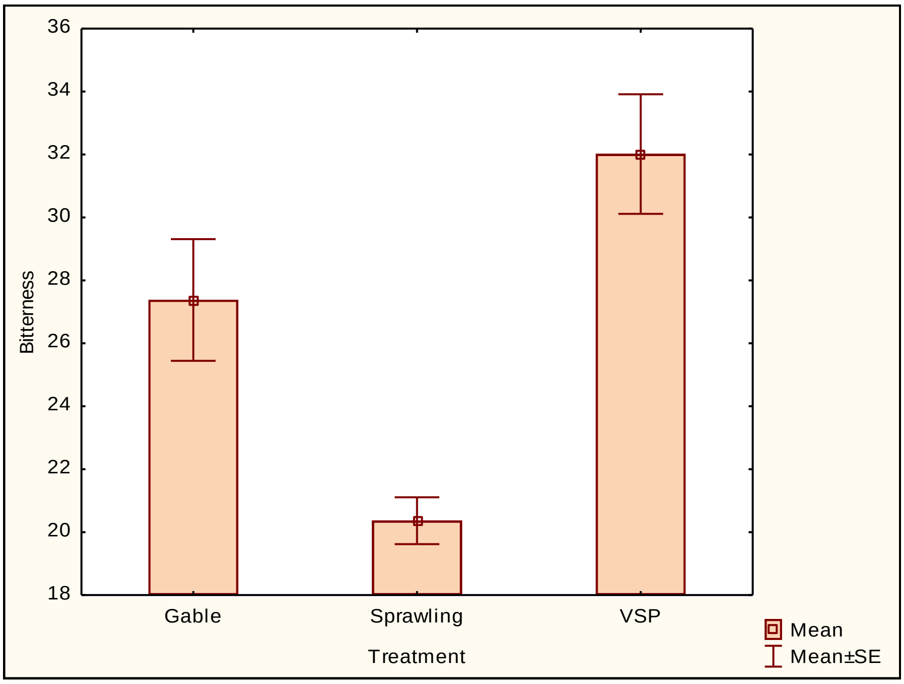


Figure 86 Wine bitterness of the experiment wines of the different treatments (means ± standard errors).

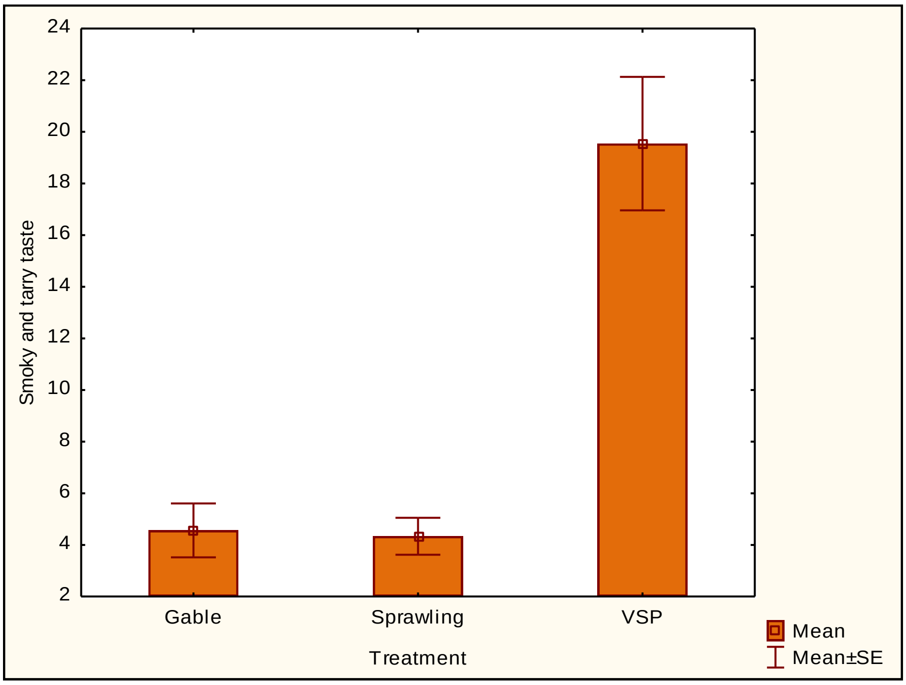


Figure 87 Smokey and tarry taste of the experiment wines of the different treatments (means ± standard errors).

3.4 Conclusions

Since there was much less rainfall in the 2012/13 season, together with higher wind speeds, grapevines were irrigated more regularly in 2012/13 compared to 2013/14. Growing degree day accumulation was similar between seasons which indicated that temperature differences between the two seasons were not substantial. General wetter soils, lower Ψ_{PD}, higher canopy PAR variation and higher stomatal conductance were evident during the 2012/13 growing season possibly due to increased growth in season 2013/14. The increased grapevine growth, in terms of both vigour and bunch mass, improved during the 2013/14 season, with the exception of the S grapevines due to high November rainfall, except for the S treatment where it was also due to the implementation of a different pruning system.

Increased bud load resulted in decreased budburst percentages which were also accompanied by decreased total cane mass as well as mass per cane. However, the amount of shoots was still higher than the systems containing standard bud loads. Grapevine vigour, in terms of cane mass and canopy leaf area, of GA grapevines increased considerably from season 2012/13 to 2013/14. Trellis conversion of the GA treatment may have led to the presence of increased root compensatory growth and improved soil colonisation in season 2012/13.Decreased budburst percentage resulted in decreased shoot numbers and ultimately decreased canopy leaf area and pruning mass. The main difference between the DS and SS treatments was decreased grapevine vigour in terms of shoot length, total cane mass and mean mass per cane. Yet, the number of shoots produced by the DS treatment produced a larger canopy in terms of total leaf area per vine.

Increased bud load resulted in increased yield and bunches per vine. Bunch mass decreased in the treatments pruned to higher bud numbers but the increased number of shoots and number of bunches per shoot (fertility) was responsible for the eventual increased yields. In the case of the GA treatment in the 2012/13 season, the main yield component responsible for the expression of yields2.5 times greater than the VSP treatment, was fertility with the GA treatment producing almost three bunches per shoot resulting in three times more bunches per grapevine than the VSP treatment. The GA treatment seemed to reach maximum productivity where yield stayed relatively constant in the 2013/14 season. In the 2013/14 season, increased budding percentage of grapevines from the GA treatment was mainly responsible for in the expression of yield. This was accompanied by the compensation of yield components such as decreased fertility and increased bunch mass. In the case of the VSP treatment, bunch mass was responsible for the expression of yield in both seasons. The DS and SS treatments produced clusters with similar bunch mass; number of berries per bunch and berry size, but the higher yield of the DS treatment was an expression of higher fertility and number of shoots per grapevine (more shoots due to increased bud load).

The lightly pruned S treatment, with the aim to simulate mechanical pruning, reacted according to expectations. A bud load of 2.5 and 5.5 times greater than the GA and VSP treatments, respectively, resulted in the treatment producing the lowest budburst percentage, total cane- and mean cane mass and the smallest bunches (in terms of bunch mass and number of berries per bunch). However, the decreased budding percentage still resulted in the production of high number of shoots per grapevine and this together with the highest fertility among treatments led to increased yield. Yet, yield did not increase to the same extent as displayed by the grapevines from the GA treatment due to the occurrence of smaller bunches.

The most vigorous treatment, in terms of shoot growth; shoot- and lateral length; total leaf area/vine and total cane- and mean cane mass were displayed by the VSP. The vigorous grapevines from the VSP treatment resulted in increased canopy density. Shoot growth of VSP grapevines did not seem to cease. Canopy bunch exposure of grapevines from the GA treatment did not increase to the extent as was expected, although higher than the VSP treatment. The S treatment displayed the highest canopy bunch exposure/ least dense canopy, which was expected from a system containing drooping shoots as well as the de-vigouration as a result of increased bud load.

It appeared that crop load did not affect water status as much as canopy exposure. The canopy of the S treatment was the most exposed between treatments and experienced severe water deficits after véraison. Disequilibrium between soil and plant water was present with reference to the GA treatment in both seasons and grapevines from the S treatment in the 2013/14 season. Nocturnal transpiration may have influenced predawn leaf water potential values and it can be recommended as to measure night-time transpiration in the future. Nevertheless, the larger trellis system of the GA treatment experienced the least stressed conditions.

The treatments producing higher yields in the first year of conversion (the GA and S treatments) increased the Y/CM ratio due to decreased vegetative growth. However, the GA treatment improved vegetative growth in the second season which led to decreased Y/CM ratios. Y/CM values higher than 10, resulted in delayed ripening (in terms of sugar accumulation, TA, berry volume), but did not seem to affect wine composition negatively. The vigorous growth and lower yields of the VSP treatment resulted in very low Y/CM ratios.

Wines produced from each treatment displayed associations between certain sensory attributes and Y/CM, bud load and canopy bunch exposure. Fruity (berry) wine attribute intensity seemed to increase with increased bud load, canopy bunch exposure and Y/CM ratios, while vegetative attribute intensity decreased. As a result, the S treatment which displayed the highest bud load and canopy bunch exposure produced wines the highest in berry characters. Although, the S treatment consisted of the most unfavourable grapevine balance (Table 12) it seemed to still produce desirable Shiraz wines. The VSP treatment produced wines high in vegetal characteristics which were assumed to be due to dense canopy conditions, promoting methoxypyrazine production, as well as the low bud load and Y/CM ratio. The GA treatment displayed bud load, Y/CM ratio and canopy bunch exposure values in between the S and VSP treatments and therefore produced wines containing both vegetal and berry aromas, the latter the most dominant attribute.

In conclusion, very desirable results were present which stated that alternative training-, trellising- and pruning methods can lead to the production of different wine styles. Increased yield did not necessarily decrease grape and wine quality. This could be important for the financial survival of the wine grape growing community.

3.5 Literature cited

Amerine, M.A. & Winkler, A.J., 1944. Composition and quality of musts and wines of Californian grapes. Hilgardia. 15, 493-637.

Archer, E., 2011. Increasing yield from wine grapes. Wynboer Technical Yearbook 2011. pp. 60-84.

Archer, E. & Van Schalkwyk, D., 2007. The effect of alternative pruning methods on the viticultural and oenological performance of some wine grape varieties. S. Afr. J. Enol. Vitic. 28, 107-139.

Barbagallo, M.G., Guidoni, S. & Hunter, J.J., 2011. Berry size and qualitative characteristics of *Vitis vinifera* L. cv. Syrah. S. Afr. J. Enol. Vitic. 32, 129-136.

Bindon, K.A., Dry, P.R. & Loveys, B.R., 2008. The interactive effect of pruning level and irrigation strategy on grape berry ripening and composition in *Vitis vinifera* L. cv. Shiraz. S. Afr. J. Enol. Vitic. 29, 71-78.

Bindon, K.A., Myburgh, P., Oberholster, A., Roux, K. & Du Toit, C., 2011. Response of grape and wine phenolic composition in *Vitis vinifera* L. cv. Merlot to variation in grapevine water status. S. Afr. J. Enol. Vitic. 32, 71-88.

Buttrose, M.S. & Mullins, M.G., 1968. Proportional reduction in shoot growth of grapevines with root systems maintained at constant relative volumes by repeated pruning. Austr. J. of Biol. Sci. 21, 1095-1102.

Bodor, P,. Baranyai, L., Ladányi, M., Bálo, B, Strever, A.E., Bisztray, Gy.D. & Hunter, J.J., 2013. Stability of ampelometric characteristics of *Vitis vinifera* L. cv. 'Syrah' and 'Sauvignon blanc' Leaves: impact of within-vineyard variability and pruning method/bud load. S. Afr. J. Enol. Vitic. 34, 129-137.

Bogart, K. & Bisson, L., 2006. Persistence of vegetal characters in winegrapes and wine. Practical Winery & Vineyard Journal March/April 2006.

Bravdo, B., Hepner, Y., Loinger, C., Cohen, S. & Tabacman H., 1984. Effect of crop level on growth, yield and wine quality of a high yielding Carignane vineyard. Am. J. Enol. Vitic. 35, 247-252.

Bravdo, B., Hepner, Y., Loinger, C., Cohen, S. & Tabacman H., 1985a. Effect of crop level and crop load on growth, yield, must and wine composition and quality of Cabernet Sauvignon. Am.J. Enol. Vitic. 36, 125-131.

Bravdo, B., Hepner, Y., Loinger, C.,Cohen, S.& Tabacman H., 1985b. Effect of irrigation and crop level on growth, yield and wine quality of Cabernet Sauvignon. Am. J. Enol. Vitic, 36, 132-139.

Carbonneau, A., 1997. General relationship within the whole-plant: examples of the influence of vigour status, crop load and canopy exposure on the sink "berry maturation" for the grapevine. Acta Horticulturae (ISHS) 427, 99-118.

Carbonneau, A., 1998. Qualitative aspects, 258-276. In. Proc. XXVIIth World Congress of Vine and Wine, Bratislava. Traité d'irrigation, Tiercelin J.R., Lavoisier Tec et Doc ed. pp. 1011.

Chalmers, Y., 2009. Insights into the relationships between yield and water in wine grapes. In: Water and vine: Managing the challenge. Fact sheet 5, Grape and Wine Reasearch and Development Corporation (GWRDC).

Chapman, D.M., Matthews, M.A.&Guinard, J.X., 2004. Sensory attributes of Cabernet Sauvignon wines made from vines with different crop yields. Am. J. Enol. Vitic. 55, 325-334.

Chaves, M.M., 1984. Photosynthesis and assimilate partition in fruiting and non-fruiting grapevine shoots. In: C. Sybesma (ed.). Advances in Photosynthesis Research. Vol. IV, Proc. 6th Int. Congr. Photosynt., Brussels, Belgium, August 1-6, 1983; 145-148. M. Nijhoff and Dr.W. Junk Publ., The Hague, Boston, Lancaster.

Chien, M.L., 2009. Vine balance and crop estimating. Wineries Unlimited March 2009.

Clingeleffer, P.R., 1988. Response of Riesling clones to mechanical hedging and minimal pruning of cordon trained vines- implications for clonal selections. *Vitis* 22, 87-83.

Clingeleffer, P.R., 1993. Vine response to modified pruning practices. In: R.M. Pool (ed). Pruning mechanization and crop control. Proc. 2nd Nelson J. Shaulis Gr. Symp., July 13-14, Fredonia New York, 20-30.

Collins, M. & Loveys, B.R., 2009. Insights into varietal and rootstock differences in water use. The Grape and wine Research and Development Corporation: Water & Vine- Managing the challenge. Fact sheet No. 04. (The Grape and Wine Research and Development Corporation, Adelaide, Australia).

Coombe, B.G., 1995. Growth stages of the grapevine: adoption of a system for identifying grapevine growth stages. Austr. J. Grape and Wine Res. 1, 104-110.

De Villiers, F.S., Schmidt, A., Theron, J.C.D. & Taljaard, R., 1996. Onderverdeling van Wes-Kaapse wynbougebiede volgens bestaande klimaatskriteria. WynboerTegnies. 78,10-12.

Deloire, A., Carbonneau, A., Wang, Z.P. & Ojeda, H., 2004. Vine and water: a short review. J. Int. Sci. Vigne et Vin. 38, 1-13.

Du Toit, M. & Pretorius, I.S., 2000. Microbial spoilage and preservation of wine: using weapons from nature's own arsenal- a review. S. Afr. J. Enol. Vitic. 21, 74-96.

Dokoozlian, N.K. & Kliewer, W.M., 1995. The light environment within grapevine canopies. I. Description and seasonal changes during fruit development. Am. J.Enol. Vitic. 46, 209-218.

Donovan, L.A., Richards, J.H. & Linton, M.J., 2001. Predawn plant water potential does not necessarily equilibrate with soil water potential under well-watered conditions. Oecologia, 129, 328-335.

Donovan, L.A., Richards, J.H. & Linton, M.J., 2003. Magnitude and mechanisms of disequilibrium between predawn plant and soil water potentials. Ecology 84, 463-470.

Downton, W.J.S., Grant, W.J. & Loveys, R.B.,1987. Diurnal changes in the photosynthesis of field-grown grapevines. New Phytol. 105, 71-80.

Dry, P.R. & Smart, R.E., 1988. Vineyard site selection. In: Viticulture Volume 1, Edition 1-Resources, B.G. Coombe and P.R. Dry (Eds). (Australian Industrial Publishers: Adelaide), pp. 190-204.

Edson, C.E., Howell, G.S. & Flore, J.A., 1993. Influence of crop load on photosynthesis and dry matter partitioning of Seyval grapevines. I. Single leaf and whole vine response pre- and post-harvest. Am. J. Enol. Vitic. 44, 39-146.

Esteban, M.A., Villanueva, M.J. & Lissarrague, J.R., 2002. Relationships between different berry components in Tempranillo (*Vitis vinifera* L.) grapes from irrigated and non-irrigated vines during ripening. J. Sci. Food Agric. 82, 1136-1146.

Fell, A., Dykes, S., Nicolau, L. & Kilmartin, P., 2007. Electrochemical microoxidation of red wine. Am. J. Enol. Vitic. 58, 443-450.

Fisher, K.H., Bradt, O.H., Wiebe, J. & Dirks, V.A., 1977. Cluster thinning ‘de Chaunac’ french hybrid grapes improves vine vigor and fruit quality in Ontario. J. Am. Soc. Hortic. Sci. 102, 162-165.

Goodwin, I. & Jerie, P., 1992. Regulated deficit irrigation: from concept to practice. Aust. N.Z. Wine Ind. J. 7, 258-261.

Hickinbotham, A.R. & Ryan, V.J., 1948. Glycerol in Wine. Aust. Chem. Inst. J. and Proc. 15, 89-100.

Hill, J.P. & Lord, E.M., 1990. A method for determining plastochron indices during heteroblastic shoot growth. Amer. J. Bot. 77, 1491-1497.

Hinreimer, E., Filipello, R., Webb, A.D. & Berg, H.W., 1955. Evaluation of thresholds and minimum difference concentrations for various constituents of wines. I. Ethyl alcohol, glycerol and acidity in aqueous solution. Food Technol. 9, 351-353.

Hofäcker, W., 1978. Investigations on the photosynthesis of vines, influence of defoliation, topping, girdling and removal of grapes. Vitis 17, 10-22.

Howell, G. S., 2001. Sustainable grape productivity and the growth- yield relationship: A review. Am. J. Enol. Vitic. 52, 165-174.

Hunter, J.J., 2000. Implications of seasonal canopy management and growth compensation in grapevine. S. Afr. J. Enol. Vitic. 21, 81-91.

Hunter, J.J., 2001. Grapevine physiology. Private Bag X5026, Stellenbosch, 7599. E-mail hunterk@arc.agric.za.

Hunter, J.J. & Visser, J.H., 1989. The effect of partial defoliation, leaf position and developmental stage of the vine on leaf chlorophyll concentration in relation to the photosynthetic activity and light intensity in the canopy of V*itis vinifera* L. cv. Cabernet Sauvignon. S. Afr. J. Enol. Vitic. 10, 67-73.

Hunter, J.J. & Visser, J.H., 1990. The effect of partial defoliation on growth characteristics of *Vitis vinifera* L. cv. Cabernet Sauvignon. I. Vegetative growth. S. Afr. J. Enol. Vitic. 11, 18-25.

Hunter, J.J. & Le Roux, D.J., 1992. The effect of partial defoliation on development and distribution of roots of Vitis vinifera L. cv. Cabernet Sauvignon grafted onto rootstock 99 Richter. Am. J. Enol. Vitic. 43, 71-78.

Iland, P., Ewart, A., Sitters, J., Markides, J. & Bruer, N., 2000a. Determination of red pigments (colour) and total phenolics of grape berries. In: Techniques for chemical analysis and quality monitoring during winemaking. Patrick Iland Wine Promotions,PTY LTD. Campbelltown, Australia.pp. 78-79.

Iland, P., Ewart, A., Sitters, J., Markides, J. & Bruer, N., 2000b. Red wine colour and phenolic measures. In: Techniques for chemical analysis and quality monitoring during winemaking. Patrick Iland Wine Promotions, PTY LTD. Campbelltown, Australia.pp. 98-99.

Iland, P., Dry, P., Proffitt, T. & Tyerman, S., 2011. The grapevine: from the science to the practice of growing vines for wine. Patrick Iland Wine Promotions Pty Ltd 2011. Adelaide, Australia.

Jackson, D.I. & Lombard, P.B., 1993. Environmental and management practices affecting grape composition and wine quality of Shiraz vines. Am. J. Enol. Vitic. 44, 409-430.

Kappel, F. & Flore, J.A., 1983. Effect of shade on photosynthesis, specific leaf weight, leaf chlorophyll content, and morphology of young peach trees. J. Amer. Soc. Hort. Sci. 108,541-544.

Kaps, M.L. & Cahoon, G.A., 1989. Berry thinning and cluster thinning influence vegetative growth, yield, fruit composition and net photosynthesis of Seyval blanc grapes. J. Am. Soc. Hort. Sci. 114, 20-24.

Kaps, M.L. & Cahoon, G.A., 1992. Growth and fruiting of container- grown Seyval blanc grapevines modified by changes in crop level, leaf number and position, and light exposure. Am. J. Enol. Vitic. 21, 37-47.

Keller, M., Smithyman, R.P. & Mills, L.J., 2008. Interactive effects of deficit irrigation and crop load on Cabernet Sauvignon in an arid climate. Am. J. Enol. Vitic. 53, 268-274.

Kjergren, R., 2010. Isohydric and anisohydric water use considerations in species selection for the great green wall of Africa. In: Le projet majeur africain de la grande muraille verte. Concepts et mise oeuvre. pp.63-72.

Kliewer, W.M., 1970. Effect of time and severity of defoliation on growth and composition of 'Thompson Seedless' grapes. Am. J. Enol. Vitic. 21, 37-47.

Kliewer, W.M. & Antcliff, A.J., 1970. Influence of defoliation, leaf darkening, and cluster shading on the growth and composition of Sultana grapes. Am. J. Enol. Vitic. 21, 26-36.

Kliewer, W.M. & Weaver, R.J., 1971. Effect of crop level and leaf area on growth, composition and coloration of 'Tokay' grapes. Am. J. Enol. Vitic. 22, 172-177.

Kliewer, W.M. & Dokoozlian, N.K., 2000. Leaf area/crop weight ratios of grapevines: Influence on fruit composition and wine quality. Proc. Amer. Soc. Enol. Viticult. 50th Anniv. Annu. Mtg. p. 285-295.

Kurtural, S.K., Dami, I.E. & Taylor, B.H., 2006. Effects of pruning and cluster thinning on yield and fruit composition of 'Chambourcin' grapevines. HortTechnology. 16, 233-240.

Lakso, A.N., 2009. Vine vigor, balance, and methoxypyrazines in Cabernet Franc - some data, some thoughts. A presentation by Alan N. Lakso. Fruit Crop Physiology, Cornell University, Geneva.

Lawless, H.T. & Heymann, H., 1998. Sensory Evaluation of Food, Principles and Practices. New York, Chapman and Hall, 341-378.

Mabrouk, H. & Sinoquet, H., 1998. Indices of light microclimate and canopy structure determined by 3-D digitising and image analysis and their relationship to grape quality. Aust. J. Grape Wine Res. 4, 2-13.

MacMillan, I., 2003. Problems with downward-orientated grapevine canopies. The Australian and New Zealand Grapegrower & Winemaker. 468, 20-22, 24.

Marini, R.P. & Marini, M.C., 1983. Seasonal changes in specific leaf weight, net photosynthesis, and chlorophyll content of peach leaves as affected by light penetration and canopy position. J. Amer. Soc. Hort. Sci. 108,600-605.

May, P., Shaulis, N.J. & Antcliff, A.J., 1969. Effect of controlled defoliation in the Sultana vines. Am. J. Enol. Vitic. 20, 237-250.

McCarthy, M.G., 1997. Timing of water deficit on fruit development and composition of *Vitis vinifera* cv. Shiraz. PhD disseration, University of Adelaide, Adelaide, Australia.

Mellet, J., 2010. Ballerina trellis system for sustainable increased production. Wynboer Technical Yearbook 2010, 25 - 26.

Miller, D.P. & Howell, G.S., 1998. Influence of vine capacity and crop load on canopy development, morphology, and dry matter partitioning in Concord grapevines. Am. J. Enol. Vitic. 49, 183-190.

Nabi, G., Trought, M.C.T.& Whitehead, D., 2000. The influence of short-term partial shading on photosynthesis and stomatal conductance in relations to cropload of grapevines (*Vitis vinifera* L.). Paki. J. Biol. Sci. 3, 279-283.

Naor, A., Gal, Y. & Bravdo, B., 2002. Shoot and cluster thinning influence vegetative growth, fruit yield, and wine quality of ‘Sauvignon blanc’ grapes. J. Am. Soc. Hortic. Sci. 127, 628-634.

Oberholster, A., 2003. Chemical and sensory properties of grape and wine phenolics: part I. Wynboer March 2003.

Ourcival, J.M., Floret, C., Le Floc'h, E. & Pontainer, R., 1994. Water relations between two perennial species in the steppes of southern Tunisia. J. Arid. Environ. 28, 333–350.

Partridge, N.L., 1925. Growth and yield of Concord grape vines. Proc. Am. Soc. Hortic. Sci. 22, 84-87.

Petrie, P.R., Trought, M.C.T. & Howell, G.S., 2000. Influence of leaf ageing, leaf area and crop load on photosynthesis, stomatal conductance and senescence of grapevine (*Vitis vinifera* L. cv. Pinot noir) leaves. *Vitis* 39, 31-36.

Preszler, T., Schmit, T.M. &Van den Heuvel, J.E., 2013.Cluster Thinning reduces the economic sustainability of Riesling production. Am. J. Enol. Vitic. 64, 333-341.

Ravaz, M.L. 1911. L’effeuillage de la vigne. Ann. École Nat. Agric. Montpellier. 11, 216-244.

Reynolds, A.G., Edwards, C.G., Wardle, D.A., Webster, D. & Dever, M.C., 1994. Shoot density affects Riesling grapevines II. Wine composition and sensory response. J. Am. Soc. Hortic. Sci. 119:881-892.

Reynolds, A.G., Yerle, S., Watson, B., Price, S.F & Wardle, D.A., 1996. Fruit environment and crop level effects on Pinot noir. III. Composition and descriptive analysis of Oregon and British Columbia wines. Am. J. Enol. Vitic. 47, 329-339.

Richards, D., 1983. The grape root system. Hort. Rev. 5, 127-159.

Ristic, R., Downey, M.O., Iland, P.G., Bindon, K., Francis, I.L., Herderich, M. & Robinson, S.P., 2007. Exclusion of sunlight from Shiraz grapes alters wine colour, tannin and sensory properties. Aust. J. Grape and Wine Res. 13, 53-65.

Rogiers, S.Y., Greer, D.H., Hatfield, J.M., Hutton, R.J., Clarke, S.J., Hutchinson, P.A. & Somers, A., 2012. Stomatal response of an anisohydric grapevine cultivar to evaporative demand, available soil moisture and abscisic acid. Tree Physiology 32, 249-261.

Scheiner, J.J., Sacks, G.L. & Van den Heuvel, J.E., 2009. How viticultural factors affect methoxypyrazines- water levels, cluster shading and temperature all play roles. Wines & Vines November 2009.

Schubert, A., Lovisolo, C. & Peterlunger, E., 1996. Sap flow and hydraulic conductivity of grapevine shoots trained to upward or downward position. In: Proc. of the 4th International Symposium on Cool Climate Viticulture and Oenology T. Henick-Kling, T.E. Wolfe and E.M. Harkness (eds). (New York State experimental Station: Geneva, New York). pp. 39-42.

Schultz, H.R., 1992. An empirical model for the simulation of leaf appearance and leaf area development of primary shoots of several grapevine (*Vitis vinifera* L.) canopy-systems. Sci. Hortic. 52, 179-200.

Schultz, H.R., 2003. Differences in hydraulic architecture account for near-isohydric and anisohydric behaviour of two field-grown *Vitis vinifera* L. cultivars during drought. Plant, Cell & Environment. 26, 1393-1405.

Scholander, P.F., Hammel, H.T., Bradstreet, E.D. &Hemmingsen, E.A., 1965. Sap pressure in vascular plants. Sci. 148, 339-346.

Shrinivasan, C. & Mullins, M.G., 1978. Control of flowering in the grapevine (*Vitis vinifera* L.). Formation of inflorescences *in vitro* by isolated tendrils. Plant Physiol. 61, 127-130.

Smart, R.E., 1973. Water needs of wine grapes. Proc. of the 2nd Aust. Wine Industry Technical conference, Tanunda, Australia. Aust. Wine Res. Institute. pp. 7-10.

Smart, R.E., 1982. Vine manipulation to improve wine grape quality. Proc. Symp. Grape and Wine Cent. June 1980 A.D. Webb (Ed). (University of California, Davis). pp. 362-375.

Smart, R. E., 1985. Principles of grapevine canopy microclimate manipulation with implications for yield and quality: A review. Am. J. Enol. Vitic. 36, 230-239.

Smart, R.E., 1988. Shoot spacing and canopy light microclimate. Am. J. Enol. Vitic. 39, 325-333.

Smart, R.E., 1991. Canopy microclimate implications for nitrogen effects on yield and quality. Proc. International Symposium on Nitrogen in Grapes and Wine, Seattle, U.S.A. Amer. Soc. Enol. Vitic. pp. 90-101.

Smart, R.E., 1992. Canopy management. In: Coombe, B & Dry, P. (eds.). Viticulture, Vol. 2. Practices. Winetitles, Adelaide. pp. 85-103.

Smart, R.E., 2001. Good wines stem from balanced vines. Austr. NZ Wine Industr. J. 16, 53-54.

Smart, R.E. & Barrs, H.D., 1973. The effect of environment and irrigation interval on leaf water potential of four horticultural species. Agr. and Forest Met. 12, 337-346.

Smart, R.E., Dick, J.K. & Gravett, I.M., 1989. Shoot devigouration by natural means. Proc. of the 7th Aust. Wine Industry Technical Conference, Adelaide, Australia. Aust. Wine Res. Institute. pp. 58-65.

Smart, R.E. & Robinson, M., 1991. Sunlight into Wine. A Handbook for Wine grape Canopy Management.Winetitles, Adelaide, Australia.

Smart, R.E. & MacMillan, I., 2003. Downward-growing grapevine shoots re-visited. The Australian and New Zealand Grapegrower & Winemaker. 472, 64; 66-68.

Southey, J.M. & Archer, E., 1988. Soil preparation studies: I. The effect of depth and method of soil preparation and of organic material on the performance of *Vitis vinifera* (var. Chenin Blanc) on a Hutton/Sterkspruit soil. S. Afr. J. Enol. Vitic. 1,107-121.

Stolk, R.A., 2014. The effect of irrigation and canopy management on selective vegetative growth and reproductive parameters of Vitis vinifera L. cv. Shiraz in the Breede River Valley. MSc thesis, Stellenbosch University, Private Bag X1, Matieland (Stellenbosch) 7602, South Africa.

Stoll, M., Loveys, B.R. & Dry, P.R., 2000. Hormonal changes induced by partial rootzone drying of irrigated grapevines. J. Exp. Bot. 51, 1627-1634.

Strever, A.E., 2012. Non-destructive assessment of leafcomposition as related to growth ofthe grapevine (*Vitis vinifera* L. cv. Shiraz). PhD dissertation, Stellenbosch University, Private Bag X1, Matieland (Stellenbosch) 7602, South Africa.

Swanepoel, J.J., Hunter, J.J. & Archer, E., 1990. The Effect of Trellis Systems on the Performance of *Vitis vinifera*L. cvs. Sultanina and Chenel in the Lower Orange River Region. S. Afr. J. Enol. Vitic. 11, 59-66.

Tomic, O., Luciano, G., Nilsen, A., Hyldig, G., Lorensen, K. & Naes, T., 2010. Analysing sensory panel performance in a proficiency test using the PanelCheck software. Eur. Food Res. Technol. 230, 497-511.

Vasconcelos, M.C. & Castagnoli, S., 2001. Leaf canopy structure and vine performance. Practical Winery and Vineyard Journal September/October 2001.

Varela, P. & Ares, G., 2012. Sensory profiling, the blurred line between sensory and consumer science: A review of novel methods for product characterization. Food Res.Intern. 48, 893-908.

Van Zyl, J.L. & van Huyssteen, L., 1980. Comparative studies on wine grapes on different trellising systems: I. Consumptive water use. S. Afr. J. Enol. Vitic. 1, 7-14.

Volschenk, C.G. & Hunter, J.J., 2001. Effect of Trellis Conversion on the Performance of Chenin blanc/99 Richter Grapevines. S. Afr. J. Enol. Vitic. 22, 31-35.

Walker, R.R., Blackmore, D.H., Clingeleffer, P.R., Kerridge, G.H., Rühl, E.H. & Nicholas, P.R., 2005. Shiraz berry size in relation to seed number and implications for juice and wine composition. Aust. J. Grape Wine Res. 11, 2-8.

Waring, R.H. & Cleary, B.D., 1967. Plant moisture stress evaluation by a pressure bomb. Sci. 155, 1248-1254.

Weaver, M., 2006. The emergence of vine cultivation in cooler-climate viticulture areas in South Africa with specific reference to Elim and Elgin. A thesis, Cape Wine Masters Diploma.

Willmer, C. & Fricker, M., 1996. Stomatal responses to environmental factors. In: Stomata. Chapman & Hall, 2-6 Boundary Row, London SE1 8HN, UK. pp. 164-165.

Zeeman, A. S. & Archer, E., 1981. Stokontwikkeling, wintersnoei en somerbehandeling. In: Burger, J. & Deist, J. (eds). Wingerdbou in Suid- Afrika. ARC Infruitec- Nietvoorbij, Private Bag X5026, 7599 Stellenbosch, South Africa. pp. 202-233.

Chapter 4

GENERAL CONCLUSIONS AND RECOMMENDATIONS

CHAPTER 4: GENERAL CONCLUSIONS AND RECOMMENDATIONS.

4.1 Brief overview

The study aimed to provide insights into popular belief that high yielding grapevines generally tend to produce lower quality grapes and wine. The results may help to determine what is required for high yielding Shiraz grapevines to produce a desirable new-world cultivar wine getting closer to the elusive concept of high yield combined with superior wine attributes. In this study three trellis/training systems were investigated to determine how grapevine productivity and grape- and wine composition can be altered as a result of differing canopy microclimate, grapevine balance regimes and yield component compensation reactions.

4.2 General conclusions of findings according to original objectives

4.2.1 Objective I: Canopy microclimate and grapevine water status

Bunch temperatures in the GA and S treatments displayed the greatest differences relative to ambient temperatures during season 2013/14. The GA treatment had the highest mean bunch temperatures throughout the season as well as increased degree hours (DH) accumulation which was a function of higher maximum and higher minimum bunch temperatures. Large variability was present with regards to the canopy light microclimate during season 2012/13 for all treatments. The highest variability was evident for the SS, DS and GA treatments, which was expected due to higher canopy gap fraction. The highest canopy density and lowest quality and quantity light were present within the bunch zone of the VSP treatment during season 2013/14. The S treatment had the most exposed bunch zone throughout the day. The GA treatment's canopy bunch zone was not as exposed as expected being slightly higher than the VSP treatment. The presence of more bunches may have contributed to this, as well as the horizontal canopy configuration, which may have restricted airflow more than in the canopies from the VSP treatment. This may have caused higher minimum and maximum bunch temperatures, especially in the afternoon in Stellenbosch where the effect of the cooling breeze would not have been so effective (Moffat, 2013). The minimum and maximum bunch temperatures of the S treatment varied the most with very high maximum temperatures and low minimum temperatures. The more exposed bunch zone together with high canopy gaps could have been responsible for this, where the grapes would also have been more exposed to the inversion effect of temperature during early mornings (Moffat, 2013). The GA treatment also had higher vigour in the second season, which could have led to the denser canopy.

With regards to grapevine water status, it was speculated that the conversion of the GA system led to compensatory root growth in terms of increased root density and thus improved utilisation of the soil volume (Richards, 1983). With this, the roots possibly acted as stronger sinks for carbohydrates than the growing shoots (Hunter & le Roux, 1992), which was evident with regards to generally higher PAR (lower canopy density), lower budburst percentage and decreased shoot growth. It is possible that the compensatory root growth may also have played a role in the GA treatment's water status. The driest soils accompanied by the least negative predawn leaf water potentials were present here. It may be that root density or root soil colonisation increased, increasing water absorption, but the decreased shoot growth (and lowest leaf area) led to decreased transpiration. It may also be that the stomatal recovery during the night was better due to an improved root system, contributing to the least negative predawn values. It was first thought that vines from the GA treatment displayed Isohydric-like behaviour by conserving water in the presence of possible deficits, but the stomatal conductance of the GA treatment was not different than the rest of the treatments and regulated when water was abundant (rain and irrigation) - which is known for anisohydric like behaviour. The S treatment's grapevines experienced water deficits to great extents after véraison, possibly due to the highly exposed bunch zone, to a point where recovery was impaired resulting in early leaf senescence, possibly also contributing to the low pruning- and cane mass and sunburned bunches. The S treatment also displayed disequilibrium between soil and plant water, but in this case consisted of the wettest soils and most negative predawn leaf water potentials. This may be due to increased night-time transpiration; however the S treatment definitely displayed signs of severe stress conditions after véraison.

It will therefore be beneficial for future studies to measure night-time transpiration as some evidence suggests that stomata are not completely closed during the night, allowing nocturnal transpiration and leading to night-time soil-plant water disequilibrium which can influence plant water relations in the day (Kathleen, 2007; Rogiers, 2009). With this information, it could be established whether the grapevines of the GA treatment decrease nocturnal transpiration to greater extents than the grapevines of the S treatment. When high nocturnal transpiration does occur, it will be better to measure stem water potential as an indicator of plant water deficits (Choné *et al*., 2001). Stem water potential measurements indicating whole-plant transpiration and soil/root hydraulic conductivity, together with stomatal conductance measurements should therefore be performed on the same day.

4.2.2 Objective II: Effect on grapevine yield components

The GA and DS treatments were pruned to double the amount of buds during season 2012/13 and as expected, yield increased in relation to the other systems. The number of shoots bursting in spring was however lower than expected on the GA treatment, probably due to the GA trellis still being in the establishment phase and as a result having lower effective bud load on the cordons. Another assumption was the presence of possible subterranean compensatory growth rather than above-ground growth. The higher fertility however fully compensated for the loss of shoots. Despite high canopy light variability that occurred during the first season, the GA treatment displayed the highest PAR values, which could have resulted in the high fertility in the next season, indicating a favourable light environment in the canopies from the GA treatment. Fertility alone in season 2013/14 was however not the main yield component responsible for high yields, but also an increase in budburst percentage and bunch mass, consequently increasing shoot numbers as well as bunches per vine. The GA treatment seemed to reach optimal productivity with the yield remaining constant throughout seasons, but it compensated through alterations in budburst percentage and fertility. Slightly decreased fertility in season 2013/14 resulted in the production of larger bunches. The number berries remained similar, but larger berries were produced in season 2013/14. In general the second season brought more favourable conditions for the VSP and GA treatments, with an increase in budburst percentage, shoot growth and berry- and bunch mass. This was most probably due to favourable early-season conditions (high rainfall during November), stimulating early shoot growth as well as berry and bunch development.

The lightly pruned S treatment in season 2013/14 showed decreased budburst percentage as expected, but the number of shoots was still equal to those of the GA treatment. These high shoot numbers together with the highest fertility between treatments resulted in the presence of a large number of bunches. The number of bunches per vine was the main yield component responsible for the retention of relatively high yields, as bunch sizes were reduced.

4.2.3 Objective III: Vegetative and reproductive balance with reference to compensation reactions and grapevine adaption.

The theory of increased root compensation of vines from the GA treatment can be supported by grapevine balance ratios. The GA treatment had a very high Y/CM ratio and very low LA/Y ratio during season 2012/13. This indicated that the yield exceeded vegetative growth. Yet, during the following season the Y/CM ratio decreased and LA/Y ratio increased considerably which led to the conclusion that the subterranean growth had enough reserves to support growth in the next season, to increase vegetative growth and sustain ripening. Increased biomass in season 2013/14 was the response of increased shoot numbers due to increased budburst percentage. However, increased shoot lengths were also evident, therefore the presence of sufficient reserves is assumed. The VSP treatment displayed the lowest Y/CM ratio during both seasons and although yield was increased during the second season, vegetative growth also increased which led to constant Y/CM ratios between seasons. The high Y/CM ratios of VSP were due to low yields (half of the yield produced by GA grapevines) and very vigorous growth (high leaf area/vine, pruning- and cane mass and shoot lengths). The vigorous growth of vines from the VSP treatment was evident as shoot growth cessation did not seem to occur, while growth ceased for the GA treatment at 71 DAB. Very dense canopies of the VSP treatment were the result of vigorous growth and this greatly affected the resulting wine quality.

Shorter and thinner shoots produced by the S treatment suggests a clear vigour decrease effect, but it also led to less vegetative growth in relation to the high yield. As a result a very high Y/CM ratio occurred, delaying ripening and possibly affecting future grapevine longevity. Nevertheless, the canopy compensated and produced larger leaves resulting in an improved and seemingly sufficient LA/Y ratio. Decreased shoot growth may also be the result of severe topping during anthesis, which eliminated high amounts of vegetative growth which was not replaced by compensatory lateral growth. As a result, shoot growth cessation could not reliably be determined.

A favourable relationship between reproductive and vegetative growth should show a linear correlation between yield and cane mass, meaning that as yield increases, cane mass increases correspondingly (and vice versa). This desirable relationship will therefore ensure that sufficient vegetative growth occur to sustain the increased amounts of fruit and as a result improve grapevine sustainability. A steeper slope (between yield and total cane mass) indicates grapevines more in favour of reproductive growth, while a flattened slope favours vegetative growth, with both extremes probably not being in favour of either sustainable yields or sustained growth and reserve allocation. It appeared that the DS and SS treatments in season 2012/13 and the GA treatment in season 2013/14 contained a favourable relationship (Figure 88). The VSP treatment showed the most constant relationship, but with increased vegetative growth in season 2013/14. The GA treatment indicated a more favourable relationship in season 2013/14 due to increased vegetative growth improving grapevine balance. The lightly pruned S treatment clearly displayed an enormous shift between seasons with yield exceeding vegetative growth. Even though this seemed to be unfavourable grapevine balance, the S treatment produced the most desirable wine (more detail in paragraph 4.2.4). The question is: will this be sustainable in terms of reserve status, especially if subsequent seasons present more difficult conditions?

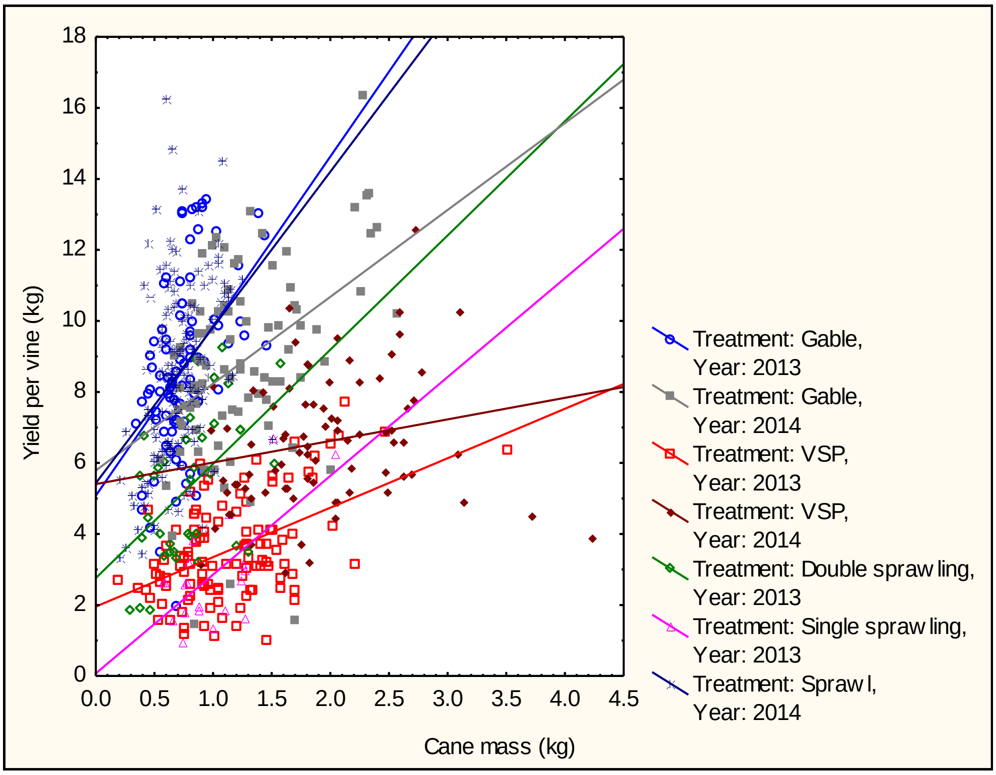


Figure 88 Relationship between yield (kg) and total cane mass (kg) for the treatments during both seasons.

4.2.4 Objective IV: Grape and wine composition differences by means of ripening evolution and wine sensory evaluation.

Ripening (in terms of sugar accumulation, TA, berry volume) was delayed when very high Y/CM ratios occurred with reference to the GA treatment in season 2012/13 and the S treatment in season 2013/14. This concluded that a more balanced grapevine can impact ripening favourably (Miller & Howell, 1998). The GA treatment also had the lowest pH between treatments in season 2012/13, which can support the occurrence of a more exposed canopy environment.

The difference in canopy microclimate, bud load and Y/CM ratios correlated strongly with wine sensory attributes. Canopy density, bud load and Y/CM were proportional to fruity attributes and inversely proportional to vegetal attributes. As a result, the VSP treatment produced the most vegetal wines and the S treatment the fruitiest in terms of berry taste and aromas. The GA treatment, occurring in between the above mentioned measurements, displayed both vegetal and berry characteristics but shifted more to fruity attributes possibly due to the higher bud load, more beneficial Y/CM ratio and better microclimate than VSP grapevines.

New world Shiraz wines are generally characterised as fruity and peppery rather than smoky (Clarke & Rand, 2007). Fruity characters, mainly presented by the S treatment, could arguably therefore be the most desired wine of the treatments, which had more vegetal/smoky and neutral wine characteristics. Questions can however be raised with regards to the desirability of the sprawling system, especially in the Stellenbosch context. Labour intensity was increased during harvest due to high bunch numbers and small bunches. Pruning was however the easiest comfortable between treatments with no canes strangled and tendrils gripping between foliage wires. As a result, pruning could be executed in one action, without first brush cutting the grapevines (pre-pruning). Stressed conditions however also increased when berry colouring initiated and the grapevines struggled to recover thereafter. This led to possibly smaller bunches, early leaf senescence and thinner shoots. Some literature suggest that a sprawling system may be a viable alternative for grapevine training, but they emphasised that this system may only be sustainable on soils where the grapevine water deficit and nutrient levels can be maintained (Stolk, 2014), and where mechanical harvesting would be feasible. In addition to this, judicial water and nutrient management in the soils would need to be applied.

The combined vegetal and fruity effect of the GA treatment on wine attributes concludes that increased yield did not affect grape and wine quality negatively or positively. If not, the GA treatment might be more complex containing both sides of the comparable wine attributes but more fruity, which is desired in a Shiraz wine.

Excessive vigour did produce wines high in vegetal attributes and correlated to bitterness as well as horsey, smoky and tarry attributes, which is certainly not desirable. A denser canopy of the VSP treatment did not seem to be the primary cause for these aromas, due to higher grape phenolics, wine- hue and total red pigment produced by the VSP treatment. It appears that the Y/CM and bud load rather played a significant role. Furthermore, the presence of *Brettanomyces* in the experimental wines can also be ascribed to the tarry, horsey and smoky characters and should be considered as a research topic in the future.

The results displayed evidence that different trellis- and training systems can produce different styles Shiraz wines. Implementing various training/trellising systems in order to produce different wine styles may be a viable marketing strategy as well as provide interesting blending options. This together with increased yield produced by alternative trellising may improve economical sustainability, if not increase production income/profitability. The construction of a larger trellis system does increase establishment costs, but the increased yields will ensure positive cumulative cash flow in five to seven years (Landbouweekblad, 2010). Thereafter, income profitability will increase if the trellis system is sustainable and therefore it is important to ensure adequate grapevine balance.

4.3 General recommendations

It would have been better to construct the GA trellis system along the whole first and second row, followed by the VSP and S systems. The reason for this is that we now have evidence of vigour differences within the plot, decreased vigour towards the end of plot (as described in Chapter 3), and it could with surety be established if the grapevines only react according to alternative cultivation practices and/or to a response of soil variability.

The neutron probes should be calibrated for the specific soil physical attributes to know if the values obtained is high or low for the specific area. The disequilibrium between plant water status and soil moisture content might have been due to variation in the soil water holding capacity and matrix potential due to soil texture variability as well as grapevine growth variation. Neutron probe positions should be re-positioned and distributed within the plot according to vigour and possibly according to soil texture (if soil variation exists in the plot) to be a more reliable representation of the soil environment.

It will be very interesting and helpful to note the sustainability for each grapevine in the years to come by repeating the measurements as displayed in the spatial plots (see Chapter three) as well as performing reserve status measurements/carbohydrate analysis to determine the carbohydrate content of certain demarcated grapevines (according to different vigour classes) within each treatment. Non-structural carbohydrates located in vegetative parts of the grapevine (wood and roots) provides important contributions in grapevine sustainability and grape quality potential (Zufferey *et al*., 2012) Studies on the seasonal carbohydrate variation in canes, trunks and roots can provide information regarding non-structural carbohydrate dynamics and allocation of carbohydrates between the various source and sink organs of the grapevine (Williams, 1996).

Furthermore, root studies for each treatment would have been beneficial and recommended in the future, to establish if the assumptions made with regards to the root compensation of the GA treatment were accurate. Root studies will also provide information regarding root distribution within the soil environment of each treatment. The effect of trellis conversion on root distribution and the allocation of carbon between above-ground and subterranean growth (Hunter & Volschenk, 2001) can therefore be established.

In conclusion, the implementation of alternative trellis- and/or training systems should be considered according to wine production goals. Not only can vigorous growth be maintained and consequently improve the canopy microclimate, but also increased yield is attained which may improve economic sustainability.

4.4 Literature cited

Choné, X., Van Leeuwen, C., Dubourdieu, D.& Gaudillère, J.P., 2011. Stem water potential is a sensitive indicator of grapevine water status. Ann. Bot. 87, 477-483.

Clarke, O. & Rand, M., 2007. Oz Clarke's Grapes and Wines: The Definite Guide to the World's Great Grapes and the Wines They Make. Oz Clarke's encyclopedia of grapes. Harcourt Inc. 2007.

Hunter, J.J. & Le Roux, D.J., 1992. The effect of partial defoliation on development and distribution of roots of Vitis vinifera L. cv. Cabernet Sauvignon grafted onto rootstock 99 Richter. Am. J. Enol. Vitic. 43, 71-78.

Hunter, J.J. & Volschenk, C.G., 2001. Effect of altered canopy:root volume ratio on grapevine growth compensation. S. Afr. J. Enol. Vitic. 22, 27-30.

Kathleen, L.K., Pangle, R. & Schotzko, A.D., 2007. Nocturnal transpiration causing disequilibrium between soil and stem predawn water potential in mixed conifer forests of Idaho. Tree Physiology. 27, 621-629.

Landbouweekblad, 19 November 2010. 'n Spesiale fokus: wyn-oorweeg ander prieel vir beter gehalte.

Miller, D.P. & Howell, G.S., 1998. Influence of vine capacity and crop load on canopy development, morphology, and dry matter partitioning in Concord grapevines. Am. J. Enol. Vitic. 49, 183-190.

Moffat, T., 2013. Sensor technology to assess grape bunch temperature variability in *Vitis vinifera* L. cv. Shiraz. MSc thesis, University of Stellenbosch, Private Bag XI, Matieland (Stellenbosch) 7602, South Africa.

Richards, D., 1983. The grape root system. Hort. Rev. 5, 127-159.

Rogiers, S.Y., Greer, D.H., Hutton, R.J., & Landsberg, J.J., 2009. Does night-time transpiration contribute to anisohydric behaviour in a *Vitis vinifera* cultivar? J. Exp. Bot. 60, 3751-3763.

Stolk, R.A., 2014. The effect of irrigation and canopy management on selective vegetative growth and reproductive parameters of *Vitis vinifera* L. cv. Shiraz in the Breede River Valley. MSc thesis, University of Stellenbosch, Private Bag XI, Matieland (Stellenbosch) 7602, South Africa.

Williams, L.E., 1996. Grapes. In: Photoassimilate distribution in plants and crops source-sink relationships. E. Zamski, A.A. Schaffer (Eds.), Marcel Dekker, New York. pp. 851-880.

Zufferey, V., Murisier, F., Vivin, P., Belcher, S., Lorenzini, F., Spring, J.L. & Viret, O., Carbohydrate reserves in grapevine (*Vitis vinifera* L. 'Chasselas'): the influence of leaf area to fruit ratio. Vitis 51, 103-110.

ADDENDUM

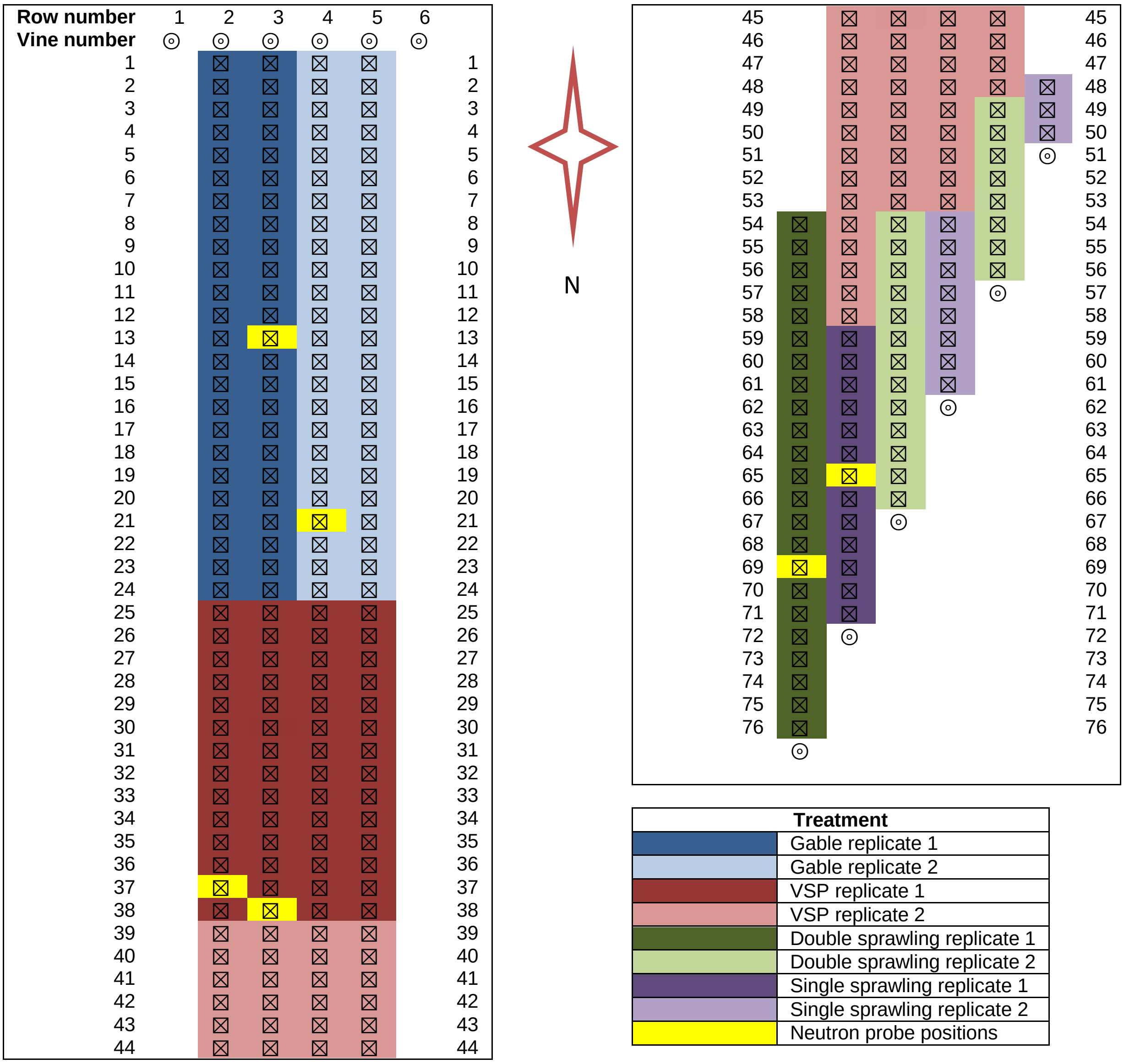
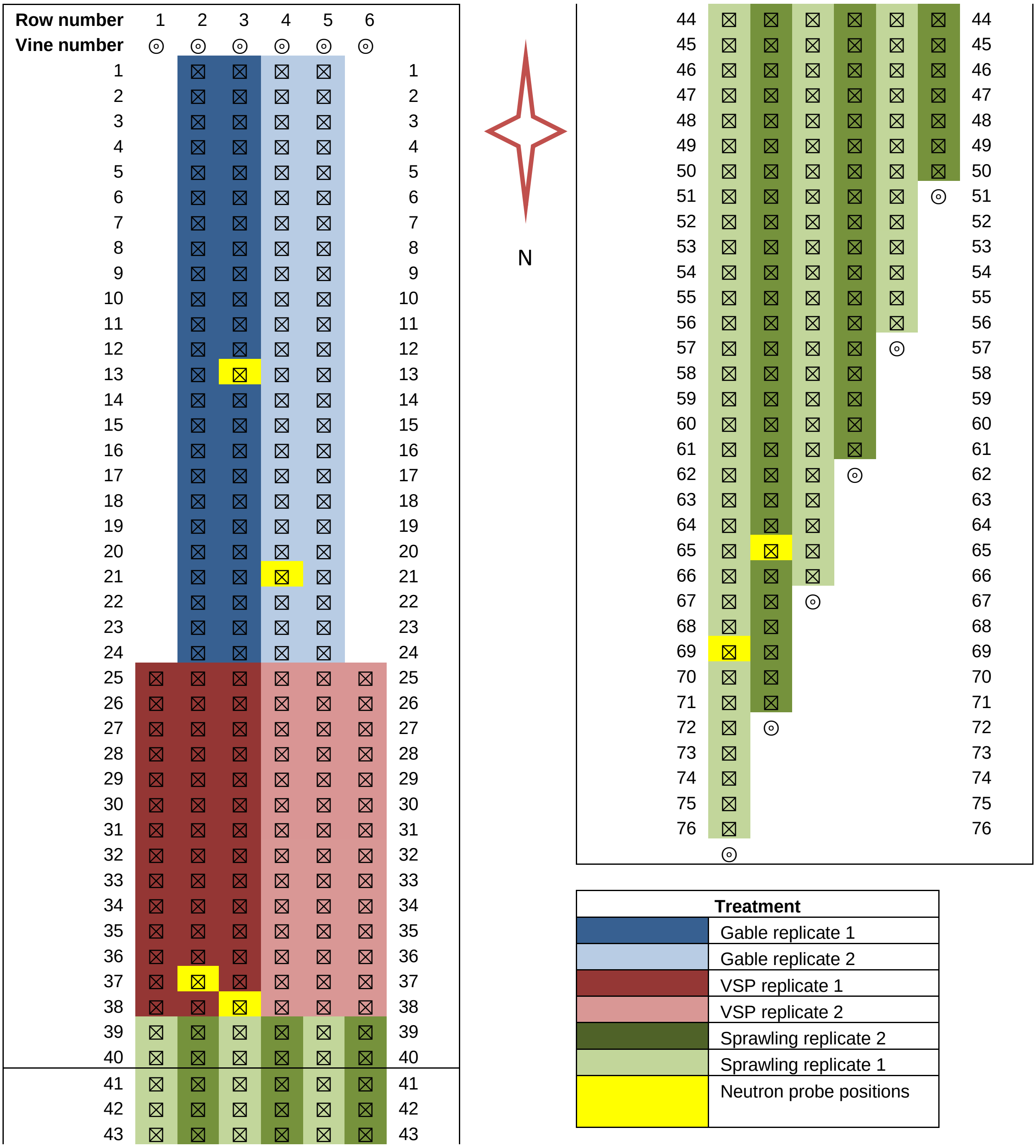


Figure 89A schematic diagram of the experimental layout of *V. Vinifera* L. Cv. Shiraz growing in the Stellenbosch area for the 2012/13 season.



Treatment	
🟦	Gable replicate 1
🟦	Gable replicate 2
🟥	VSP replicate 1
🟥	VSP replicate 2
🟩	Sprawling replicate 2
🟩	Sprawling replicate 1
🟨	Neutron probe positions

Figure 90A schematic diagram of the experimental layout of *V. Vinifera* L. Cv. Shiraz growing in the Stellenbosch area for the 2013/14 season.

Figure 91An Aerial image depicting the location of the different treatments and the positions of Tinytag data loggers (TTT-Tinytag Talk; RS-radiation shield containing Tinytag logger) at Welgevallen Experimental Farm at the University of Stellenbosch.

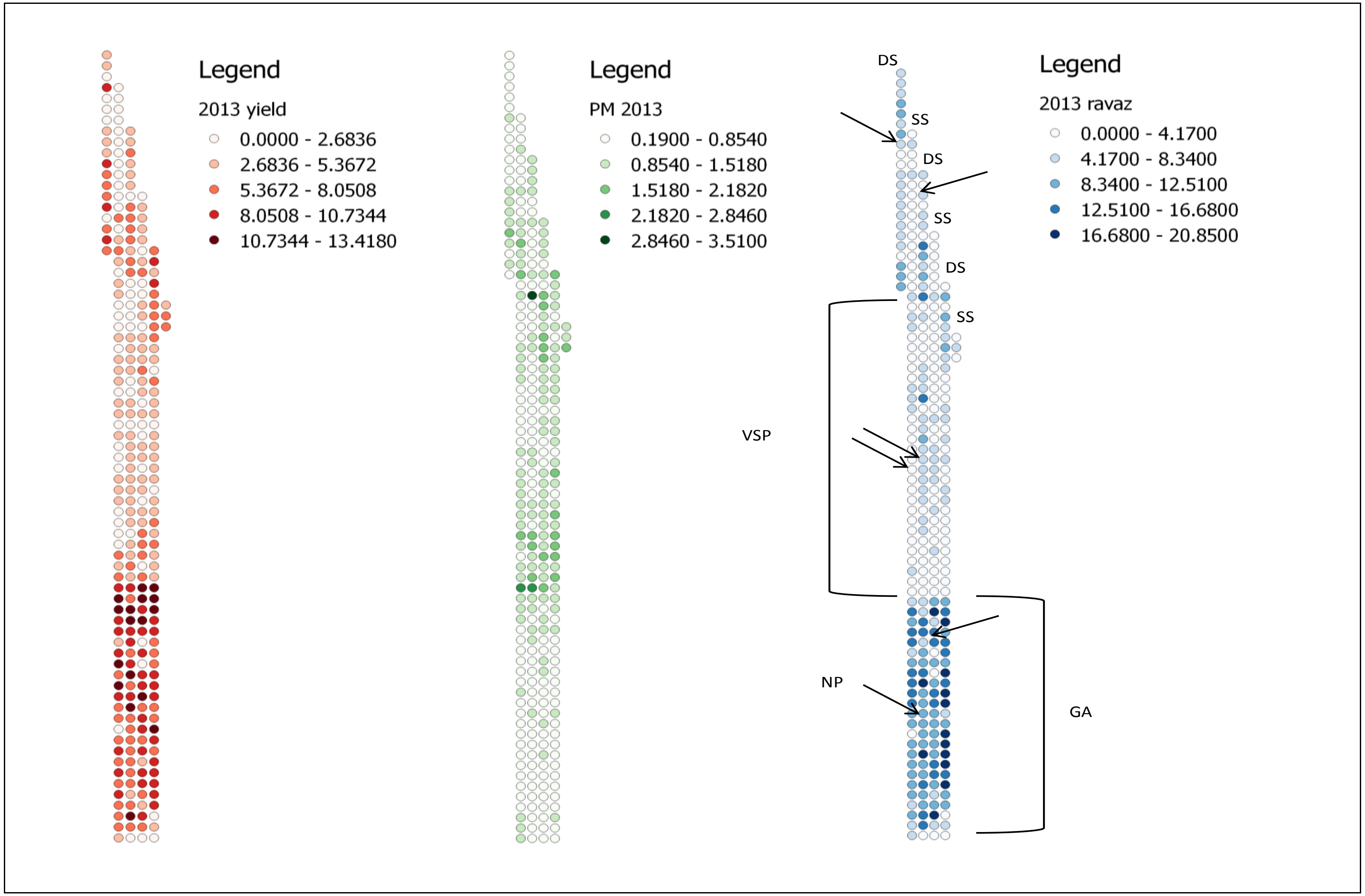


Figure 92 Spatial illustration of yield, pruning mass and Ravaz index for each grapevine during season 2012/13. Neutron probe positions (NP) indicated by arrows (see indicator vine positions inFigure 89).

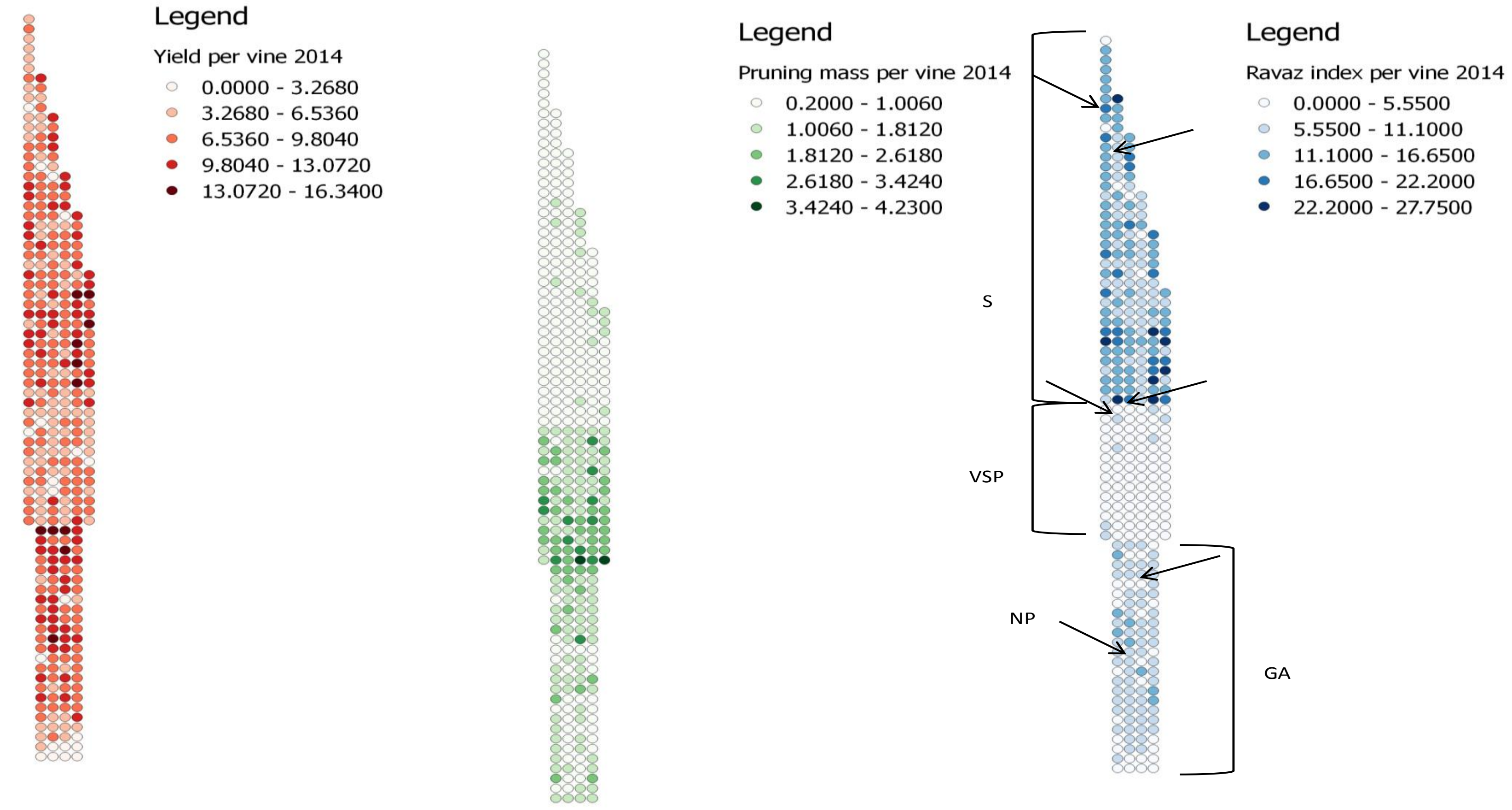


Figure 93 Spatial illustration of yield, pruning mass and Ravaz index for each grapevine during season 2013/14. Neutron probe positions (NP) indicated by arrows (see indicator vinepositions in Figure 90).

Table 26 The date and corresponding days after budburst (DAB) for specific phenological stages and measurements of the gable treatment during season 2012/13.

Gable 2012/13		
Phenological stage and measurements	**Date**	**DAB**
Budburst	29/09/2012	0
Flowering	12/11/2012	44
Full bloom	18/11/2012	50
Berry set	30/11/2012	62
Berry pea size	10/12/2012	72
Berry pea size measurements	19/12/2012	81
Sample begins at 5 °B	17/01/2013	110
Véraison	21/01/2013	114
Ripening measurements	20/02/2013	144
harvest measurements	25/03/2013	177
Harvest	26/03/2013	178
Pruning	17/09/2013	353

Table 27 The date and corresponding days after budburst (DAB) for specific phenological stages and measurements of the VSP treatment during season 2012/13.

VSP 2012/13		
Phenological stage and measurements	**Date**	**DAB**
Budburst	29/09/2012	0
Flowering	12/11/2012	44
Full bloom	18/11/2012	50
Berry set	30/11/2012	62
Berry pea size	10/12/2012	72
Berry pea size measurements	19/12/2012	81
Sample begins at 7 °B	17/01/2013	110
Véraison	21/01/2013	114
Ripening measurements	07/02/2013	131
harvest measurements	25/03/2013	177
Harvest	25/03/2013	178
Pruning	17/09/2013	353

Table 28 The date and corresponding days after budburst (DAB) for specific phenological stages and measurements of the double and single sprawling treatments during season 2012/13.

Double & single sprawling 2012/13		
Phenological stage and measurements	**Date**	**DAB**
Budburst	29/09/2012	0
Flowering	12/11/2012	44
Full bloom	18/11/2012	50
Berry set	30/11/2012	62
Berry pea size	10/12/2012	72
Berry pea size measurements	19/12/2012	81
Sample begins at 9 °B	17/01/2013	110
Véraison	21/01/2013	114
Ripening measurements	07/02/2013	131
Ripening/ before harvest measurements	15/03/2013	167
Harvest	14/03/2013	168
Pruning	17/09/2013	353

Table 29 The date and corresponding days after budburst (DAB) for specific phenological stages and measurements of the gable treatment during season 2013/14.

Gable 2013/14		
Phenological stage and measurements	**Date**	**DAB**
Budburst	07/10/2013	0
Suckering	04/11/2013	28
Flowering	20/11/2013	44
Flowering measurements	25/11/2013	49
50% berry set	27/11/2013	51
Berry set	04/12/2013	58
Berry pea size	12/12/2013	66
Pea size to bunch closure	17/12/2013	71
Berry 1-1.5 cm in diameter	08/01/2014	93
Sample begins at 9 °B	21/01/2014	106
Véraison	21/01/2014	106
Harvest	08/04/2014	183
Pruning	07/08/2014	304

Table 30 The date and corresponding days after budburst (DAB) for specific phenological stages and measurements of the VSP treatment during season 2013/14.

VSP 2013/14		
Phenological stage and measurements	**Date**	**DAB**
Budburst	07/10/2013	0
Suckering	04/11/2013	28
Flowering	20/11/2013	44
40% berry set	27/11/2013	51
Berry set	04/12/2013	58
Berry pea size	10/12/2013	64
Berry pea size to bunch closure	17/12/2013	71
Berry 1-1.5 cm in diameter	08/01/2014	93
Sample begins at 7 °B	21/01/2014	106
Véraison	21/01/2014	106
Ripening/ before harvest measurements	20/02/2014	136
Harvest	04/04/2014	179
Pruning	07/08/2014	304

Table 31 The date and corresponding days after budburst (DAB) for specific phenological stages and measurements of the sprawling treatment during season 2013/14.

Sprawling 2013/14		
Phenological stage and measurements	**Date**	**DAB**
Budburst	30/09/2013	0
Suckering	04/11/2013	35
Flowering	16/11/2013	47
80% set	27/11/2013	58
Berry set	30/11/2013	61
Topping	02/12/2013	63
Berry pea size	07/12/2013	68
Pea size to bunch closure	13/12/2013	74
Sample begins at 9 °B	21/01/2014	113
Véraison	21/01/2014	113
Ripening/ before harvest measurements	20/02/2014	143
Harvest	08/04/2014	190
Pruning	08/08/2014	312

Table 32 List of sensory wine attributes indicating significant ($p<0.05$) correlations (red) to grape- and wine measurements.

Measured parameters	Sensory attributes													
	Blackberry	Blackcurrant	Prune	Tea/ Tobacco	Jalapeno/ Gherkin	Cooked Veg	Dairy	Tar/Smokey	Horsey/ Plaster	Berry Taste	Smokey/ Tarry Taste	Cooked Veg Taste	Sour	Bitter
Wine colour density	0.74	0.75	0.80	0.64	-0.74	-0.77	-0.62	-0.84	-0.78	0.92	-0.89	-0.64	0.83	-0.63
Hue	-0.80	-0.73	-0.78	-0.63	0.82	0.81	0.68	0.91	0.83	-0.98	0.97	0.71	-0.88	0.71
Wine modified density	0.07	0.04	0.11	0.52	-0.08	-0.13	-0.36	-0.36	-0.32	0.36	-0.45	-0.05	0.35	0.08
Wine modified hue	-0.56	-0.47	-0.55	-0.56	0.54	0.52	0.44	0.83	0.60	-0.83	0.88	0.41	-0.67	0.41
Wine total red pigment	0.75	0.76	0.81	0.63	-0.75	-0.78	-0.61	-0.85	-0.78	0.93	-0.90	-0.65	0.83	-0.65
Wine total phenolics	-0.85	-0.92	-0.95	-0.58	0.81	0.83	0.47	0.79	0.74	-0.86	0.77	0.70	-0.73	0.77
Colour/berry	-0.80	-0.66	-0.71	-0.98	0.78	0.73	0.67	0.77	0.88	-0.71	0.69	0.81	-0.58	0.74
Colour/g berry	-0.72	-0.75	-0.74	-0.74	0.73	0.77	0.68	0.44	0.79	-0.51	0.40	0.82	-0.53	0.75
Total phenolics/berry	-0.37	-0.20	-0.30	-0.80	0.33	0.27	0.35	0.66	0.50	-0.53	0.62	0.28	-0.35	0.20
Total phenolics/ g berry mass	-0.87	-0.77	-0.79	-0.91	0.86	0.82	0.68	0.73	0.90	-0.71	0.64	0.90	-0.59	0.86
Berry fresh mass	-0.34	-0.37	-0.39	0.08	0.38	0.41	0.26	0.53	0.29	-0.65	0.66	0.22	-0.62	0.28
Berry Volume	-0.37	-0.32	-0.37	-0.03	0.40	0.39	0.29	0.62	0.34	-0.69	0.73	0.24	-0.62	0.29
Grape balling	-0.80	-0.85	-0.89	-0.62	0.80	0.84	0.62	0.82	0.80	-0.92	0.86	0.69	-0.84	0.71
Grape pH	-0.89	-0.90	-0.91	-0.67	0.82	0.78	0.35	0.64	0.71	-0.62	0.48	0.80	-0.44	0.88
Grape TA	-0.56	-0.43	-0.49	-0.26	0.51	0.42	0.14	0.77	0.39	-0.72	0.74	0.33	-0.48	0.45
Wine pH	-0.88	-0.77	-0.81	-0.63	0.92	0.89	0.76	0.93	0.91	-1.00	0.98	0.84	-0.91	0.84
Wine volatile acid	-0.80	-0.52	-0.58	-0.75	0.81	0.69	0.67	0.95	0.84	-0.88	0.93	0.76	-0.71	0.73
Wine total acid	0.80	0.83	0.86	0.51	-0.84	-0.88	-0.71	-0.81	-0.82	0.96	-0.90	-0.74	0.93	-0.75
Wine malic acid	0.37	0.69	0.68	0.27	-0.37	-0.54	-0.33	-0.22	-0.39	0.42	-0.29	-0.32	0.51	-0.32
Wine lactic acid	-0.73	-0.65	-0.69	-0.61	0.80	0.82	0.84	0.85	0.88	-0.95	0.97	0.74	-0.94	0.67
Wine glucose	0.59	0.43	0.47	0.46	-0.66	-0.64	-0.72	-0.82	-0.72	0.88	-0.95	-0.58	0.85	-0.52
Wine fructose	-0.52	-0.49	-0.45	0.02	0.46	0.38	-0.05	0.23	0.20	-0.21	0.08	0.44	-0.07	0.60

Table 33 (Continued) List of sensory wine attributes indicating significant (p<0.05) correlations (red) to grape- and wine measurements.

	Sensory attributes													
Measured parameters	**Blackberry**	**Blackcurrant**	**Prune**	**Tea/ Tobacco**	**Jalapeno/ Gherkin**	**Cooked Veg**	**Dairy**	**Tar/Smokey**	**Horsey/ Plaster**	**Berry Taste**	**Smokey/ Tarry Taste**	**Cooked Veg Taste**	**Sour**	**Bitter**
Wine ethanol	-0.65	-0.46	-0.44	-0.26	0.60	0.44	0.13	0.46	0.40	-0.36	0.29	0.59	-0.15	0.71
Wine glycerol	-0.15	0.08	0.12	0.02	0.12	-0.04	-0.11	-0.03	-0.01	0.19	-0.20	0.21	0.29	0.26
Spurs/vine	0.77	0.73	0.78	0.46	-0.78	-0.77	-0.56	-0.87	-0.73	0.95	-0.92	-0.65	0.84	-0.69
Canes/vine	0.89	0.90	0.92	0.58	-0.91	-0.93	-0.71	-0.86	-0.88	0.97	-0.90	-0.83	0.91	-0.85
Pruning mass/vine (g)	-0.95	-0.90	-0.92	-0.77	0.96	0.96	0.78	0.89	0.97	-0.96	0.89	0.92	-0.87	0.91
Cane mass (g)	-0.89	-0.79	-0.84	-0.72	0.92	0.89	0.77	0.94	0.93	-1.00	0.98	0.85	-0.90	0.83
Estimated bud load	0.90	0.99	0.98	0.62	-0.91	-0.96	-0.69	-0.69	-0.87	0.82	-0.69	-0.89	0.79	-0.90
Estimated budburst %	-0.98	-0.95	-0.97	-0.77	0.96	0.94	0.66	0.83	0.92	-0.87	0.77	0.93	-0.74	0.95
Bunches/vine	0.94	0.95	0.97	0.67	-0.95	-0.96	-0.71	-0.85	-0.91	0.94	-0.86	-0.88	0.86	-0.90
Yield (g)	0.83	0.69	0.75	0.61	-0.84	-0.79	-0.64	-0.96	-0.82	0.98	-0.98	-0.73	0.84	-0.75
Bunch mass (g)	-0.95	-0.87	-0.91	-0.71	0.94	0.92	0.69	0.94	0.91	-0.98	0.93	0.87	-0.85	0.89
Fertility	0.96	0.92	0.94	0.82	-0.91	-0.87	-0.55	-0.79	-0.86	0.78	-0.67	-0.89	0.61	-0.92
Y/PM ratio	0.95	0.96	0.97	0.73	-0.96	-0.97	-0.74	-0.81	-0.94	0.90	-0.80	-0.93	0.83	-0.93