A study of the interaction between grapevine vigour and water status for *Vitis vinifera L. cv* Merlot noir in Stellenbosch

by

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Thesis presented in partial fulfilment of the requirements for the degree of
Master of Agricultural sciences

at
Stellenbosch University
Department of Viticulture and Oenology, Faculty of AgriSciences

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March 2010

DECLARATION

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the owner of the copyright thereof (unless to the extent explicitly otherwise stated) and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

Date: 23 February 2010

SUMMARY

Grapevine water status is considered to be the most important factor limiting plant growth and production in the Mediterranean zones. In these regions with limited summer rainfall and limited water resources for irrigation grapevines may experience water deficits for an extended period of time. The demand of water for agriculture is constantly increasing, and will continue to do so due to the rise in the world population and to the effects of climate change on rainfall and evaporative demand in these regions. The Western Cape wine region is also classified as Mediterranean and grapevines grown in this region are often exposed to water "stress" conditions due to high evaporative demand and low water availability in the soil.

Plant water status of grapevines may dependent on, amongst other factors, the water potential of soil layers close to the root system, canopy size and evaporative demand. The canopy size of a grapevine can inherently be seen as a measure of grapevine vigour, and vigour variation among grapevines within a vineyard is a common phenomenon in the Western Cape. The importance of the contributions from several factors causing vigour variation within vineyards is still a subject of debate. This may be largely ascribed to the significant amount of variability in vineyards that researchers have to deal with during viticultural studies. However, the recent advances in remote sensing technology have established new methods to assess grapevine vigour variability.

In the face of the recognized variation within vineyards and the importance of a sustained grapevine water status, for wine grape productivity and -quality, it is alarming to think that a vineyard block is generally managed as a homogeneous entity when it comes to irrigation scheduling. What is more alarming is the assumption that grape, juice and wine quality will be homogeneous throughout a vineyard block – even without irrigation.

With this in mind, a study was conducted to study the interaction between grapevine vigour and grapevine water status within a commercial vineyard with variable vigour by implementing various irrigation regimes. Vigour variation was identified through multispectral aerial imagery and plant-based water status determinants were used to assess grapevine water status in plots of differing vigour within the vineyard. Soil water status was also assessed, and vegetative growth quantified to ultimately determine the variability in vigour and its possible contribution to the variability through the water status of the plant. Reproductive growth was monitored continually before evaluating the effect of water status and grapevine vigour on grape composition and subsequent wine quality.

The various methods used to evaluate grapevine vigour showed good correspondence. Pruning mass measured at the end of the season confirmed leaf area measurement (main leaves and lateral leaves) during vegetative growth, and corresponded well, in terms of main vigour

classifications with the NDVI images collected. Berry weight and volume responded to the various classifications, with a decrease in water deficits from one classification to the next accompanying an increase in berry weight and volume.

Analyses of the berry composition and wines showed statistically significant differences between the classifications. This was found for sugar content per berry, total phenols, total red pigment, malic acid, nitrogen and pH for the grape juice analyses. Wine pH and total acidity also differed significantly.

OPSOMMING

In die Mediterreense sones word plantwaterstatus beskou as `n hooffaktor wat groei en produksie van `n wingerdstok negatief beinvloed. In hierdie sones kan wingerdstokke vir lang periodes `n tekort aan water ervaar a.g.v `n tekort aan reënwater gedurende die somer en lae beskikbaarheid van besproeingswater. Die vraag na water vir landbou is ook konstant besig om toe te neem in dié sones en die tendens sal voorduur a.g.v die groei in die wêreldbevolking, die effek van klimaatsveranderig op reënvalpatrone en die hoë verdampingsfaktor. Die wingerd- en wynstreek van die Wes-Kaap word ook geklassifiseer as Mediterreens en wingerdstokke in hierdie streek ervaar dikwels waterspanning wat deur hoë evapotranspirasie en min beskikbare grondwater veroorsaak word.

Van die faktore wat die waterstatus van `n wingerdstok bepaal is onder andere die waterpotensiaal van die grondlae rondom die wortelstelsel, die grootte van die wingerdlowerraamwerk en die evapotranspirasiebehoefte. Die omvang van `n wingerdstok se lower binne die prieel word beskou as `n aanduiding van wingerdstokgroeikrag en variasie in groeikrag tussen wingerdstokke is `n algemene verskynsel in die Wes-Kaap. Die rangorde, wat die effek van die verskeie faktore wat groeikragvariasie tussen wingerdstokke bepaal, word steeds gedebatteer. Die debat kan groottendeels toegeskryf word aan die beduidende hoeveelheid variasie tussen wingerde waarmee navorsers te doen kry in wingerdkundige studies. Hoewel, met onlangse vordering aangaande afstandswaarnemingstegnologie is daar nou nuwe metodes beskikbaar om wingerdgroeikrag te evalueer.

Dit is kommerwekend om te dink dat `n wyndruifwingerd normaalweg as `n homogene eenheid bestuur word as dit kom by besproeiing. Veral met die wete dat groeikragvariasie tussen wingerde algemeen erken en aangeteken word, en dat volhoubare waterstatus van `n wingerdstok van kardinale belang is vir produksie en kwaliteit van wyndruiwe. Die aanname dat wyndruiwe, die sap- en ook wynkwaliteit homogeen sal wees regdeur `n wingerdblok is egter meer kommerwekkend.

Na aanvang van dié denke is daar `n studie geloods om die interaksie tussen wingerdstokgroeikrag en wingerdstokwaterstatus te evalueer. Met die studie is verskeie besproeiingsregimes aangebring binne `n kommersiële wingerd wat interne groeikragvariasie tentoonstel. Groeikragvariasie was geïdentifiseer deur middel van multispektrale lugfotos terwyl die wingerdstok se waterstatus geëvalueer is met behulp van plantgebaseerde metings in die verskillende groeikragareas. Die waterstatus van die grond is geëvalueer tesame met die vegetatiewe groei van die wingerd sodat die groeikragvariasie en die invloed van die plantwaterstatus op die groeikrag bepaal kon word. Die reproduktiewe groei is deurlopend gemonitor voor die effek van wingerdstokwaterstatus en wingerdstokgroeikrag op druifsamestelling en wynkwaliteit bepaal is.

Daar was `n goeie ooreenkoms tussen die verskeie metodes wat gebruik is om wingerdgroeikrag te bepaal. Snoeimassa aan die einde van die seisoen was ooreenkomstig met die blaaroppervakte (hooflootblare en sylootblare) wat tydens vegetatiewe groei gemeet is, en het ook goed korreleer, met die multispektrale lugfotos se hoof groeikragklassifikasie. Korrelgewig en -volume het reageer op die verskeie besproeiingsregimes, en daar was `n toename in korrelgewig en -volume saam met die afname in watertekort van een regime tot `n ander.

Daar was beduidende verskille tussen die verskeie klassifikasies t.o.v. korrelsamestelling analise en wynevaluasie. Die suikerinhoud per korrel, totale fenole, totale rooi pigment, appelsuur, stikstof en pH het verskil in druiwesap analises. Die pH en suur van die wyne het ook beduidend verskil.

This thesis is dedicated to
My parents Pierre and Jackie Boshoff, and to my grandmother Dilene Boshoff, whom without their support this would never, had been possible

This thesis is also dedicated to Annell Burden for all her support, love and motivation she gave me during this study

BIOGRAPHICAL SKETCH

Corné J Boshoff was born in Bellville on 2 January 1983. He attended seven different schools throughout South Africa and matriculated at Bellville High School in 2001. Corné enrolled at Stellenbosch University in 2002 and obtained the degree BScAgric in Viticulture and Oenology in January 2006. In that same year he enrolled for the degree MScAgric in Viticulture, also at the Stellenbosch University.

ACKNOWLEDGEMENTS

I wish to express my sincere gratitude and appreciation to the following persons and institutions:

- Mr. Albert Strever of the Department of Viticulture and Oenology, for acting as my supervisor, for his advice, encouragement, determination and positive attitude;
- Prof. Martin Kidd, for his assistance with the statistical analysis of the data;
- The academic and technical staff at the Department of Viticulture and Oenology for their assistance;
- Colleagues with associated projects that worked with me in the vineyard;
- My brother and sister for their support
- The Burden family, for their support and reassurance throughout my studies

PREFACE

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Chapter 1

GENERAL INTRODUCTION AND PROJECT AIMS

GENERAL INTRODUCTION AND PROJECT AIMS

1.1 INTRODUCTION

Variability is inherently present in and between all vineyards. Grape producers have known this for as long as they have been growing grapes, but still vineyards are sometimes managed on the assumption that they are homogenous. Within-vineyard variability in vigour is a phenomenon very common to South African vineyards, and especially in the Western Cape region because of its highly variable soils and terroir units. The spatial variation in these factors may also lead to spatial variation in grape quality and yield within vineyards, potentially leading to a reduction in average wine quality and productivity. With an increasing differentiation in pricing between grapes based on measured quality attributes becoming inevitable, increasingly intelligent management decisions are required to moderate vineyard variability in order to produce a higher-quality, higher-value product. Also, vineyard potential will be under-exploited and sub-economic end-products obtained when vigour and water deficit variability are not accommodated in management decisions. It is fundamental that these decisions are based on accurate and reliable data to describe the variability exhibited by the grapevines. Increasing knowledge of the causes and effects surrounding within-vineyard variation, mainly in grapevine water status and grapevine vigour is leading to an emphasis on developing methods of irrigation that would potentially minimise variability. However, irrigation is mostly scheduled at the level of a single vineyard block, and localised soil or plant measurements are mostly used to make decisions on timing (frequency) and intensity. The advent of precision irrigation methods, such as regulated deficit irrigation (RDI) and partial rootzone drying (PRD), has played a major role in the optimisation of grapevine water status, vegetative growth and water required for irrigation, but has highlighted the need for advanced methods of accurate irrigation scheduling and control.

Irrigation scheduling has conventionally aimed to achieve an optimum water status (supply) for productivity, with soil water content being maintained close to field capacity (Myburgh, 2005). The soil water status is reminiscent of plant available water, seeing that it represents the relationship between the soil water content and soil water potential. Soil water status has thus traditionally been used as a reference to estimate water deficit in a grapevine. However, indicators of grapevine water deficit based on soil water status are not comprehensive, as it has questionable value in vineyards with considerable spatial variation in soil properties and root distribution. According to Schmitz and Sourell (2000), the possible errors in many types of soil moisture readings are usually also high for field applications, mainly due to possible spatial variability in soil water content and other factors affecting soil moisture measurements. In recent

years new scheduling techniques have been introduced, many of them based on sensing the plant water status to water deficits rather than sensing the soil moisture status directly.
Jones (2004) believes that indicators based on plant attributes may present a useful alternative to direct physical measurements of soil water availability, provided that they respond sensitively to soil water status. Thus, more attention is being paid to monitoring plant water status in field-grown grapevines, as researchers believe it would allow the diagnosis of the onset of and severity of water deficits so as to schedule irrigation according to actual plant needs (Patakas *et al.*, 2005). Changes in plant water status could be described by using a sensitive physiological indicator that integrates both soil and climatic conditions. The pressure chamber is considered to be a reliable method for determining the water status of field-grown grapevines (Choné *et al.*, 2001). Use of the pressure chamber technique can provide values for various parameters, such as pre-dawn leaf water potential (pre-dawn Ψ), midday leaf water potential (leaf Ψ) and stem water potential (stem Ψ).

Although a substantial body of literature characterises the impact of water deficits on grapevine physiological responses, and given the complexity of grapevine vigour and the pronounced effect water deficits may have on grapevine growth and productivity, there is little information that quantitatively relates to an interaction between these two variables. Also, considering the potential for variability in plant water status encountered in blocks where there is variability in vigour (Deloire *et al.*, 2004), the question arises where and how soil or plant water status should be measured to be representative of the whole block.

In this study, NDVI multispectral images were used to establish vigour variation within a commercial vineyard block. The experimental plots were then laid out according to the areas of differing vigour. Plant-based water status determinants were used to assess grapevine water status at the plots of differing vigour within the vineyard, while soil water status was also assessed using soil-based measurements. Vegetative growth was quantified to ultimately conclude the variability in vigour identified with the NDVI images and to determine the possible contribution to the variation by the water status of the plant. Reproductive growth was monitored continually before evaluating the effect of grapevine water status and grapevine vigour on grape composition and subsequent wine quality.

1.2 PROJECT AIMS

The aim of the study was to investigate relationships between grapevine vigour and plant water status in order to assess the potential impact on irrigation scheduling for quality wine production.

Main aims:

(i) To define and characterise grapevine vigour using multispectral images and to establish different irrigation regimes based on monitoring of plant water status

(ii) To analyse soil water content and plant water status in reaction to the established irrigation regimes

(iii) To assess the interaction between grapevine vigour and soil and plant water status and to investigate correlations between these factors

(iv) To assess grape composition and wine characteristics resulting from specific grapevine vigour and grapevine water status combinations

The main hypothesis is that the interactions studied may be used to incorporate the important factor of grapevine vigour into the management of the soil-plant-water relationship, which may in turn facilitate whole-block or sub-block water status monitoring and irrigation scheduling, especially where multispectral imagery is available as a management tool.

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Chapter 2

LITERATURE REVIEW

A REVIEW OF GRAPEVINE VIGOUR AND WATER STATUS AS VARIABLES ENCOUNTERED WITHIN VINEYARDS

LITERATURE REVIEW

2.1 INTRODUCTION

Viticultural studies in recent years were strongly focused on within-vineyard variability and what should be done to achieve vineyard uniformity. Researchers mainly believe that vineyard uniformity would have a carry-over effect to production, which consequently would lead to consistent yields, grape composition and even wine quality. Bramley and Hamilton (2004) emphasised this when they said that grape growers and winemakers are searching for answers to a number of questions relating to vineyard variability. According to them, these people firstly want to know what the key drivers of vineyard variation are and whether these may be managed and, secondly, whether targeting the management of variation delivers an economic benefit over conventional, uniform management. The answers to these two questions would enable growers to better observe and develop an understanding of the variability in their production systems, and to use this to better match the production inputs to desired or expected outputs (Lamb *et al.*, 2004a).

Within vineyards, variability in grapevine vigour and grapevine water status are seen as the two phenomena most common in grape-producing countries. Therefore, the causes of vigour and water status variability and the effects thereof on production and quality have been relatively well examined. Precision practices (so-called “Precision Viticulture”) are increasingly being employed in wine grape production, particularly regarding canopy management and irrigation, to control vigour and to optimise grapevine water status (Hall *et al.*, 2008). Despite the availability of numerous soil moisture and plant water status monitoring devices, the application of specified irrigation may not always be consistent from one season to the next, as it will be influenced by environmental factors, in particular by rainfall and evaporative demand (Patakas *et al.*, 2005). The responses of the grapevine will also be influenced by genotype and grafting combinations (Smart and Coombe, 1983). Added to this is the increasing prevalence of once-off events, such as heat waves, periods of drought and subsequent restrictions on water availability, potential increases in irrigation water and soil salinity as well as diminished root systems under drip irrigation and the need for increased fruit loads to ensure financial viability in the current economic environment.

Productivity per unit area is a key factor, along with homogeneous grape composition, in determining grapevine performance (McCarthy, 1997). Grapevine performance can be linked to numerous single factors, but the combined effect of these factors is more important. Creating an understanding of the influential factors consists of identification, quantification and analysis of

the outcome on the end product. This review follows these steps to evaluate grapevine vigour and grapevine water status as factors determining grapevine performance.

2.2 GRAPEVINE VIGOUR

2.2.1 VIGOUR AS A FACTOR OF GRAPEVINE CAPACITY

When discussing the characteristics of grapevine growth, Winkler *et al*. (1974) differentiated between the terms “vigour” and “capacity”. They interpreted vigour as the rate at which the parts of the grapevine actively grow and capacity as the ability of total production, rather than the rate of activity. Thus, a grapevine with a well-established permanent structure and more shoots may have a substantially higher capacity (ability to ripen fruit) than a grapevine with only a few shoots. This ability arises due to the perennial nature of the grapevine. It stores surplus carbon in sinks in order to facilitate fruit growth and sugar accumulation during the season, and to assist early-season grapevine growth in the following season until carbon supply from the mature leaves can sustain the grapevine. In contrast to this, the vigour (ability to grow faster and longer) of a grapevine with only a few shoots may be much higher than that of a grapevine with many shoots (Archer, 1985). The term “vigour” used by Winkler *et al.* (1974) mainly gives a measure of the grapevine’s ability to maintain a certain level of vegetative growth, but Smart (1985) mentions that he refers to a grapevine’s “capacity for growth” when using the term vigour.

For a grapevine, vigour and capacity for production can also vary between single shoots, resulting in a vigorous shoot to potentially have a larger capacity than a weak shoot. In a study by Cloete *et al.* (2006), comparisons based on certain vegetative growth parameters were made between normally developed and underdeveloped shoots. The normally developed shoots had an average length of 112 cm and were significantly longer than the underdeveloped shoots, which had an average length of 50 cm. The study showed that higher levels of starch formation and accumulation occurred in the normally developed shoots. Reserves within these shoots were also more evenly distributed. The normally developed shoots seemed to have a greater potential for producing a sustainable higher yield of better quality than the underdeveloped shoots, as they had a more desirable leaf area composition (more and longer secondary shoots) and a larger total leaf area per shoot. This correlates with Winkler *et al*. (1974), who stated that the total active leaf area determines capacity. So, in theory, by increasing the number of vigorous shoots on a grapevine you consequently enlarge the total active leaf area, and this expansion of leaf area could lead to an increase in the capacity of the grapevine. The leaves are the primary sources of carbon assimilates for the plant’s respective organs and the four biggest sinks are the bunches, seasonal growth (including leaves and tendrils), perennial structures (cordons and trunks) and the root system. An increase in leaf number (source) would thus benefit the sinks during the growth period (vegetative and reproductive). The role played by

source-sink relationships in grapevine yield and quality was assessed firstly by Ravaz (1906), who proposed the yield/pruning mass ratio to estimate the balance between vegetative growth and grapevine productivity. This index also supports the definition of grapevine capacity by Winkler *et al.* (1974).

An increase in the number of shoots and an expansion of leaf area can also have an inverse effect on a grapevine's capacity. Smart *et al.* (1985a) emphasised that canopies become crowded or dense when there is too much leaf area within the volume bounded by the canopy surfaces. They correlated the degree of shading in the canopy to the amount of foliage and the way the foliage was arranged within the canopy – for example a high value of the ratio leaf area:canopy surface area (LA/SA), or leaf layer number (LLN) (Smart, 1985) or shoot density (shoots/m canopy) (Smart, 1988). Light levels in dense canopies are very low, often less than 1% of the values measured at the exposed surfaces of the canopy (Smart, 1985). Transmitted light found in shade conditions alters quality as well as quantity, with important physiological implications for the leaves found there (Smart, 1987). Thus, by increasing the leaf area and causing excess shade within the canopy there will be a decrease in effective leaf area and consequently in grapevine capacity. In a vineyard with vigour variation it is thus possible to find grapevines for which the capacity is either under- or over-utilised, and under utilisation of capacity can also be negative due to increase in vigour over growing seasons in these conditions (Strever, 2003).

2.2.2 ASSESSING THE PARAMETERS THAT DEFINE VIGOUR

By definition, the leaf and shoot system of the grapevine is called the canopy, and the dimensions of the canopy (width, length, height, etc.) are used as a quantitative measure to classify vigour (Smart *et al*., 1990). By quantifying the foliage height, lateral growth and leaf area density within a growth timeframe, it is possible to differentiate between grapevines of varying vigour (Carbonneau *et al*., 1997). This vigour quantification of a grapevine can be sustained from year to year or be dependent on seasonal influences, such as climate or season-specific management practices. In general terms, it has always been assumed that plants with high vigour are healthier and more productive than plants with low vigour, mainly because of the visual image of vitality and productive potential depicted by plants with higher vigour (Howell *et al*., 1987). Fig. 2.1 is a theoretical image of a high and low vigour grapevine. Smart (1985) used a diagram of the grapevine canopy to demonstrate the geometry of a trellised grapevine (Fig. 2.2). The diagram gives an indication of the dimensions available to each grapevine within the grapevine row and consequently in a vineyard. The grapevine spacing and trellising system is used to create boundaries of space (width, length, height, etc.).

Low vigour grapevine

High vigour grapevine

Figure 2.1 Images of what a grapevine with low vigour and a grapevine with high vigour would look like theoretically.

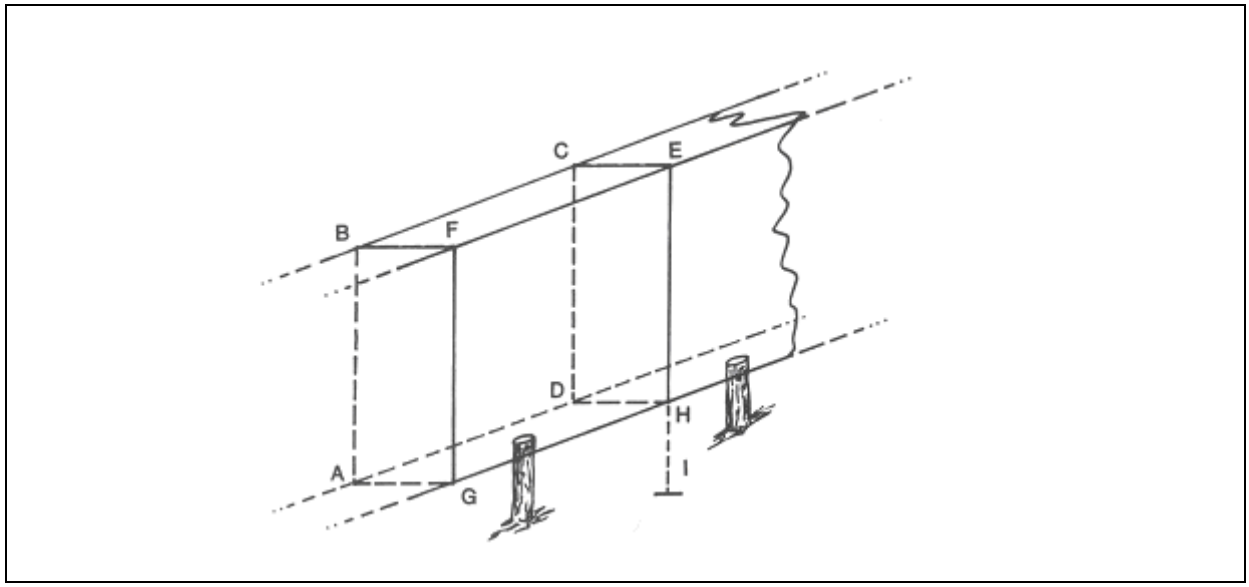

Figure 2.2 A diagram of the geometrical dimensions of a grapevine canopy (Smart, 1985).

The dimensions of a canopy, consisting of shoots and leaves, will visually increase in volume with an increase in grapevine vigour. Shoots exhibiting excessive growth are commonly found in vigorous vineyards. Vigorous shoots are characterised by a relatively large diameter, long internodes and large leaves, and there is a distinct tendency for active lateral growth (Smart *et al*., 1990). For instance, the distinguishing characteristics recognised in vineyards with high

vigour are grapevines with longer shoots, larger leaves and more lateral shoots compared to grapevines in lower-vigour vineyards (Smart *et al*., 1985a). The study by Smart *et al.* (1985a) conducted in a dryland Shiraz vineyard is a good example of how canopy dimensions differ when vigour variation is present. Experimental plots were arranged across a distinct vigour gradient (replicate nine was the most vigorous and replicate one the least), which was the result of soil depth variability that affected water supply to the grapevine roots. Table 2.1 shows the effect of variable vigour on shoot growth, canopy dimensions and yield. A notable trend was the larger leaves, longer shoots and higher yield of the more vigorous grapevines, with a resulting increase in shading as indicated by the ratio leaf area (LA) / canopy surface area (SA).

Table 2.1 Effect of vigour level on vegetative growth, canopy dimensions and yield. Vigour increases from experimental plots 1 to 9, situated within a single vineyard block (Smart, 1985a).

Canopy & grapevine characteristics	Units	Experimental block									Sign.
		1	2	3	4	5	6	7	8	9	
Canopy surface area	(1000 $m^2.ha^{-1}$)	8.38	8.71	8.96	8.69	9.94	9.94	9.66	9.88	10.51	*
Canopy volume	($m^3.vine^{-1}$)	2.3	2.3	2.3	2.4	2.7	2.7	2.7	2.7	3.0	NS
Mean main leaf area	(cm^2)	81	92	92	101	101	108	105	116	107	**
Mean lateral leaf area	(cm^2)	30	32	28	33	32	34	36	28	35	NS
Nodes / main shoot		10.5	10.6	11.1	11.2	10.6	11.8	12.1	12.7	13.7	**
Nodes / lateral shoot		1.8	1.1	1.1	1.4	0.7	3.7	3.8	1.9	9.2	**
Leaf surface area	(1000$m^2.ha^{-1}$)	13.2	14.3	15.1	18.0	15.6	19.2	23.3	25.7	29.0	**
Leaf area/canopy surface area		1.7	1.7	1.8	2.0	1.7	2.0	2.5	2.7	3.0	*
Yield/grapevine	(kg)	11.5	14.7	15.4	16.5	16.1	17.2	15.5	22.5	24.7	*
Shoots / grapevine		135	132	133	141	133	126	145	154	151	NS
Pruning mass / grapevine	(kg)	1.2	1.6	1.7	1.6	1.8	2.4	2.7	2.4	2.8	**
Mean shoot mass	(g)	9.0	12.6	12.6	11.1	13.6	19.1	18.2	15.6	18.9	**

Significance levels:

(*) = $p \leq 0.05$; (**) = $p \leq 0.01$; NS = not significant

2.2.3 FACTORS CAUSING VIGOUR VARIATION

The variability amongst grapevines is not a new phenomenon to viticulturists. They are generally well aware that grapevine performance (vigour) varies within their vineyards (Bramley and Hamilton, 2004). The variability in vigour between vineyards is of an intricate nature, and therefore so are the relationships between the factors that affect or cause it (Strever, 2003). The variation is even more complex if it occurs within a single vineyard. Research has shown that plants integrate the effects of variable environmental conditions, which include climate, soil properties, management practices, grapevine stress (due to disease incidence or nutrient and water over- or undersupply) and, in some cases, plant factors, through their expressed canopy (Dobrowski *et al.*, 2003; Strever, 2003). All of these factors have the ability to enhance or reduce grapevine vigour. Detailed reports on the factors causing vigour variation within vineyards have been made over the years, but vigour alone cannot as yet be used as a parameter for wine quality. This does not mean that the impact of vigour on the grapevine and subsequently on the grapes is totally unknown. Substantial research has shown that vigour affects fruit ripening (Winkler, 1958; Winkler *et al*., 1974), pest infestation and disease (English *et al.*, 1989; Baldy *et al.*, 1996), water use (Evans *et al.*, 1993; Williams *et al.*, 2003), yield (Smart *et al.*, 1990; Baldy *et al.*, 1996; Dry, 2000), as well as fruit characteristics (Smart, 1985; Jackson and Lombard, 1993; Mabrouk and Sinoquet, 1998, Lamb *et al.*, 2004b).

2.2.4 POTENTIAL IMPACT OF GRAPEVINE VIGOUR ON GRAPE AND WINE COMPOSITION

Berry size at harvest depends on many factors that modify berry growth at any stage of development, and grapevine vigour is known to be such a factor (Smart *et al.*, 1985a; Strever, 2003). High-vigour grapevines have been shown to produce larger berries than low-vigour grapevines and this, in turn, modifies the physiology of the berry to change its composition. The ‘dilution’ effect of larger berries is also a determining factor when it comes to grape composition at harvest and, ultimately, the quality of the wine produced (Jackson and Lombard, 1993). Berry sugar concentration is generally lower and berry pH higher with an increase in berry volume. Larger berries are also the main factor behind the negative correlation found between high vigour, total phenolics and colour in red grapes due to the increased dilution of skin constituents (Lamb *et al.*, 2004b). The smaller berries in the lower-vigour areas are thus seen by some as an important factor in the achievement of high wine quality. These berries produce quality wine, more often than not as they have a high skin/pulp ratio. Pirie and Mullins (1977) favoured small berries, mainly due to the existing linkage between the accumulation processes of sugar and phenolics. Even for white cultivars, wine composition is normally favoured by a high skin/pulp ratio in the berries. However, low-vigour grapevines accompanied by smaller berries have also recently shown negative correlations with wine quality, seeing that the low vigour was disadvantageous to reproductive growth and berry sugar loading.

Grapevine vigour can also have an indirect effect on grape composition via its impact on the canopy dimensions of the vineyard, seeing that the vigour expressed is of a natural occurrence. If canopy management is performed, such as topping and leaf removal, it is assumed that the modified canopy dimensions would directly affect grape composition. According to Carbonneau (1995), berry maturation, yield and wine quality are dependent on canopy structure, as it defines the microclimate and thus the photosynthetic activity and carbon output of the grapevine. Mabrouk and Sinoquet (1998) have shown that the end result of increased grapevine vigour is typically increased within-canopy shade and, according to Kliewer and Dokoozlian (2005), open type canopies that have moderate shoot vigour are rated highest in the 80-point scoring system of Smart and Robinson (1991), which evaluates potential fruit quality. In general, biomass production and yield potential have been shown to be related to the amount of solar radiation intercepted by the foliage canopy, while grape composition has been associated with the exposure to sunlight of leaves and bunches (Smart *et al.*, 1990). Shade within the canopy is thus seen as a major cause of poor grape quality, and hence poor wine quality.

The ultimate source of sugar produced in grapevines is leaf photosynthesis, which is dependent on the total amount of exposed leaf area (Kliewer and Dokoozlian, 2005). Thus, the sugar concentration of the berry is related to the amount of available functional leaf area and to the light environment. Smart *et al.* (1985a) demonstrated that canopy shading causes an increase in must potassium (K^+) levels and a consequently higher must pH. Shade has also been shown to decrease the levels of tartaric acid in the berries and increase that of malic acid (Carbonneau, 1995). The development of flavour and colour in red wine grapes is also greatly influenced by canopy shade. A study by Lamb *et al.* (2004b) showed that the location of grapes within a given canopy, as well as canopy density and size, influenced the concentrations of anthocyanins and phenolics in the berries. The synthesis and accumulation of flavonoids were related to direct effects of light on leaves and to interactions between light and temperature effects on bunches.

2.2.5 ASSESSMENT OF GRAPEVINE VIGOUR

Vigour variation within a vineyard block can only be managed or incorporated into management practices if it is identified and quantified. Information regarding relative vigour levels has many applications for improving management at a sub-vineyard scale. There are numerous conventional techniques found throughout the literature to identify differing levels of grapevine vigour. In studies where vigour measurements were done, the authors did not use all of the techniques nor highlighted a single one as the optimal method to monitor vigour variability. These measurements include leaf area (Van Zyl and Van Huyssteen, 1980; Myburgh, 2005; Cloete *et al*., 2006), pruning mass (Howell *et al*., 1987; Smart *et al*., 1990; Carbonneau *et al*.,

1997; Hunter, 2000; Kliewer and Dokoozlian, 2005), trunk circumference (Strever, 2003), shoot length (Smart *et al*., 1985a; Constanza *et al*., 2004) and remote sensing (Johnson, 2003).

It can be said, however, that the techniques used most frequently in viticulture research and commercial farming include the measurement of leaf area, pruning mass and shoot length. Some of the main problems with the conventional techniques of vigour measurement used in viticultural management were identified by Strever (2003) as: i) the limited scale of these measurements; ii) the extensive labour inputs; iii) possible experimental error; and iv) the difficulty to quantify and explain differences between these measurements. Remote sensing technology, which has the ability to quantify spatial vigour variation, has become relatively commonplace in agricultural applications. One example of this technology is multispectral aerial imagery, which can be used to map and monitor vineyard canopy (vigour) variation (Johnson, 2003) with the goal of characterising the nature and understanding the source of vineyard variability.

2.2.5.1 LEAF AREA

It is well established that grapevine vigour has an effect on shoot length (determining the quantity of leaves), leaf size, extent of lateral growth and the production of leaves situated on lateral shoots (Smart, 1985). In a vineyard, the leaf area (LA) and leaf area index (LAI), which is defined by the ratio of canopy leaf surface area to vineyard ground surface area, can be measured on a single grapevine, unit length, or unit basis. These measurements may be used as indicators of grapevine vigour (Smart *et al.*, 1985a, 1990), whole-grapevine photosynthesis (Hunter, 1998), evapotranspiration (Evans *et al*., 1993; Williams and Ayars, 2005), canopy density (Johnson, 2003) or to estimate potential sunlight penetration (Smart, 1987, 1988). Leaf area measurement is an acknowledged technique used during or at the end of the vegetative growth period to evaluate the vigour of a grapevine.

There are various direct or indirect methods to measure leaf area. Direct measurement by leaf removal is a technique that is regarded as very accurate, yet time consuming and destructive (Johnson *et al*., 2003). Removal and measurement of all the leaves on a grapevine is not a standard practice, seeing that this action would seriously reduce the longevity of the grapevine and would possibly end the grapevine's growth cycle. This is why shoots are sampled from representative positions on a grapevine, as well as from grapevines representing the average growth vigour in a specific area or whole vineyard. The surface area of each primary and secondary leaf of a sampled shoot is measured by means of an electronic leaf surface area meter. By determining the leaf area of selected shoots, total grapevine leaf area can be estimated by multiplying the average leaf area per shoot by the average or total number of shoots per grapevine (Van Zyl and Van Huyssteen, 1980; Hunter, 2000; Constanza *et al*.,

2004). When experimental treatment plots consist of only a limited number of grapevines, it would not be suitable to make use of a destructive method where leaf sampling entails removal of more than one shoot (Myburgh, 1998). Given the complexity of the canopy and the well-defined effect it may have on the microclimate, photosynthetic activity, yield, grape composition and, ultimately, wine quality (Smart *et al*., 1985b, 1990; Hunter, 2000; Constanza *et al*., 2004; Kliewer and Dokoozlian, 2005), destructive methods should be applied with great care and only after thorough consideration of the possible effects on the source-sink balance of the grapevine.

Vineyard management practices such as suckering, topping and leaf removal are noted to have an effect on the vegetative and reproductive growth balance of a grapevine (Smart *et al*., 1990; Jackson and Lombard, 1993; Hunter, 2000), which in part would have a quantifiable affect on the canopy and its dimensions. The extent of these practices should therefore be considered when leaf area is used to estimate the vigour level of a grapevine, and especially within vineyards where vigour variability may lead to inconsistency in these management actions, and therefore skewed results.

Various indirect methods of leaf area measurement have been developed, mainly to eliminate the destructive and time-consuming nature of the direct methods (Johnson, 2003). Non-destructive indirect methods include measurement of canopy-intercepted solar radiation (Ollat *et al.*, 1998) and regressions based on shoot length, shoot number and the lengths of the leaves' secondary nerves (Constanza *et al.*, 2004; Santesteban and Bernardo Royo, 2006).

2.2.5.2 CANE LENGTH AND PRUNING MASS

Grapevine vigour is one of the main factors that influence the length of a grapevine shoot. Smart *et al.* (1990) reported a strong linear relationship between vigour and shoot length, shoot diameter, length of the internodes and the amount of nodes per shoot. These relationships are not only confined to the main shoots, as the production and length of lateral shoots are also affected by the vigour of a grapevine (Smart, 1985). Regressions between leaf area and shoot length are a clear indication of how accurately grapevine vigour can be computed using shoot length. A study by Constanza *et al.* (2004), done on grapevines that were not manipulated and grapevines to which seasonal canopy management practices were applied, confirmed this by reporting a good correlation between shoot length and total leaf area for primary shoots (Fig. 2.3) and secondary shoots on the grapevines to which no seasonal canopy management practices had been applied.

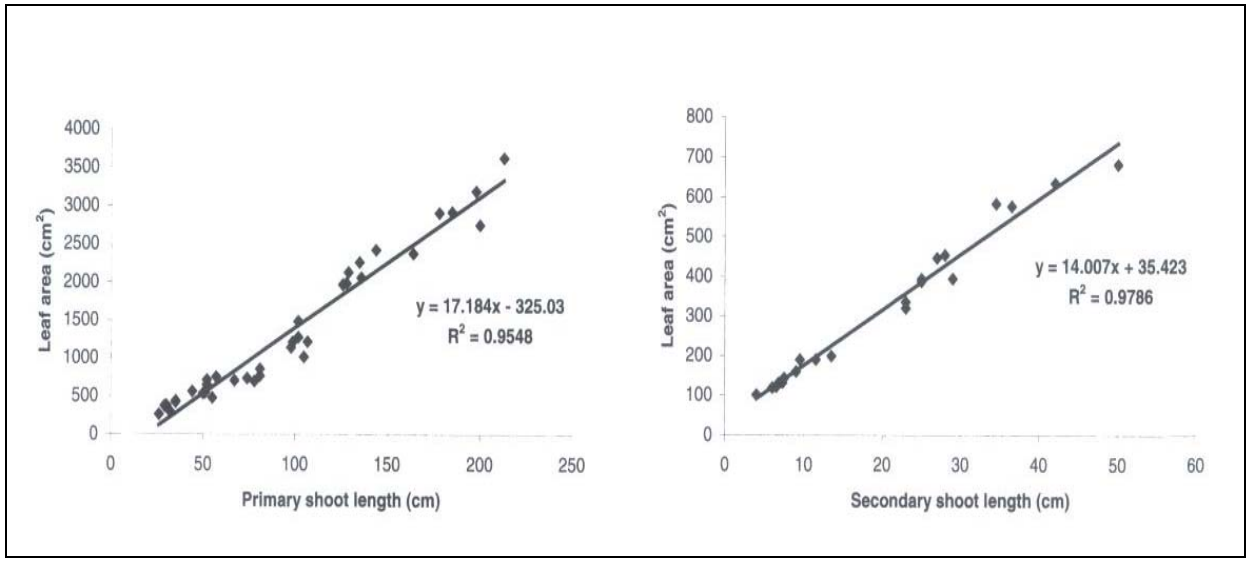

Figure 2.3 Relationship between the primary/secondary shoot length and leaf area (Constanza *et al.*, 2004).

These correlations may also explain visual observations of vigour differences perceived as larger canopies encountered in trellised grapevines (Smart *et al.*, 1985a). Estimates of leaf area throughout the vineyard are difficult because of the time-consuming and labour-intensive nature of the process. As a result, viticulturists started to utilise the correlation found between pruning mass, which is comparatively easy to collect, and leaf area to characterise variation in grapevine vigour (Dobrowski *et al.*, 2003). The mass of pruned canes contributes to useful information on vigour differences within vineyards, because vigour affects the amount (mass) of new wood that will be produced during the growing season (Smart *et al.*, 1985a). It is safe to say that shoot length would influence post-season dormant pruned cane length and mass. In the literature it has also been shown that dormant grapevine pruning mass can be used to measure average shoot mass (Van Zyl and Van Huyssteen, 1980), grapevine size (Howell *et al*., 1987), vegetative growth (Myburgh, 2005) or even if grapevines are well balanced, i.e. the vegetative:reproductive relationships (Kliewer and Dokoozlian, 2005). Ravaz (1906) first documented the use of pruning mass measurements in conjunction with yield measurements ("Ravaz-index") to calculate the yield-to-pruning mass ratio, estimating the balance between vegetative growth and grapevine productivity. According to Smart and Robinson (1991), these representations can be viewed as indirect measurements of fruit quality. In recent years, different vegetative growth and grapevine productivity indices, all incorporating pruning mass, have been evaluated, including: **EV** (sum of values of yield, pruning weight and grape sugar content), **EVP** (sum of yield and pruning weight) and **L/EVP** (pruning weight *x* 100/EVP) (Maccarrone *et al.*, 1996). However, as previously stated in the discussion on leaf area, seasonal canopy management practices (suckering, topping and leaf removal) may have a large effect on the vegetative and reproductive growth of the grapevine. It is known that topping, for example, stimulates the growth of laterals and thereby may decrease the grapevine's total

leaf area (Jackson and Lombard, 1993; Hunter, 2000). Topping may thus decrease the length and mass of single shoots, but may also cause an increase in total grapevine shoot length and pruning mass by stimulating lateral growth. Constanza *et al.* (2004) found this to be true on grapevines to which seasonal canopy management practices had been applied. They found that the leaf area estimation based on primary shoot length was largely over-predicted for these grapevines, and that estimations based on the secondary shoots were under-predicted. Growth compensation seems to be an integral part of the balancing act of the grapevine canopy upon manipulation and may have a direct impact on the shoot length and pruning weight. When using these measurements to assess grapevine vigour, it may be most feasible on grapevines that are not confined to the boundaries of the trellis system by management practices.

2.2.5.3 MULTISPECTRAL AERIAL IMAGERY

Although geographical information systems (GIS) and remote sensing have been part of agricultural management for quite some time, their specific use in “precision viticulture” may be deemed a more recent phenomenon. Precision viticulture has been described by Lamb and Bramley (2001) as the monitoring and management of spatial variation in productivity and quality parameters within single vineyards. This approach, originally developed for perennial crops and pastures, is based on the principle of monitoring yield, growth (vigour), and fertilizer application, amongst other factors (Cook and Bramley, 1998). Collecting multispectral images by aircraft or satellite is the most commonly available methods of remote sensing in vineyards (Dobrowski *et al.*, 2002). Hall *et al.* (2008) showed that remotely sensed imagery provides information on a large scale. This information is shown to be appropriate for determining canopy attributes on multiple spatial scales and of greatest importance is that the “sampling” intensity is much higher than that achievable at ground level. The use of this technology as a means of monitoring grapevine growth and development (vegetative and reproductive) has made commercial farmers just as curious as researchers. As with everything in commercial farming, this interest is driven primarily by the opportunities for the cost-effective generation of spatial data (Hall *et al.*, 2002) and the potential for rapidly generating data of appropriate spatial resolution (Lamb *et al.*, 2004a). This data, when used in conjunction with computer-based GIS incorporating soil and other plant measurements, provides viticulturists with the capability to process and map spatial relationships between grapevine attributes and make evaluations of vigour based on numerous layers of information (Taylor, 2000). The key to this technology remains the ongoing development of an understanding of the links between remotely sensed imagery and grapevine canopy characteristics.

The quantification of differences in the reflectance of vegetation at the green, red and near infrared wavelengths is the principle behind multispectral image technology (Hall *et al.*, 2001). Hence the term “multispectral”, because it describes a radiometric sensor that records

information in only a small number of wavebands, typically two to ten (Hall *et al.*, 2002). Most of the applications of remote sensing are based on observing crops in distinct areas of the electromagnetic spectrum. Visible (red, blue and green light) and infrared energy are the two primary components of solar energy interacting with the leaves of the grapevine. The palisade chlorophyll present in the leaf absorbs incoming visible light for use in photosynthesis. The better absorption of red and blue light by the palisade cells compared to green light gives the grapevine its green appearance. Infrared is not affected by chlorophyll, but the cell structure of the leaf influences the path of this specific energy through the leaf. The open cell structure of the spongy layer reflects half of the incoming infrared light back through the leaf, while the other half passes through the leaf unchanged. Healthy plants will reflect more near infrared light and on the other hand, damaged leaves reflect more visible light, mainly due to decreased chlorophyll levels and therefore decreased absorbance of red and blue light.

The response of vegetation in the visible red and near-infrared (NIR) wavelengths has been used to form "Vegetation Indices," which typically involve some ratio of near-infrared to visible red reflectance (Jackson, 1986). Vegetation indices (VI) are seen as combinations of spectral measurements in different wavelengths, as recorded by a radiometric sensor. The indices aid in the analysis of multispectral image information by maximising the sensitivity towards plant biophysical parameters and by converting the data into a single value (Dobrowski *et al.*, 2002). When Huete *et al*. (1994) defined vegetation indices, they concluded that “vegetation indices serve as indicators of relative growth and/or vigour of green vegetation, and are diagnostic of various biophysical vegetation parameters”. In viticulture, vegetation indices are seen as common measures of vigour or photosynthetically active biomass (PAB). Remote sensing work (Hall *et al.*, 2001, 2002; Dobrowski *et al.*, 2002; Johnson *et al.*, 2003; Lamb *et al.*, 2004a) has shown that differences in grapevine vigour (also quantified in part by the PAB) can be identified from image data using the Normalised Difference Vegetation Index (NDVI).

The NDVI is calculated as

$$NDVI = \frac{(NIR - R)}{(NIR + R)}$$

where near infrared (NIR) and red (R) are the reflectance values in those respective bands of the electromagnetic spectrum. Calculating this index is based on the principle that photosynthetically active vegetation shows high absorption of incident sunlight in the visible red wavelengths, and strong reflectance in the near-infrared wavelength (NIR) (Dobrowski *et al.*, 2002).

NDVI-classified imagery is still only used informally by growers to identify canopy variability in order to aid in monitoring vineyard health, as well as identifying areas of common canopy growth to incorporate into management operations (Hall *et al.*, 2002). These types of applications of remote sensing products identify relative differences in grapevine canopy status across the vineyard as opposed to absolute differences. However, Johnson and Lobitz (1998) showed that classified NDVI imagery of a vineyard could be used to separate a three hectare study vineyard into areas of low, medium and high vigour. In order to use remote sensing technologies in such a direct and strategic manner to classify vigour variation, it is necessary to establish a relationship between remotely sensed data and direct measurements of grapevine canopy attributes (Dobrowski *et al.*, 2003). Strever (2003) also pointed out the importance of using ground truth data to quantify vigour variation in establishing strong links between quantitative measurements and image data, allowing for both spatial and temporal comparisons of data between vineyards. Several remote sensing studies have shown that vineyard NDVI values correlate with canopy attributes like the leaf area index (LAI), which defines the ratio of canopy leaf surface area to vineyard ground surface area (Johnson, 2003; Hall *et al.*, 2001, 2008), as well as with pruning mass (Dobrowski *et al.*, 2003).

Grapevines express vigour not only in terms of density of the canopy, but also in the spatial extent of the canopy itself. Therefore, the relationship between spatial variations in grapevine vigour, as perceived by a remote sensing instrument, and spatial variations in grapevine productivity (yield and quality) may be complex. However, recent studies have shown by implication that spatial variation in other qualities, such as grapevine yield or berry properties, may be inferred from the vegetation indices. The potential of determining grape composition and eventual wine quality for differing areas in a vineyard, based on relationships between grapevine vigour (described by NDVI imagery) and fruit composition has been demonstrated by Lamb *et al*. (2004b).

Vineyard canopies can present some remote sensing challenges. The canopies are highly discontinuous, with foliage clumped in individual grapevines or along rows and a relatively low overall ground cover fraction and soils may contain foliage as cover crops or weeds (Johnson *et al.*, 2003). In addition, canopy architecture can vary between vineyards because of the use of different trellising systems. All of these affect the image properties and could result in erratic interpretation of vigour variation (Hall *et al.*, 2002; Lamb *et al.*, 2004a).

2.3 GRAPEVINE WATER STATUS

2.3.1 THE FUNCTION OF WATER IN THE GRAPEVINE

The main functions of water in the grapevine, as described by Mullins *et al.* (1992), are to fill the symplast, to carry solutes, to maintain carbohydrate production through photosynthesis and to promote heat dissipation by evaporation. To an extent, all physiological processes in the grapevine are dependent on water and, if we focus on the larger scheme of plant processes, it is known that water plays a fundamental role in driving grapevine growth (Winkler *et al.*, 1974; Smart *et al.*, 1985). Turgor pressure is a pressure exerted outward by the cells of adequately watered plants and this pressure causes cell enlargement, which in turn leads to an increase in tissue and organ size, such as the lengthening of shoots (Mullins *et al.,* 1992). All of these functions involve the movement of water between “compartments”, over short or long distances. These water movements within the grapevine are controlled by a gradient of water potential crossing a structure formally analogous to a resistance (Ohm’s law) (Delrot *et al.*, 2001).

2.3.2 THE SOIL-PLANT-ATMOSPHERE CONTINUUM

The dynamics behind water movement is best described by Van Rooyen *et al.* (1980), who compare it to a stream flowing from a source of unlimited capacity and of variable potential, namely the soil moisture reservoir, to a sink of unlimited capacity and of variable potential, i.e. the atmosphere. This also entails that, as the sink potential become less negative (increase in evaporative demand), moisture will be lost from the plant, with a subsequent loss of turgor and eventual physiological ability. Thus, water moves from the soil via the grapevine to the atmosphere through a complex series of conductance, as shown in Fig. 2.4: the soil-root interface is indicated by (a), radial transfer from the cortex to the xylem vessels and through the xylem to the foliage is indicated by (b), and to the atmosphere through the stomata is indicated by (c). This water movement through the soil-plant-atmosphere continuum (SPAC) occurs along a gradient of water potential that becomes more negative from the soil, through the plant, to the atmosphere (Smart and Coombe, 1983).

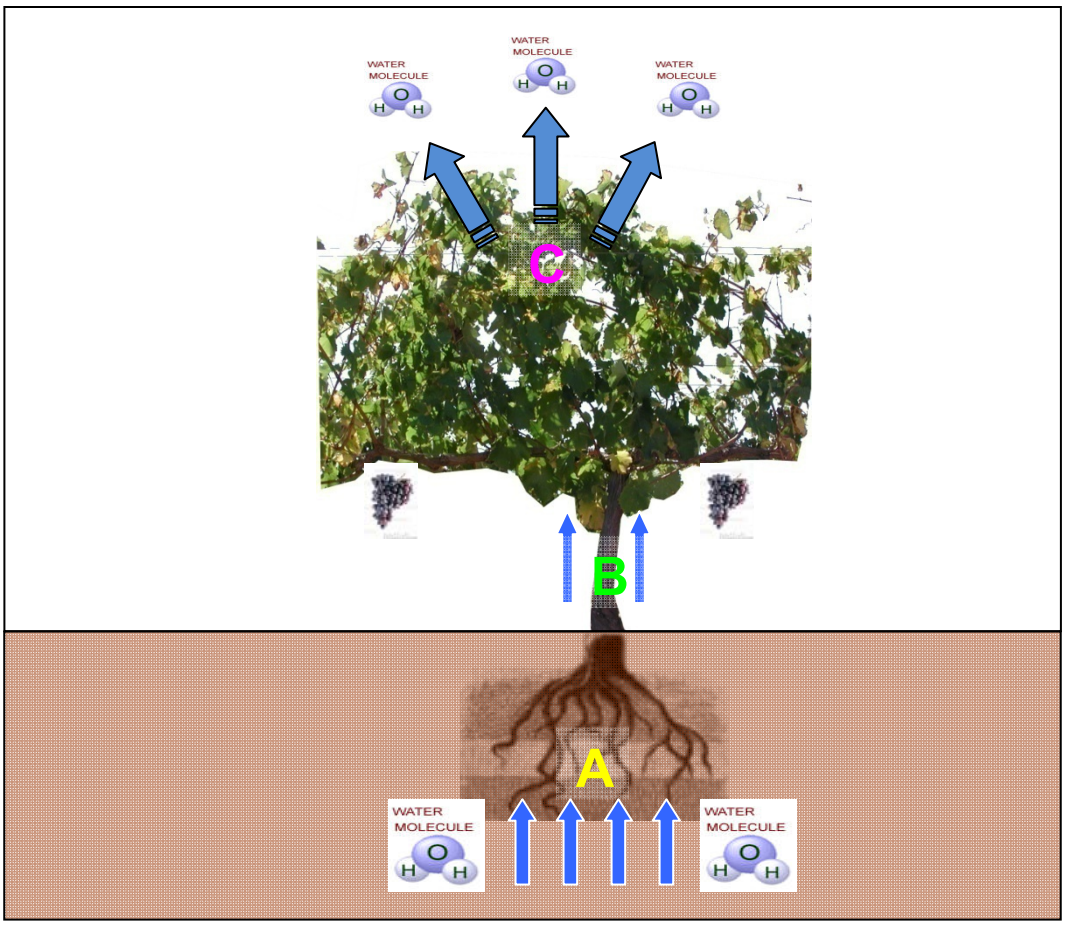

Figure 2.4 A diagram of water flow through the soil-plant-atmosphere continuum.

The soil plays a fundamental role in the SPAC, since it is the only source of water to the grapevine. Therefore, the effect of soil water storage and availability, and the extent of its effect on the SPAC, is a topic that receives a great deal of attention in the viticultural industry, as well as the literature. A lack of water is associated mainly with climate, storage of water in the soil and root access to the stored water (Schmitz and Sourell, 2000). Root penetration and limitations to water storage may arise from soil texture characteristics (Gebregiorgis and Savage, 2006). Soil texture refers to the relative relationship of various particle sizes (sand, silt and clay) and a texture triangle is used to classify the soil into texture groups, as indicated in Fig. 2.5. Coarse-textured soils have higher percentages of sand particles, while finer-textured soils have greater amounts of the smaller silt and clay particles.

Texture is shown to influence soil behaviour through its effect on soil structure, water retention, aeration, drainage, temperature and nutrient retention (White, 2003). One of the most important factors affecting the amount of water and oxygen harboured in a soil is its void space or its porosity, which in turn influences the soil moisture content (Ley *et al*., 1994). Sandy soils have

large pores due to the large individual particle sizes, but smaller total porosity overall compared with finer-textured soils. Thus, because of pore size and total porosity differences, sandy soils are free-draining and have a subsequent lower soil water-holding capacity, whereas fine and medium-textured soils (clay, silty clays and clay loams) have a heavy texture and a higher water-holding capacity (White, 2003). Clay particles have the largest surface area to volume ratio, making water storage much higher than in other soils, but it could influence plant water uptake.

Soil structure is determined by the arrangement of primary soil particles relative to each other into secondary units, also referred to as “peds” (White, 2003). The secondary units are characterised and classified on the basis of size, shape and comprehensibility into four types. Soil structure is important in developing large pores (macro-pores) that are essential for the rapid movement of water and air through soils (Ley *et al*., 1994). Soil structure is seen as a more important factor contributing to water availability than texture due to the high degree of macro-porosity.

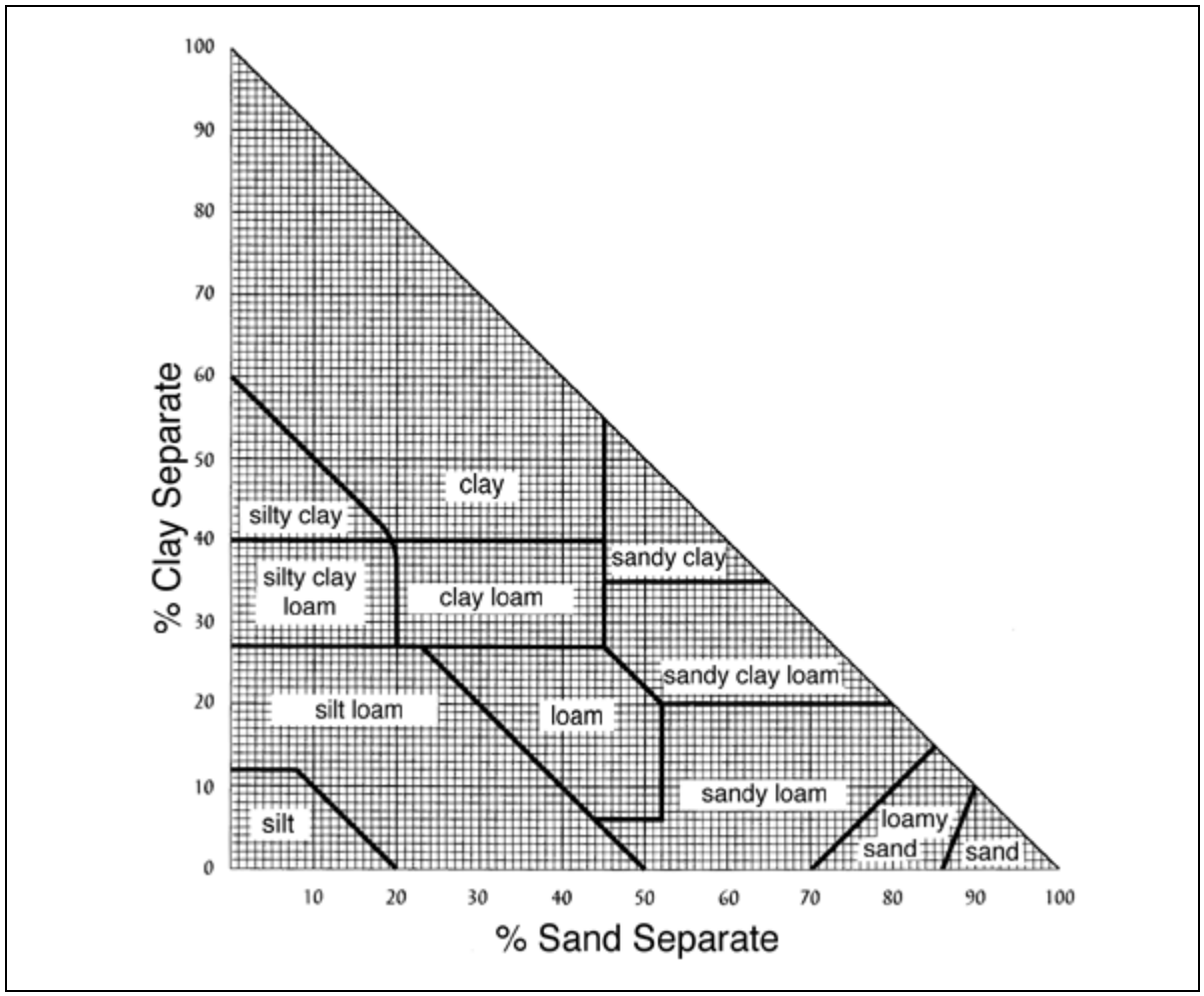

Figure 2.5 Textural triangle based on the USDA particle-size classification (Ley *et al*., 1994).

The relationship between soil water content and soil water potential determines the water status of a soil, which is indicative of plant-available water. Hunter (1998) found soil water depletion to be a very important regulator of plant performance. Hence, the availability of water to the grapevine, which is essentially controlled by soil properties and irrigation, plays an important role in determining the ability to achieve a target grapevine performance. The availability of soil water to the grapevine affects yield, fruit quality and grape quality – both directly and indirectly. The major effects are indirect and act via vegetative growth due to the direct effects of leaf water potential, turgor, translocation of organic and inorganic substances, and canopy photosynthesis (Pellegrino *et al*., 2005). Soil water status is also a fundamental property affecting the transport and transformation of soil nutrients in the soil-plant system. In general, grapevine growth and productivity are effected by grapevine water status, which is strongly correlated with the amount of available soil moisture (Van Zyl and Weber, 1981).

2.3.2.1 ASSESSMENT OF SOIL WATER STATUS

According to Hsiao (1990), monitoring and measuring the soil water status of irrigated grapevines is part of an integrated management package and helps avoid: 1) the economic losses due to effects of both under-irrigation and over-irrigation on grape yield and berry quality, and 2) the environmentally costly effects of over-irrigation: wasted water, energy and the leaching of nutrients. The information obtained from assessing soil water status is thus used for irrigation scheduling, achieving high irrigation efficiencies, optimising yield and berry quality and minimising lost yield due to water logging and excess vigour. Soil-based irrigation scheduling is conventionally based on ‘soil water measurement’, where the soil water status is measured directly to determine the need for irrigation. There are two ways to assess the soil water status: by measuring the soil water content and by measuring soil water potential. It should be noted, however, that while soil water status can provide a direct measure of soil water potential and volume, it does not provide any insight into the water status of the grapevine.

The concept of soil water content leads to the assumption that a given soil can hold a certain amount of water in the root zone of the plant, against gravity and flow to the underground water table (Schmitz and Sourell, 2000). In contrast to this, soil water potential is the measure of soil water tension, which is the suction that the root has to exert to withdraw water from the soil (Lebon *et al*., 2003). Direct determination of soil water availability is difficult because of the heterogeneity of soils and uncertainty about the rooting depth of grapevines (Lebon *et al*., 2003). Knowledge of the spatial variability of the soil water content is important for managing soil water in spatially variable soils, but spatial variability in soil water potential may be more important than water content, because it determines plant water availability. The characterisation of soil water profiles along the root zone may also need to be taken into account when assessing soil water status. Indicators used to measure soil water status are time

consuming and have questionable value in vineyards with considerable spatial variation in depth and lateral spread of roots. Furthermore, grapevine roots may explore localised water confined in cracks or soil pockets that develop in heterogeneous soils (Pellegrino *et al*., 2005). Under such conditions, it is not possible to report the quantity of water that is, in effect, available for grapevine growth and yield maturation. This may produce a large degree of uncertainty, as the development of plant water deficits depends on the fraction of water consumed by the grapevine, which must consequently be replaced in the soil, and also on soil water-holding capacity (Girona *et al*., 2006).

2.3.2.1.1 NEUTRON PROBE

The neutron moisture meter or probe has been universally used since the early 1950s and is seen as a time-tested technique for measuring total soil water content by volume (Mc Dougall *et al*., accessed 2008). This method estimates the amount of water in a volume of soil by measuring the amount of hydrogen atoms present. According to Bell (1987), the neutron probe has the ability to provide precision *in situ* measurements of change in soil moisture and it is a rapid and non-destructive technique with a high degree of repeatability (Reichardt *et al*., 1997). Measuring soil water status by means of neutron dispersion has been used extensively as an effective and reliable technique in both research and commercial viticulture, and is one of the techniques that is currently being utilised for everyday irrigation scheduling applications.

The neutron moisture meter consists of two main components, namely (i) a probe that contains a source of high-energy, rapidly-moving neutrons as well as a sensor that is sensitive to slow-moving neutrons, and (ii) a control unit that includes electronics for time control, a pulse counter that can register the flow of slow-moving neutrons in the soil, and memory (Ley *et al*., 1994). The control unit remains on the surface, while the probe, which is connected by cable to the control unit, is lowered into the ground. Access tubes are usually installed beyond the depth of the expected rooting zone and clips on the cable allow the probe to be set at pre-selected depths in the soil profile.

The probe contains a radioactive source that emits fast neutrons through the access tube into the surrounding soil. Collisions with the nuclei of the soil atoms, predominantly those of hydrogen in the soil water, cause the neutrons to scatter, to slow and to lose kinetic energy (Bell, 1987). Hydrogen molecules are particularly effective in slowing the fast neutrons, since they are both of near equal mass (Ley *et al*., 1994). As the speed of the once fast-moving neutrons declines, it reaches the speed of particles that is characteristic of the prevailing environmental temperature. The neutrons are now called slow-moving or thermal neutrons, and their collisions with the atomic nuclei in the soil continue until they are absorbed by the nuclei (Ley *et al*., 1994). Thus a “cloud” of slow neutrons is generated in the soil around the source.

The density of this cloud, which is largely a function of the soil water content, is sampled by a slow neutron detector, which is also in the probe. The electrical pulses from the detector are amplified and shaped before they are passed to the control unit, where their mean count rate is displayed (Bell, 1987). For a specified interval of time, the mean count rate is linearly related to the total volumetric soil water content (Hignett and Evett, 2002). A higher count indicates higher soil water content and vice versa. However, the neutron probe unfortunately does not give a measure of the matrix potential of the soil, therefore the measured soil water content cannot be regarded as plant available water. This potential problem can be overcome by using a tensiometer in combination with a neutron probe at all the measuring depths, because the tensiometer gives a measure of soil water tension, or the force with which the water is being held by the soil (E. Hoffman, Stellenbosch University, personal communication, 2008).

The neutron count and subsequent soil water content would be affected by a number of factors relating to soil characteristics. Both soil density and chemical composition affect the concentration of thermalised neutrons by changing the scattering and absorption properties of the soil (Hignett en Evett, 2002). Because H and C are both effective neutron thermalisers, the organic matter content of soils is one of the main factors that should be taken into consideration when measuring water content by means of neutron dispersion. There are also other atomic nuclei in the soil besides hydrogen, carbon and oxygen that have a considerable ability to moderate the fast-moving neutrons. These are B, Cd, Cl, Fe, F, Li and K. Therefore, the necessity of calibrating the neutron probe for the measurement of soil moisture in individual soils has been widely debated and is seen by Reichardt *et al*. (1997) as the main constraint of this technique. A calibration equation must consequently be developed for every soil type that differs with respect to the content of organic matter, texture, bulk density, porosity, particle composition and even soluble salt content (Bell, 1987). The count rate displayed by the counter can only be translated into soil moisture content (by volume) using the appropriate calibration equation or curve.

2.3.3 GRAPEVINE WATER USE

The availability of soil moisture to grapevines and the extent of the effect thereof on the growth and plant water relationships have been controversial subjects for years. Taken to extremes, either excessive or severe lack of water appeared to have detrimental influences on vineyard growth, yield and grape quality (Pellegrino *et al.*, 2005). Some water management techniques in a vineyard require that water use is evaluated to assist in the quantification of grapevine water status (Lebon *et al.*, 2003). However, grapevine water use cannot be directly used as an indication of grapevine water status. Estimating grapevine water use can be accomplished with models that simulate grapevine water consumption. These simulations are commonly based on reference atmospheric evaporative demand (Class A-pan), or potential evapotranspiration and a

crop coefficient (Van Zyl and Weber, 1981; Evans *et al.*, 1993). Lebon *et al.* (2003) indicated that other approaches have partitioned evapotranspiration into plant and soil components or inverted the Penman-Monteith equation to estimate canopy conductance and then grapevine transpiration. The seasonal water use of mature grapevines has been estimated in several studies using various methods or models (Van Zyl and van Huyssteen, 1980, 1988; Peacock *et al.*, 1987; Grimes and Williams, 1990; Evans *et al.*, 1993; Stevens and Harvey, 1996), and the basic water relations in grapevines have been reviewed by Smart and Coombe (1983). The results obtained during these studies indicate that vineyard water use varies greatly, and that water use is substantially affected by the cultivar, soil structure/texture and depth, cultural practices (pruning, crop level and cover cropping), trellis height and width, grapevine or row spacing, row direction, as well as water management programmes and climate (Evans *et al.*, 1993; Hunter 1998). An important point raised by Williams *et al.* (2003) was that it is unknown how much of the variability from vineyard to vineyard reported in grapevine water use studies is the result of differences in production practices or the method of determining grapevine water use, where measuring devices are often placed without consideration of soil variation.

2.3.4 INFLUENCE OF GRAPEVINE WATER STATUS ON THE GRAPEVINE

It is important at this point to give a definition of “water stress”, seeing that this term is used without a lot of explanation or validation in the literature. A “stress”, as seen in the context of viticulture, is normally an external factor that exerts a disadvantageous effect on the grapevine. The influence of the stress is usually apparent as changes in the vegetative or reproductive growth of the grapevine. However, stress can be classified as either an elastic stress or a plastic stress (Mr A.E Strever, personal communication, 2008). An elastic stress is better defined as a “strain”, seeing that this type of stress is reversible. The effect that elastic stress has on the grapevine is not of a permanent nature and would be normalised as soon as the stress is neutralised. Plastic stress, on the other hand, is usually associated with negative and permanent effects on the grapevine; it is irreversible, unmanageable and seen as long term. Thus, water stress is usually indicative of nothing more than a grapevine water deficit. During the rest of this review, a water deficit would, for all practical purposes, point out a water shortage within the grapevine, or an altered grapevine water status.

In general, grapevine growth and productivity are affected by grapevine water status, which serves as an excellent indicator of the availability of soil moisture to the plant (Van Zyl and Weber, 1981). When internal demand for water is high in plants and supply is limited, water uptake by the roots becomes insufficient, causing plants to experience a plant water deficit. While a grapevine is subjected to the water deficit there are numerous ways in which the plant can and will respond, not to tolerate or resist the deficit, but to avoid it (Cuevas *et al.*, 2006).

Choné *et al.* (2001) mentioned that internal plant water deficits occur to fit xylem sap flow to leaf transpiration in relation to soil water availability. According to Tardieu (2004), as water availability to the roots decreases, a grapevine would have a tendency to decrease transpiration by two means: a) short-term effects, which entail the closure of the stomata, thereby reducing water flux through the plant, and b) long-term effects, which consist of a reduction in leaf expansion, resulting in a smaller transpiration area. By reducing transpiration via these two mechanisms, which are adaptive processes, water is conserved for later stages of plant development. This emphasises the general thought that grapevines respond to soil water deficits by mechanism of drought avoidance rather than tolerance. When stomata partially close, thereby decreasing transpiration, leaf water potential becomes less negative, resulting in increased leaf hydration. This mechanism allows the leaves to maintain their water status in an acceptable and functional range (Choné *et al.*, 2001; Tardieu, 2004). Stomatal closure is among the first processes occurring in the leaves in response to drought (Cifre *et al.*, 2005). It is certainly recognised that leaf water status interacts with stomatal closure and transpiration, and Medrano *et al.* (2002) observed that there is a good correlation between leaf water potential and stomatal conductance under water stress. Stomatal conductance is not controlled by soil water availability alone, however, but by an intricate interaction of factors internal and external to the leaf. On the basis of information in the literature, it appears likely that root ABA synthesis in response to water stress controls the stomatal responses in grapevines to some extent, although this could also be modulated by osmotic adjustment, xylem hydraulic conductivity and environmental factors such as humidity (Winkel and Rambal, 1993; Naor, 1998; Lovisolo *et al.*, 2002; Medrano *et al.*, 2002; Cifre *et al.*, 2005). A primary process also affected by altered grapevine water status is photosynthesis, primarily due to stomatal closure, which decreases water loss but also carbon flux to the sites of carboxylation (Tarara *et al.*, 2005). A high degree of co-regulation of stomatal conductance and photosynthesis is usually found in grapevines (Farquhar *et al.*, 2001). A decrease in grapevine photosynthesis would result in a decline of energy that is available to drive the grapevine's vital biochemical functions (Pool and Lakso, 2000).

2.3.5 POTENTIAL IMPACT OF GRAPEVINE WATER STATUS ON GRAPE AND WINE COMPOSITION

The effect of grapevine water status on berry development and subsequent composition is a more complex system than the effect of vigour on the latter. The double sigmoid growth curve of the berry, which is divided into three major phases, is the main reason for the complexity. It should be noted that the berries would follow this growth curve even if or not there is a difference in the water status of the grapevine. However, a change in water status would modify both the onset and duration of the individual phases (Ojeda, 2001). The reduction in cell volume will induce modifications in the composition and physical properties of the cells. Sivilotti *et al.*

(2005) and Wang *et al.* (2003) have shown that a water deficit before véraison would reduce berry size at harvest, and there could even be a loss of moisture from the berry through transpiration. This reduction would influence the sink/pulp ratio and would more or less have the same consequences for berry composition as described earlier.

Grapevine water status affects berry sugar concentration in a complex manner, as, sometimes, when there is no water deficit, a higher sugar concentration is found as a consequence of higher photosynthetic activity (Tarara *et al.*, 2005), or at other times lower sugar concentrations are measured due to the dilution of sugars that occurs as a result of increased berry growth (Santesteban and Bernardo Royo, 2006). Carbohydrates produced via photosynthesis are exported from the leaf and transported in the phloem as sucrose to the berries. When a grapevine is experiencing a water deficit, less water and assimilates are translocated to the berries (Bota *et al*., 2004). Matthews and Anderson (1988) showed that water deficit can increase phenols in the juice and skin and anthocyanins in the skin, and reduce malate. Ojeda *et al*. (2002) found that berry size influences the concentration of phenolics and that the phenolic content was dependent on the skin weight, which was dependent on deficit irrigation. In reviewing irrigation effects, Smart and Coombe (1983) noted that excessive irrigation increased yield partially by berry enlargement, and caused elevated juice pH and acid content.

2.3.6 ASSESSMENT OF GRAPEVINE WATER STATUS

Plant-based monitoring is considered to be a reliable, practical approach to measure the water status of a grapevine. These measurements assess the grapevine itself, rather than the external elements of its environment, to determine its water potential or related internal stress level. Plant water status is seen as a key metabolic indicator and the measurement provides a valuable gauge of grapevine growth and grape development. Grapevine vegetative and reproductive growth processes relate directly to the grapevine's water status, but only indirectly to the surrounding soil moisture and atmospheric conditions (Grimes and Williams, 1990; Sivilotti *et al.*, 2005). However, for any measure of plant water status to be a sensitive indicator of water deficit, it must be responsive to differences in soil moisture status and/or the resulting growth differences due to water application. The measure should also be closely related to short- and medium-term plant stress responses, and less dependent on changes in environmental conditions (Williams and Araujo, 2002).

In recent years a wide range of novel approaches to plant-based irrigation scheduling have been proposed which have not yet been widely adopted (Jones, 2004). Plant-based irrigation scheduling includes both water status measurements and plant response measurements. These approaches are focused mainly on sensing the plant response to water deficits, rather than sensing the soil moisture status directly. However, it should be noted that, while grapevine

water status can provide a direct measure of when water is required, it does not provide a direct volumetric measure of the volume of water required to effectively counteract the water deficit. The portability of the measuring equipment, potential for automation and the skills required for operation and interpretation are some of the factors setting apart the various indicators of grapevine water status. Relative advantages and disadvantages of these measurements are not unambiguously addressed here, as such comparisons should include ease of use as well as cost (time and labour) and training requirements.

2.3.6.1 VISUAL INDICATORS

Perhaps the first approach to the use of the plant itself as an indicator of grapevine water status, and one still frequently adopted today, is to evaluate visible drought symptoms (Jones, 2004). The physiological reaction of a grapevine to a water deficit will affect the growth and development of the leaves, shoots and fruit, depending on the timing and level of deficit during the season. Van Zyl and Weber (1981) noted the transformation of visual drought symptoms in vineyards from the start of shoot growth towards harvesting time. They found that, as shoot growth accelerates during spring and early summer, the rate of elongation of newly formed shoots and of the associated tendrils is very sensitive to changes in grapevine water status.

According to Smart and Coombe (1983), the wilting of young tendrils and leaves is one of the early symptoms of a grapevine water deficit. As a visual indicator, the tendrils are very useful to identify water deficit within a vineyard, considering that the second tendril at the shoot growth tips will start to droop if grapevines are stressed, forming an angle of approximately 90° with the shoot (Fig. 2.6) (Strever, 2003; original photographs by E. Archer). Tendrils at the tip of inhibited shoots are also prone to abscise.

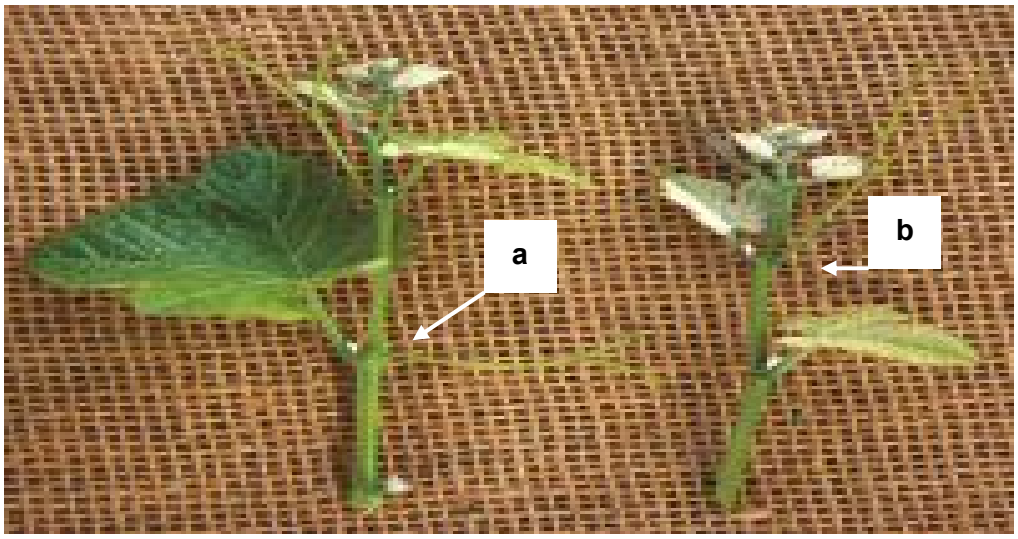

Figure 2.6 Angle of second tendril from shoot apex. An angle of 90° (a) indicates water stress, while a more acute angle (b) indicates an absence of water stress (Strever, 2003).

Shoot tip growth arrest can also be a useful indicator of the extent of the water deficit experienced by the grapevine. Smart and Coombe (1983) noted the rigorousness of water deficit in comparison to the presence of active, inactive or desiccated shoot tips at the ripening stage. Begg (1980) showed that, when leaf area development is complete, changes in grapevine leaf angle are one of the main mechanisms for adapting to water deficit. This can be an effective mechanism for reducing the radiation load on the leaves. The movements that the leaf would perform due to water deficit include leaf folding, leaf drooping and the orientation of leaves parallel to incoming sunlight (parahelionastic movement) (Smart and Coombe, 1983). From a study by Bruwer *et al*. (2004), it came apparent that leaf folding and leaf drooping were the most common leaf stress symptoms observed on Sauvignon blanc. Leaf colour is also an indicator of water deficit, since young leaves become yellow-green and mature leaves become dull grey-green (Smart and Coombe, 1983). Prolonged water deficit may lead to the development of necrotic areas at the edges of leaves, especially basal leaves, which turn yellow (chlorosis) in the bunch zone and abscise early after necrosis. Unfortunately, by the time these symptoms are apparent a substantial proportion of the potential yield may already have been lost (Jones, 2004). Although visual water deficit symptoms are important indicators of grapevine water status, they should be aided by quantitative measurements of plant water content. More rigorous and more sensitive measures of plant water status are therefore required.

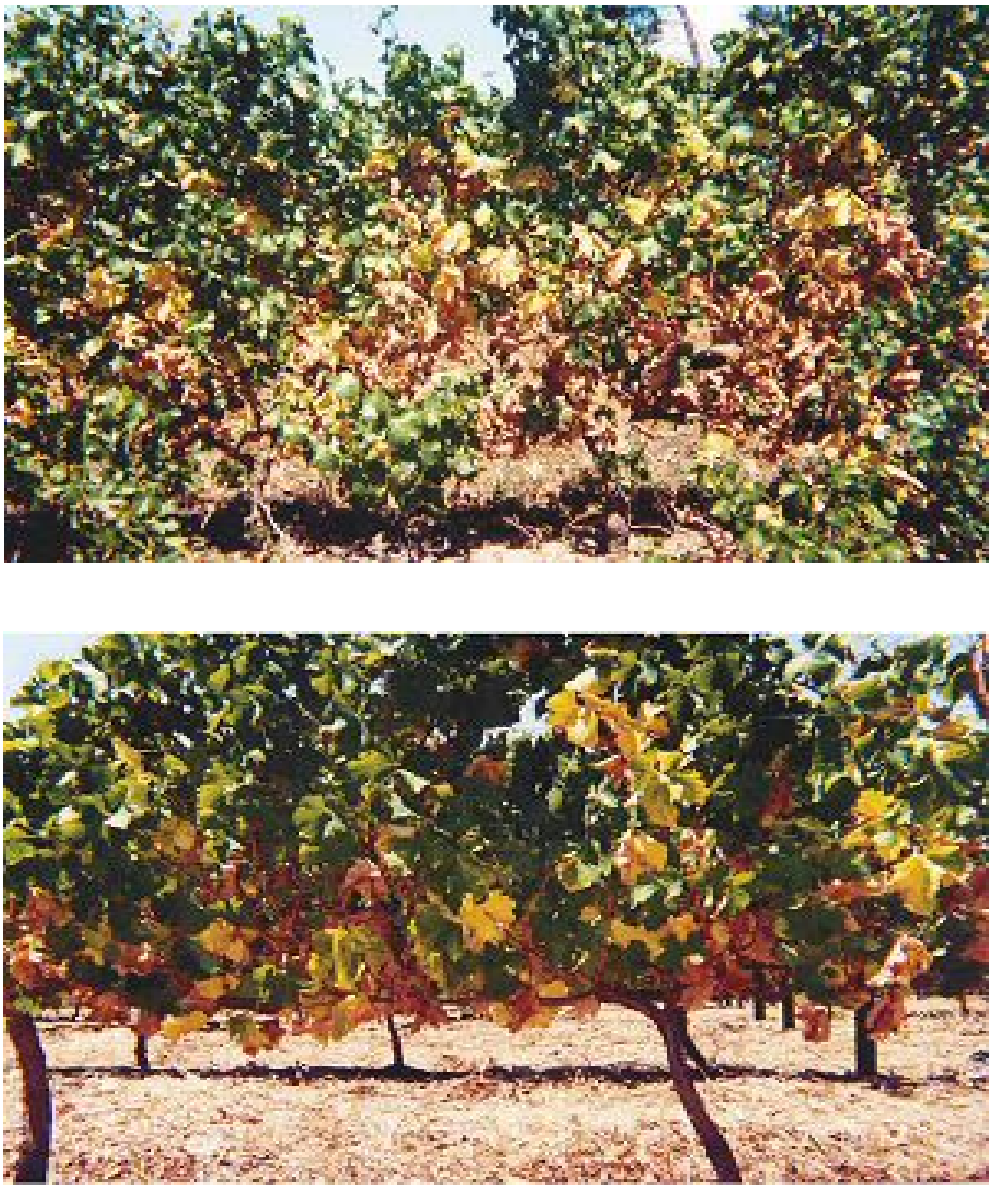

Figure 2.7 Visual symptoms of water stress – yellow or dead leaves and necrotic leaf edges within the bunch zone (Bruwer *et al.*, 2004).

2.3.6.2 PHYSIOLOGICAL PARAMETERS

When stomatal pores are open, they allow carbon dioxide diffusion into the leaf and unavoidably account for water loss from the leaf. According to Mullins *et al.* (1992), the apoplastic cavity of spongy mesophyll and palisade parenchyma is filled with moisture-saturated air, so water molecules have a strong tendency to diffuse from intercellular spaces (the point of less negative water potential) to the atmosphere (the point of more negative water potential). This control that stomata exert on transpiration and carbon assimilation is expressed in terms of the stomatal conductance or its inverse, the stomatal resistance. It is a property that relates the conductance across a unit area of a leaf, therefore it does not correspond to the effort of single stomata (Buckley, 2005). As outlined earlier, it appears that stomatal conductance is particularly sensitive to developing water deficits, with stomatal closure being among the first plant responses to drought (Cifre *et al.*, 2005). It is also known that stomatal conductance has an effect on other physiological processes. Stomatal closure is generally accepted to be the main determinant for decreased photosynthesis under mild to moderate drought (Medrano *et al*., 2002) and, according to Martin (1998), transpiration is controlled by leaf boundary layer conductance and stomatal conductance in series. Therefore, the determination of stomatal conductance (Medrano *et al*., 2002), transpiration (Delrot *et al*., 2001; Jones, 2004) and photosynthesis (Sivilotti *et al*., 2005) potentially provide a good indication of irrigation needs and these aspects have also been widely used as indicators of water status in grapevines. Stomatal conductance is measured with a porometer, which measures the mass flux and the concentration difference of water and carbon dioxide between the leaf surface and free or well-stirred air. The porometer usually comes as a portable steady-state gas exchange system (Choné *et al.*, 2001) that mainly measures stomatal conductance, but leaf transpiration can also be measured.

There are various kinds of instruments that can be used to measure the rate of photosynthesis or transpiration of a grapevine, for example an open photosynthesis system with an infrared gas analysis instrument. Net photosynthesis, transpiration, stomatal conductance and internal CO_2 concentration can also be determined with a portable gas-exchange analysis system (Sivilotti *et al*., 2005; Patakas *et al*., 2005). Measurements are conducted on single leaves throughout the canopy so that an indication of either total photosynthesis or transpiration can be obtained to assess grapevine water status.

Even though the measurement of these parameters is as easy as using a single instrument, it can be affected by various factors. Grant *et al.* (2007) pointed out that, for any given stomatal conductance, the leaf-to-air temperature difference depends not only on the atmospheric water vapour pressure deficit, but also on canopy surface roughness. Furthermore, changes in weather conditions (radiation, humidity and wind speed) during the day or between different

days also affect measurements and make the interpretation of these parameters difficult (Lebon *et al*., 2003). However, according to Medrano *et al*. (2002), stomatal conductance would represent a more integrative basis for the overall effects of drought, since stomatal conductance is responsive to all the external (soil water availability, water vapour pressure deficit, canopy dimensions) and internal (ABA, xylem conductivity, leaf water status) factors related to drought. On the other hand, Jones (2004) indicated that the complex regulation of stomatal conductance is related to important differences among cultivars and vineyards in the response of stomata to leaf water potential, relative water content, ABA and other parameters, making it difficult to define a model of responses to drought. The near-isohydric behaviour of the grapevine documented by Choné *et al.* (2001) and Schultz (2003) questioned the use of physiological parameters to assess water status. These authors found that the grapevine can show substantial photosynthetic limitations without any detectable change in its relative water content, a trait that defines isohydric plants, and this raises questions as to the suitability of physiological parameters when assessing grapevine water status.

2.3.6.3 LEAF/CANOPY TEMPERATURE

An important consequence of the stomatal closure that occurs when plants are subject to water deficit is that energy dissipation is decreased, causing leaf temperature to rise (Jones *et al.*, 2002). The decrease in transpiration affects the evaporative cooling of the plant and could also result in higher internal leaf temperatures. This rise in temperature could have a detrimental effect on the enzymes and metabolic reactions within the leaf. If the temperature of the leaves keeps increasing, or the leaf temperature is too high for a prolonged period, the leaves will overheat and become bleached or necrotic (Pool and Lakso, 2000). The temperature of the leaf can be used as an aid to determine water deficit long before the visual effects of increased temperature are present (Jones, 2004). The idea of using leaf or canopy temperature as an indicator of plant water deficit is definitely not a new one. According to Jones (1999), this initiative already gained ground in the early 1980s. Measuring leaf/canopy temperatures is a non-destructive method that has the benefit of repeated measurements on the same leaf to indicate grapevine water deficit. Measuring the temperature of a grapevine leaf can be as easy as using an infrared thermometer. Infrared thermometry (IRT) is used in conjunction with a crop water-stress index (CWSI), which presents leaf/canopy temperature as a factor of leaf or canopy temperature relative to the environmental (ambient) temperature and reference temperature values of leaves or canopies.

According to Idso *et al.* (1981) and Jones (1999), the value of the CWSI for a canopy is defined as

$$CWSI = (Ts - Tbase)/(T\max - Tbase)$$

where *Ts* is the actual canopy surface temperature under given environmental conditions, *Tmax* is the upper boundary for canopy temperature and equates to the temperature of a non-transpiring canopy, such as would occur if the stomata were completely closed as a result of drought, while *Tbase* is the 'non-water-deficit baseline', representing the "typical" canopy temperature when the stomata are fully open. This index can also be used where individual leaves are measured, or dry or wetted leaves are used to mimic leaves with fully closed or fully open stomata respectively (Jones *et al.*, 2002). A *CWSI* of 0 would indicate no water deficit, while a value of 1 represents maximum water deficit. Although the theoretical basis of the approach of IRT is well established, it does have severe limitations in environments with significant climatic variability. Grant *et al.* (2007) pointed out that, for any given stomatal conductance, the leaf-to-air temperature difference depends not only on the atmospheric water vapour pressure deficit, which is fully accounted for in the calculation of *CWSI*, but also on wind speed, canopy surface roughness and net radiation. Another difficulty that has commonly been found with the application of infrared thermometry to assess crop water status has been the difficulty of separating leaf and non-leaf (soil, sky, bark etc.) temperatures. This has led to the development of thermal imaging and associated image analysis software to overcome the problems experienced by researchers using IRT in vineyards (Jones *et al.*, 2002; Cohen *et al.*, 2005). Thermal imaging systems also allow for rapid and non-invasive measurements, which produce a collection of data, integrated over the area of individual leaves or canopies, to obtain thermal indices (Grant *et al.*, 2007). Experiments done with IRT and thermal imaging have shown that: i) the average temperatures of areas of canopies containing several leaves are perhaps more useful for distinguishing between grapevines with differing water deficits than the temperature of individual leaves and ii) canopy temperature can be used to distinguish between grapevines that are encountering water deficits and those that are not.

2.3.6.4 GRAPEVINE WATER POTENTIAL

In the literature it is often argued that plant water potential is a rigorous and generally applicable measure of plant water status, mainly because water potential gradients develop in the grapevine as a consequence of flow along the SPAC pathway, in which gravitational potential and frictional resistance are overcome (Smart and Coombe, 1983). Plant water potential, especially of the leaves, is interpreted by researchers as a measure of plant water status (Jones, 2004). Leaf water potential is therefore widely used to measure water status and does not involve very sophisticated equipment. The pressure chamber used by Scholander *et al.* (1965) to determine grapevine water potential is regarded as a reliable method for determining

the water status of field-grown grapevines. There are basically three ways it can be used to measure grapevine water status, namely to quantify pre-dawn leaf water potential (pre-dawn Ψ), midday leaf water potential (leaf Ψ) and stem water potential (stem Ψ). These three methods vary mainly in the timing of the measurement and the preparation of the leaf to be sampled.

A measurement of midday leaf Ψ is taken in the one-hour period beginning thirty minutes prior to solar noon and ending thirty minutes after solar noon. It is during this time that maximal diurnal water use or canopy conductance has been measured on grapevines with no water deficit (Naor, 1998). Midday leaf Ψ measured on a single leaf has been shown to reflect a combination of many factors: a) local leaf water demand, b) soil water availability, c) stomatal regulation and d) internal plant hydraulic conductivity (Choné *et al.*, 2001). Pre-dawn Ψ is determined using the same basic methodology as midday leaf Ψ, but the reading is taken one to two hours before sunrise. This measurement assumes that, before sunrise, the grapevine is in equilibrium with the soil's water potential, making it a sensitive indicator of soil water availability. It is assumed that pre-dawn Ψ measures plant water status when plant water fluctuations are zero, therefore providing information on the root zone soil water potential (Choné *et al.*, 2001). Stem Ψ is measured in the same timeframe as midday leaf Ψ, but the preparation of the leaf to be sampled for measurement is different. The leaf is bagged in a relatively airtight plastic bag with aluminium foil on the outside, at least one hour before it is sampled. Bagging effectively stops the natural transpiration of the leaf, allowing the leaf water potential to equilibrate with the xylem (stem) water potential. Stem Ψ, measured on a non-transpiring leaf, would provide an indication of the capacity of the grapevine to conduct water from the soil to the atmosphere (Girona *et al.*, 2006). The stem is also thought to be less susceptible to fluctuations in environmental pressures than the leaf and therefore more representative of the actual water deficits in the entire grapevine. Daily stem Ψ is seen to also exclude the near-isohydric behaviour of the grapevine and rapid temporal fluctuations observed as a function of environmental conditions, such as passing clouds.

In general, the use of any plant-based or similar indicator for irrigation scheduling requires the definition of reference or threshold values beyond which irrigation is necessary. Such reference values are defined by Deloire *et al*. (2004) in Table 2.2. This indicates the physiological responses of a grapevine when subjected to water deficit. Obtaining extensive information on the behaviour of these reference values as environmental conditions change is an important stage in the development and validation of such a method.

Table 2.2 Physiological responses of the grapevine to different levels of water deficits, expressed as pre-dawn Ψ (Deloire *et al.*, 2004)

	Pre-dawn Ψ	Vegetative growth	Berry growth	Photosynthesis	Berry ripening
1	0 to -200 KPa	normal	normal	normal	normal
2	-300 to -500 KPa	reduced	normal to reduced	normal to reduced	normal to stimulated
3	-600 to -800 KPa	reduced to inhibited	reduced to inhibited	reduced to inhibited	reduced to inhibited
4	-900 KPa and less	inhibited	inhibited	partial or total inhibition	partial or total inhibition

Williams and Araujo (2002) compared the three methods of measuring grapevine water potential and also correlated data from their trials to other measures of soil and plant water status. The results under the conditions of their study showed that all three methods of estimating grapevine water status were similarly correlated with the soil water content and applied amounts of water, and were also significantly correlated with net CO_2 assimilation and stomatal conductance at midday. A high correlation between the methods was also found, although Escalona *et al.* (1999) found midday leaf Ψ to be a poor indicator of water stress in contrast with pre-dawn Ψ or stem Ψ. This is mainly due to the large impact that climatic conditions can have on the measurement of midday leaf Ψ. Naor (1998) also found correlations of stomatal conductance with stem Ψ to be significantly higher than those with midday leaf Ψ and, according to Choné *et al*. (2001), stem Ψ was also demonstrated to be a comprehensive indicator of early water deficit in plants and appeared to be a powerful tool to assess grapevine water status. They concluded that stem Ψ was the result of whole-plant transpiration, and soil and root/soil hydraulic conductivity in the trunk and shoot sap pathway.

2.4 CONCLUDING REMARKS

Viticultural practices are focused on establishing grapevines that would produce sustainable yields, of which the grapes are homogenous in composition and of a high quality for wine production. However, this output represents the net integration of numerous factors, hence the efforts by researchers to link them and to understand the most important drivers.

Defining vigour and water status as key drivers of vineyard variability, and the verification of the methods available to assess them within a vineyard, was main aims of this review. Validation of within-vineyard variation and the quantification of the variables can be seen as half the battle won towards uniformity. Secondary to the main aim, the impact of vigour on grapevine sustainability (capacity) and the dynamics regarding grapevine water status (SPAC) were recognised. After these two aims it was only natural, from a viticultural standpoint, to investigate the possible effects of variability on grape composition and the subsequent wine quality.

It was clear from the literature studied that, even though the factors leading to variability within vineyards and their effects are very complex, the potential exists for wine grape producers to acquire detailed information to tailor the production of both grapes and the resultant wines according to expectations of vineyard performance, and according to desired goals in terms of both yield and quality. However, it is critical that more attention should be devoted to investigating the possible interactions between vigour and grapevine water status (at the level of a single grapevine), in conjunction with the particular studies of these variables. This is critical for improving our knowledge and manipulation of variables impacting grape composition and eventual wine quality.

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Chapter 3

MATERIALS AND METHODS

MATERIAL AND METHODS

3.1 EXPERIMENTAL VINEYARD

The study was carried out over two consecutive years (2006-2007) on a commercial wine estate in the Stellenbosch district, South Africa. The experimental plots were laid out in the commercial vineyard during 2006, thus all the measurements were conducted in the 2006/2007 season.

3.1.1 VINEYARD CHARACTERISTICS

The experiments were conducted on a 10-year-old commercial vineyard of *Vitis vinifera* L. cv. Merlot noir clone MO 9, grafted on Richter 110 (*Vitis berlandieri x Vitis rupestris*). The soil profile was characterised as an Oakleaf type and the soil family classified as Oa2110 (based on the South African Binomial Soil Classification System, MacVicar *et al.*, 1977). The grapevines were planted in a northeast-southwest row direction and spaced at 2.7 x 1.5 m. The training system is a vertically shoot-positioned seven-wire hedge trellis system with six moveable wires. The grapevines were spur pruned to an average of 10 spurs per grapevine. Canopy management practices included shoot positioning and mechanical shoot topping/hedging. A full cover herbicide programme was applied throughout both growing seasons. Irrigation water was supplied through a drip irrigation system consisting of 2.3 l/h drippers with a dripper spacing of 0.75 m. The system was operated by a valve that was manually controlled for each experimental plot.

3.1.2 EXPERIMENTAL LAYOUT

The experimental vineyards were divided into 48 plots consisting of 48 grapevines each. The plots were selected in zones of variable vigour determined from a multispectral image, and were classified using a normalised difference vegetation index (NDVI) that was collected in January 2006. The plots were arranged throughout the vineyard in three relative vigour zones, namely high, medium and low vigour, according to the multispectral image (Fig. 3.1).

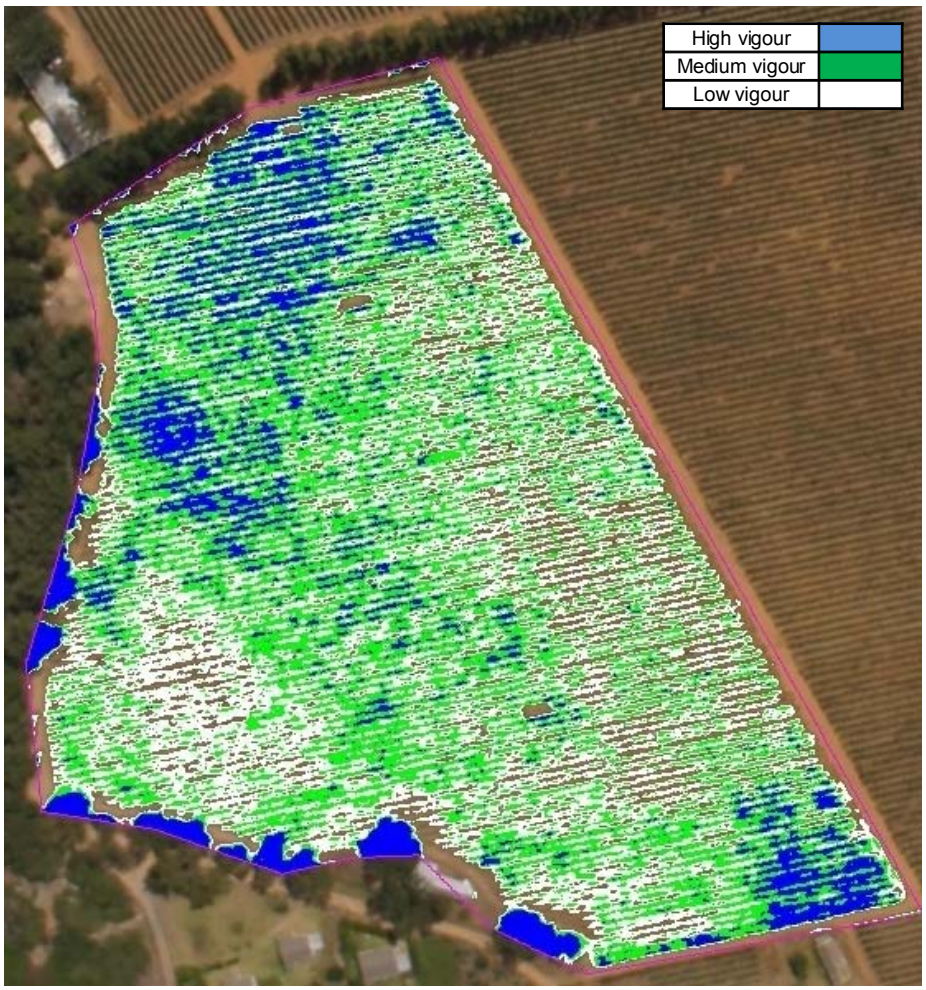

Figure 3.1 Normalised difference vegetation index (NDVI) aerial image that indicate variable vigour zones within the vineyard in January 2006.

All the plots consisted of four grapevine rows, and each row was divided into two segments of six grapevines each, as indicated in Fig. 3.2. Only the sixteen green grapevines in the two middle rows, indicated by the yellow background (rows 2 and 3), were used for the experimental measurements. The red grapevines at the ends of these rows (rows 2 and 3) acted as buffer grapevines. The other two rows with the blue background (rows 1 and 4) were buffer rows.

The aerial image in Fig 3.3 also shows 50 x 50 cm white melamine-covered hardboard panels that were placed on top of poles in the vineyard to delineate the boundaries of the various plots. The white panels act as a visual aid when colour images are viewed and can be used when the plot boundaries are drawn in on the image, as seen in Fig. 3.4. The white panels will also be used in a follow-up project on image pixel processing.

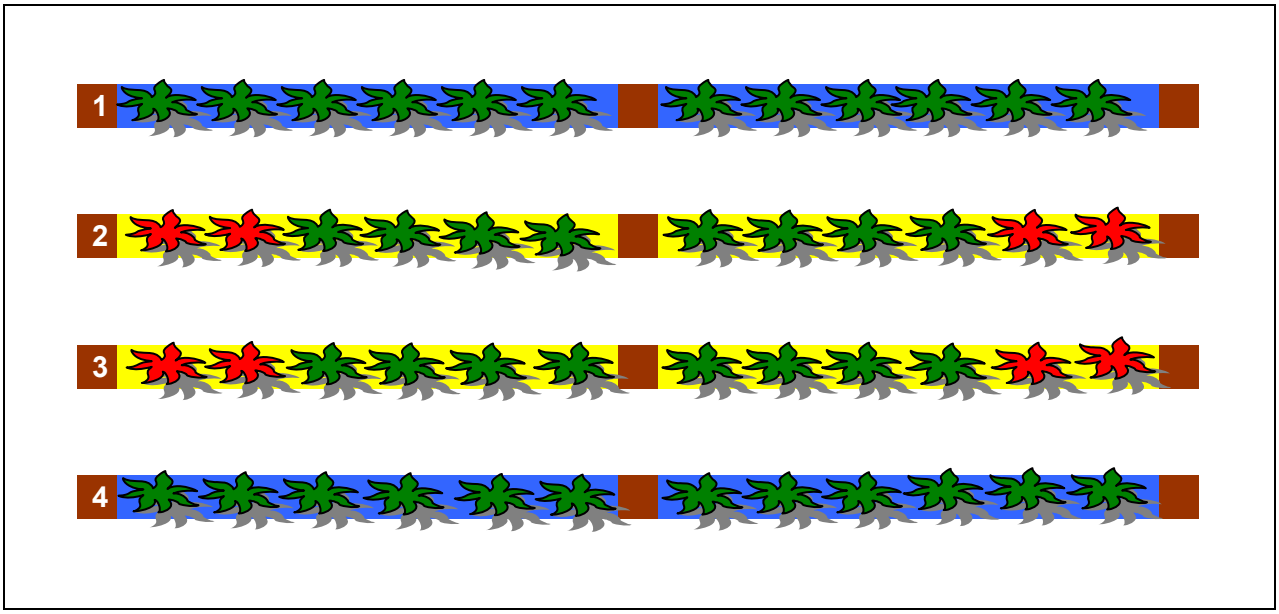

Figure 3.2 A diagram indicating the composition of each plot in the vineyard. Each of the four rows consists of two segments with six grapevines each. The rows with the blue background acted as buffer rows and the red grapevines at the end of each middle row acted as buffer grapevines, while the measurements were done on the grapevines in the remaining two rows.

Experimental plots were randomly assigned to four irrigation treatments with 12 replications each. The four irrigation regimes were established according to target pre-dawn leaf water potential (pre-dawn Ψ) and stem water potential (stem Ψ) measurements, as indicated in Table 3.1.

Table 3.1 The pre-dawn leaf water and stem water potential targets according to which the four irrigation regimes were scheduled.

Treatment	Leaf water potential	Plant water status target (KPa)
Low deficit irrigation	Pre-dawn Ψ	Between -200 and -300
	Stem Ψ	Between -1000 and -1200
Moderate deficit irrigation	Pre-dawn Ψ	Between -300 and -400
	Stem Ψ	Between -1200 and -1400
Dryland	No irrigation	Irrigate only if stem Ψ becomes more negative than -1700 KPa

The random placement of the four irrigation treatments throughout the vineyard is illustrated in Fig. 3.5. Each of the different colours corresponds to a specific irrigation treatment.

3.2 PLANT WATER STATUS MEASUREMENTS

Pre-dawn leaf water potential, as well as midday leaf water potential, was measured with a pressure chamber (bomb) as described by Scholander *et al*. (1965). Stem water potential was measured as described by Choné *at al*. (2001), also with a pressure chamber. However, the leaves used to measure stem water potential were bagged for only 20 minutes, and not for one hour as recommended by Choné *at al*. (2001). The reason for this was that another researcher had found that these measurements are generally stable with regard to plant variation after 20 minutes (P.A. Myburgh, Nietvoorbij Institute for Viticulture and Oenology, personal communication, 2006). The measurements were conducted on the 16 grapevines situated in row two and three of each plot. Ten leaves were sampled from these rows during each measurement interval. The leaves chosen were fully expanded leaves on main shoots and leaves were taken from the sun exposed and shaded sides of the canopy. These leaves were placed in a Sholander-type pressure chamber (ARIMAD-3000, M.R.C., Ltd., Rachmanov Bookstein, Isreal) for the measurement of water potential. The pressure value was recorded when the first signs of sap appeared from the petiole.

3.3 SOIL CHARACTERISTICS

3.3.1 SOIL WATER CONTENT

Soil water content was measured at 0.3 m depth intervals to a depth of 1 m at the plots indicated in Fig. 3.6, using the neutron scattering technique. Measurements started in June 2006 and were taken once a week before bud break, after bud break the frequency increased to twice a week. Polyvinyl chloride (PVC) access tubes for the 503DR Hydroprobe (CPN Corp., Pacheco, CA) were installed in the grapevine row, 0.5 m from the grapevine, for the monitoring of relative soil water content. The installation of the neutron probe access tubes was performed similarly at all the plots, and the placement of access tubes with respect to the irrigation drippers was also considered. The tubes were installed using a hand auger of the same diameter as the tube so as to ensure a tight fit between soil and tube. A 32-second neutron probe reading was taken at each 0.3 m depth interval, and the count data were converted to a count ratio (CR) using a standard count obtained from a water drum. Gravimetric soil moisture content was also measured at the same plots and at a depth of 30 cm, 60 cm and 90 cm. Gravimetric soil moisture data were used in an accompanying study to compute the calibration of the neutron probe.

3.3.2 SOIL PROFILE PREPARATION AND ROOT DISTRIBUTION ANALYSIS

Soil profile pits were dug to obtain a general soil classification, root distribution and effective root depth at nine positions in the vineyard (Fig. 3.7). These subplots were selected to represent the major vigour gradients indicated by the multispectral image. The soil profile pits were 1.2 m deep and 1.6 m wide and were dug across and parallel to the grapevine row, 50 cm from the grapevine trunks. A healthy grapevine representing the average growth vigour of the plot was selected for the placement of the profile pits. The soil profile wall was prepared according to the method of Böhm (1979). Approximately 10 cm of soil were removed from the pit wall to expose the grapevine roots. After all the necessary soil had been removed, the roots were spray-painted white to allow discrimination from the background soil on the pit wall. A lime green grid that consisted of 100 mm x 100 mm blocks was placed against the pit wall and the wall was then photographed. The descriptions of the soil in the different layers were analysed and the total number of roots observed were also counted for each depth level.

3.3.3 SOIL DESCRIPTIONS AND SOIL CHEMICAL ANALYSIS

A complete soil survey of all the pits was performed by a practising soil scientist, who provided soil descriptors and classification for the specific plots. The soil samples were collected at 30 cm intervals (0-30 cm, 30-60 cm, 60-90 cm) throughout the profile at the nine soil profile pits, and were sent to an independent laboratory, BEMLAB (Somerset-West, South Africa), for analyses. The mechanical composition, pH, electrical conductivity and base saturation for each sample were determined. Soil bulk density and porosity were determined in triplicate at 30 cm, 60 cm and 90 cm, using the core method (Blake and Hartge, 1986).

3.4 VEGETATIVE CHARACTERISTICS

3.4.1 LEAF AREA MEASUREMENTS

Plots where shoots were destructively sampled were selected to represent different vigour areas in the vineyard, as observed on the multispectral image. Two representative grapevines were identified at each specific plot directly after harvest. For both of these grapevines, one representative shoot was harvested from each cordon arm at a spur position close to the centre of the grapevine. Main shoot length, lateral shoot length, lateral shoot number and leaf number (main and lateral) were determined for these shoots. Leaves were then removed from the shoots to determine the leaf area of the main and lateral shoots separately, using a Delta-T leaf area meter (Delta-T Devices, Cambridge, UK). From this, the average leaf size, total leaf area per shoot and leaf area per grapevine could be determined.

3.4.2 CANE MEASUREMENTS

Each grapevine in all the experimental plots was pruned at the end of June to two-bud spurs. The number of canes per grapevine was counted and then tied together to be weighed, using a Micro Digital Hanging Scale (FS 30) (Scalerite, South Africa). A representative cane from each grapevine was sampled and cane length (main and lateral), internode length, node number and diameter were determined.

3.5 REPRODUCTIVE CHARACTERISTICS

3.5.1 BERRY ANALYSES

3.5.1.1 Berry sampling

Berry sampling was performed at the same plots throughout the season. An average of 150 berries was randomly sampled each time, from the inside and outside of the canopy and from the top, middle and bottom of the bunches. Both sun-exposed and inner-canopy bunches were sampled. One hundred berries were then randomly selected in the laboratory and weighed, and their volume was determined by adding the berries to a known amount (300 ml) of water in a measuring flask. The volume of water displaced was recorded as the volume of 100 berries.

3.5.1.2 Berry composition

The 100 berries selected in par. 3.5.1.1 were hand crushed in a plastic bag and the juice was separated from the skins by passing it through a sieve. Total soluble solids (°B) were measured with a PAL-1 Atago pocket refractometer (ATAGO CO., Ltd., Tokyo), and the pH of the juice was measured with a CRISON basic 20 pH meter from Crison Instruments (Lasec, South Africa). A 785 DMP Titrino automatic titration instrument (Metrohm Ltd., Herisau, Switzerland) was used to determine the titratable acidity (TA) of the juice.

The juice was also analysed using Fourier-transform mid-infrared (FT-IR) spectroscopy (WineScan spectrometer, Foss Analytical, Hillerod, Denmark). A WineScan FT 120 instrument (FOSS Electric A/S, Hillerod, Denmark) that employs a Michelson interferometer was used to obtain the FT-IR spectra. Instrument settings included a cell path length of 37 µm, sample temperature set to 40°C, and sample volume of 7 to 8 ml. Samples are pumped through the heat exchanger and the CaF_2-lined cuvette and scanned from 926 to 5012 cm^{-1} at 4 cm^{-1} intervals. Prior to the analyses, the juice was filtered in a filtration unit (Foss Analytical, Hillerod, Denmark) that uses filter paper graded at 20 to 25 µm. The instrument was cleaned with solution before any calibration and cleaning was also programmed to occur 5 min after a completed analysis of a sample set. The instrument was zeroed before any set of analyses using Zero Liquid S-6060 that was scanned prior to the sample under exactly the same conditions as described for the sample (WineScan FT 120 Type 77110 and 77310 Reference

Manual, 2001; Foss Analytical). Global calibrations of wine grape composition were used for the FT-IR spectroscopic analyses.

3.5.2 HARVEST MEASUREMENTS

The harvested plots correspond to the plots that were used for berry sampling. Only every other grapevine in the middle rows (rows 2 and 3 in Fig. 3.2) of these plots was harvested to provide sufficient grapes for small-scale vinification (and to limit the impact on the producer). Bunch number per grapevine was determined, and the bunches were weighed to determine yield per grapevine. Twelve bunches were randomly sampled from three harvesting crates at each experimental plot, placed in plastic bags and frozen to determine bunch mass, berry number and berry mass.

3.6 MICROVINIFICATION

Wines were made in triplicate for each experimental plot. After crushing the grapes and before yeast inoculation, the must was analysed using FT-IR spectroscopy, and the total soluble solids (°B), pH and TA were measured as described in Section 3.5.1.2. Standard experimental winemaking procedures were carried out as specified by the Department of Viticulture and Oenology, Stellenbosch University. The yeast used for fermentation was WE372.

3.6.1 WINE ANALYSES

Wine analyses were performed after bottling. FT-IR spectroscopy and gas chromatography-flame ionisation detector (GC-FID) analyses were performed to determine wine volatile components. Five ml of wine, with added internal standard (4-methyl-2-pentanol) and 100 µl of a 0.5mg/l soaking solution, were extracted with 1 ml of diethyl ether by placing the ether/wine mixture in an ultrasonic bath for 5 min. The wine/ether mixture was then centrifuged at 4000 rpm for 3 min. The ether layer was removed and dried on $NaSO_4$. This extract was then injected into the GC-FID (Agilent, Santa Clara, California, USA) (Witbooi, 2008).

3.6.2 WINE SENORY ANALYSIS

The sensory analysis was conducted by a trained panel consisting of 8 members to determine if any aroma and flavour differences could be quantified. The wines from the respective plots were each tasted twice in a blind tasting by every member of the panel. The wines were randomised for each taster using the Latin Square method, as specified by Cochran and Cox (1950). Wine tasting sheets with unstructured line scales, marked from 0 to 100%, were created to account for different aroma components potentially present in the wine of this specific cultivar. Training involved calibration sessions held with all of the tasters during which they were

familiarised with the different aroma components. The standards used during the calibration sessions were present throughout the formal sensory evaluation sessions.

3.7 STATISTICAL ANALYSIS

The data were analysed by repeated measures analysis of variance (ANOVA) using the mixed model approach. Pruning mass was included in the model as a covariant. Pruning mass was also analysed using ANOVA. These statistics were used to investigate the effects between plots, as well as the interactions between repeated measures and between treatments. Descriptive statistics were also performed to display the means and standard deviations for the variables.

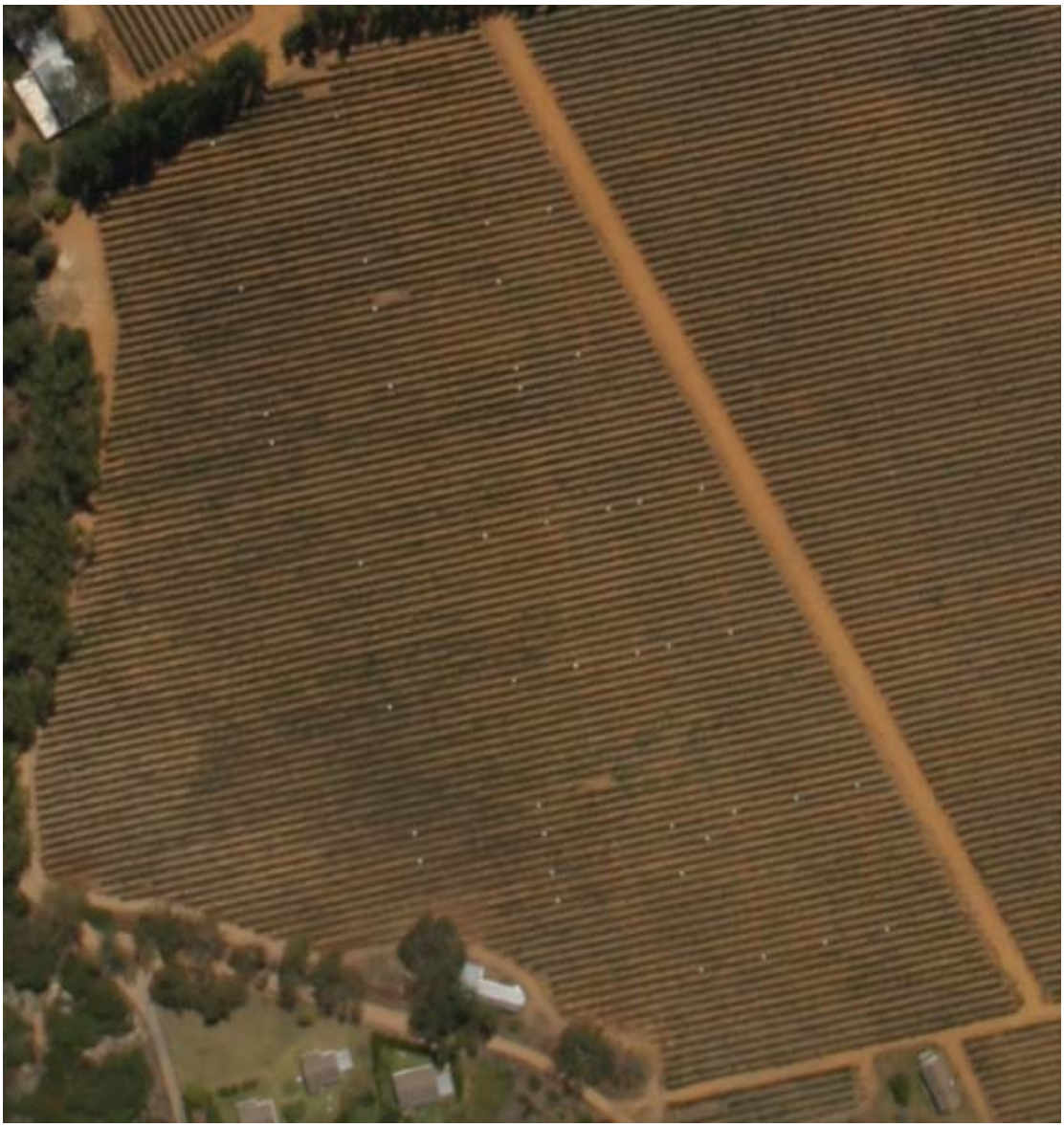

Figure 3.3 Aerial image that indicate white panels placed in the vineyard to delineate the boundaries of the plots laid out in the experimental vineyard.

Figure 3.4 Aerial image that indicate the 48 plots laid out in the vineyard. The borders of each plot is indicated via the white lines drawn on the image.

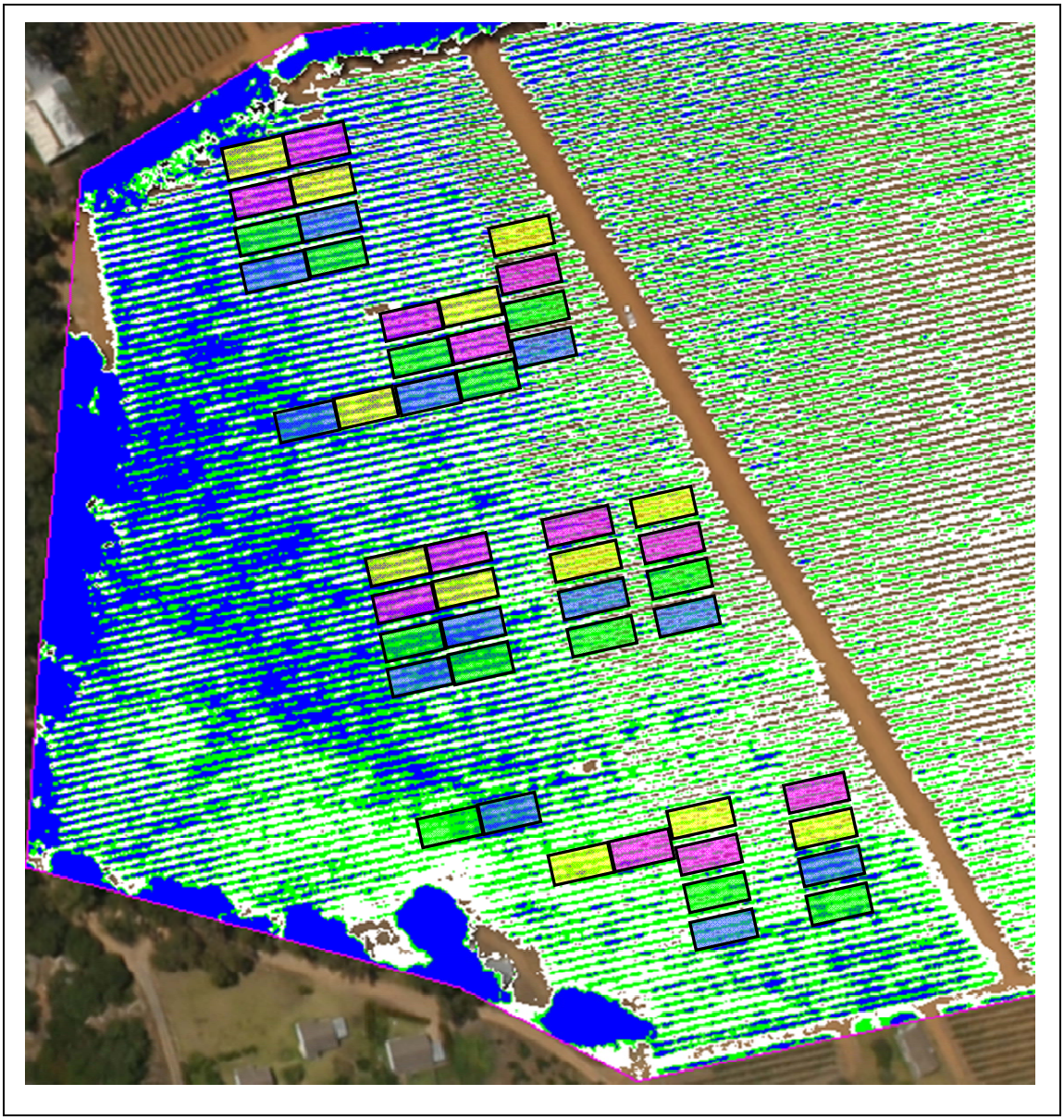

Figure 3.5 Aerial image that indicate the outlines of each of the 48 plots laid out in the vineyard. The 48 plots are randomly divided into the four treatments mentioned and each of the four colours corresponds to a treatment. The blue plots represent the wet treatment, the green plots represent the dry treatment, the pink plots represent the dry-land treatment and the yellow plots represent a ripening treatment that is not applicable to this particular project.

Low deficit irrigation treatment
Moderate deficit irrigation treatment
Dry-land treatment
Ripening treatment

Figure 3.6 Aerial image that indicate the plots where soil water content was measured at 0.3 m depth intervals to a depth of 1 m using a neutron probe. Gravimetric soil moisture content was also measured at the same plots at a depth of 30cm, 60cm and 90cm.

Figure 3.7 Aerial image where the white plots indicate the plots where soil profile pits were dug to obtain a general soil classification, root distribution and effective root dept.

3.8 LITERATURE CITED

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Chapter 4

RESEARCH RESULTS

RESEARCH RESULTS

4.1 RECLASSIFICATION OF TREATMENTS

Manipulation of soil water content using different irrigation regimes was done mainly to establish a desired grapevine water status, in an attempt to consequently study the interaction between grapevine vigour and grapevine water status. Grapevine vigour variability was present naturally within the vineyard, and therefore no manipulation was needed to obtain canopy microclimate variability in this trial. The four irrigation regimes, as described in the materials and methods, were maintained throughout the season. Water was applied only when and if the grapevine's water status was in the desired deficit ranges. However, it became apparent during soil moisture measurements that the amount of water in the soil at an experimental plot did not always correspond to the amount of water that was applied. Some of the plots that received the low deficit (wet) irrigation treatment did not reflect the large amounts of water applied. The inverse effect was also present at plots that received the moderate deficit or dry-land treatment, where the soil profile was just as wet as some of the low deficit irrigation treatment plots. The two graphs in Fig 4.1 is a clear indication of such an example. Plot A3 (B) received the low deficit irrigation treatment and plot B1 (A) is part of the moderate deficit irrigation treatment. The neutron count ratios of the soils, measured at a depth of 60 cm, for the two plots is shown over time. The arrowed line on the graphs is an indication of the average count ratio (CR) for all the plots throughout the vineyard, measured at 60 cm. It is clear from Fig 4.1 that the neutron count ratio of plot B1 (A) is higher than plot A3 (B) for all the measuring dates and that the CR of plot B1 stayed above average until harvest, whereas the count ratio of plot A3 were way below the average. It is predominantly topographic and soil characteristic differences within the block that may be responsible for these observations. However, it is not only the variation in soil characteristics (such as texture) and the lateral movement of water throughout the vineyard that is accountable but also the inevitable effect of rain during the season. Water applied to the other parts of the vineyard (excluding experimental plots) could also be a factor, considering that the experiment was conducted in a commercial irrigated vineyard. In a commercial setting the count ratios would be calibrated for different soils by taking into account soil characteristics such as texture and gravimetric soil water content, yielding volumetric soil water content. These calibrations have been performed in another study on this vineyard block. It can be seen from Table 3 in the Appendix that the texture of plots B1 and A3 (situated next to plot 3) is very similar.

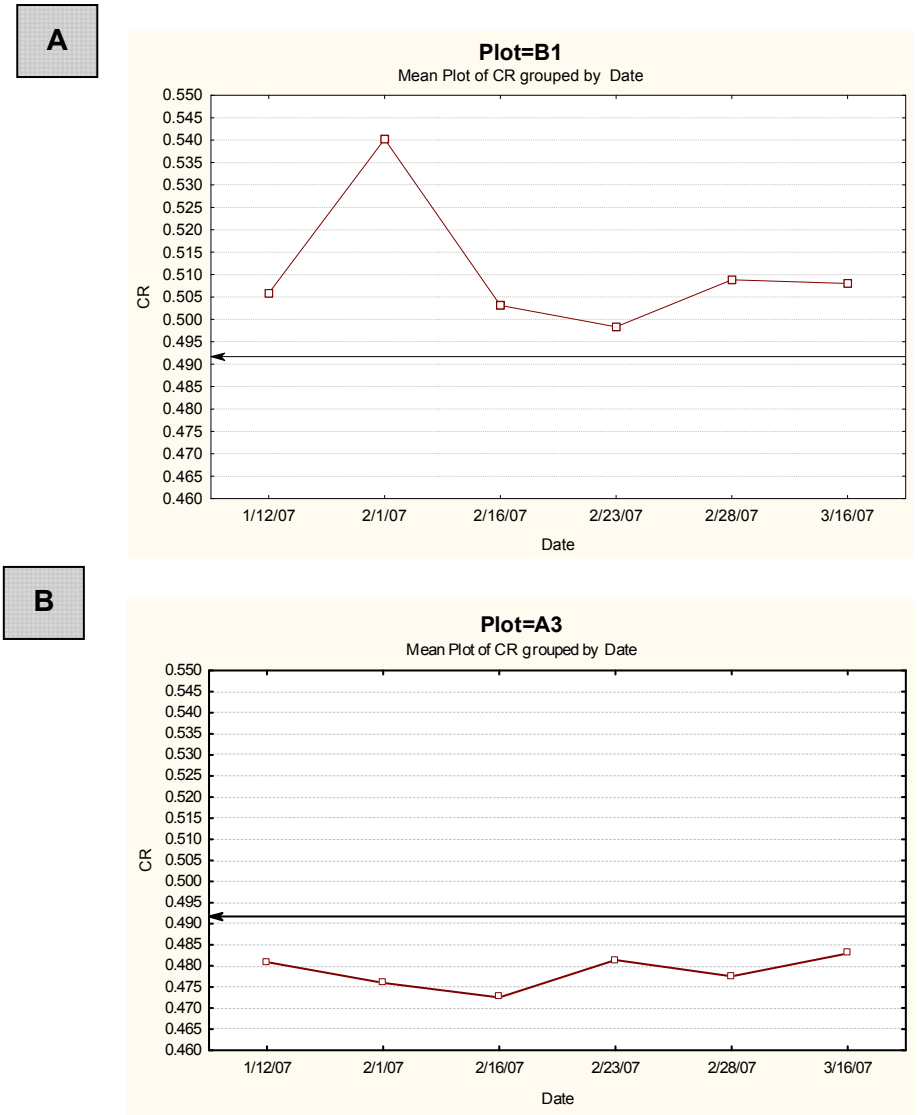

Figure 4.1 Relative soil water content of plot B1 (A) and plot A3 (B) over time for a depth of 60 cm. The arrowed line on the graphs is an indication of the average count ratio (CR) for all the plots throughout the vineyard, measured at 60 cm.

In terms of quantifying the interaction between plant vigour and water deficits, the experimental plots could thus no longer be classified according to the irrigation regimes initially applied. Assessing the effect of differences in soil gravimetric water content and bulk density to ascertain possible effects on volumetric water content was not in the scope of this study, and is part of a companion project on this same site from 2007. Reclassification of treatments was therefore inevitable, seeing that the water status and grapevine vigour interaction could still be evaluated if the plots are grouped according to plant reaction to primarily soil water content. Pre-dawn leaf water potential (pre-dawn Ψ) was the defining parameter used as an aid to establish the reclassification treatments.

Pre-dawn Ψ was used as a parameter for irrigation scheduling and gave a clear indication of the plant water status of the grapevines throughout the season. Thus, during reclassification it

became apparent that the accumulative grapevine water status (the sums of means at the different measuring dates throughout the season) is more significant than comparing the single measurements at specific dates. The total pre-dawn Ψ during the season for the experimental plots (Fig. 4.2) were used to classify them as “dry” or “wet”. In the scope of this experiment, the plots with an accumulative pre-dawn Ψ higher than 1400 KPa were primarily classified as dry and plots with an accumulative pre-dawn Ψ lower than 1400 KPa were classified as wet. However the pre-dawn Ψ of each plot over time were also evaluated during classification, in order to ensure that the seasonal water status (and especially the situation during grape ripening) of the grapevines was still accounted for. The exception to the 1400 KPa “rule” was plot A3 and B3 that was classified as wet even though they had an accumulative pre-dawn Ψ higher than 1400 KPa. The reason for this was because the pre-dawn Ψ of these plots for the latter part of the season (from vèraison to ripeness) was indicative of the other wet plots.
Fig. 4.3 shows the pre-dawn Ψ of plot A3 over time and indicates the lower water potential during the final part of the season, the pre-dawn Ψ of plot B3 followed the same trend. Plot P12 on the other hand had a “dry” water potential throughout the season except for one measuring date and were thus classified as dry, even though the accumulative mean pre-dawn Ψ was lower than 1400 KPa.

The adapted classifications are summarised in Table 4.1. The data is thus further discussed according to the grouping classifications of wet and dry. After reclassification of the treatment plots it was grouped in Fig. 4.4 according to ‘wet” and “dry” to indicate the outcome of the accumulative pre-dawn Ψ.

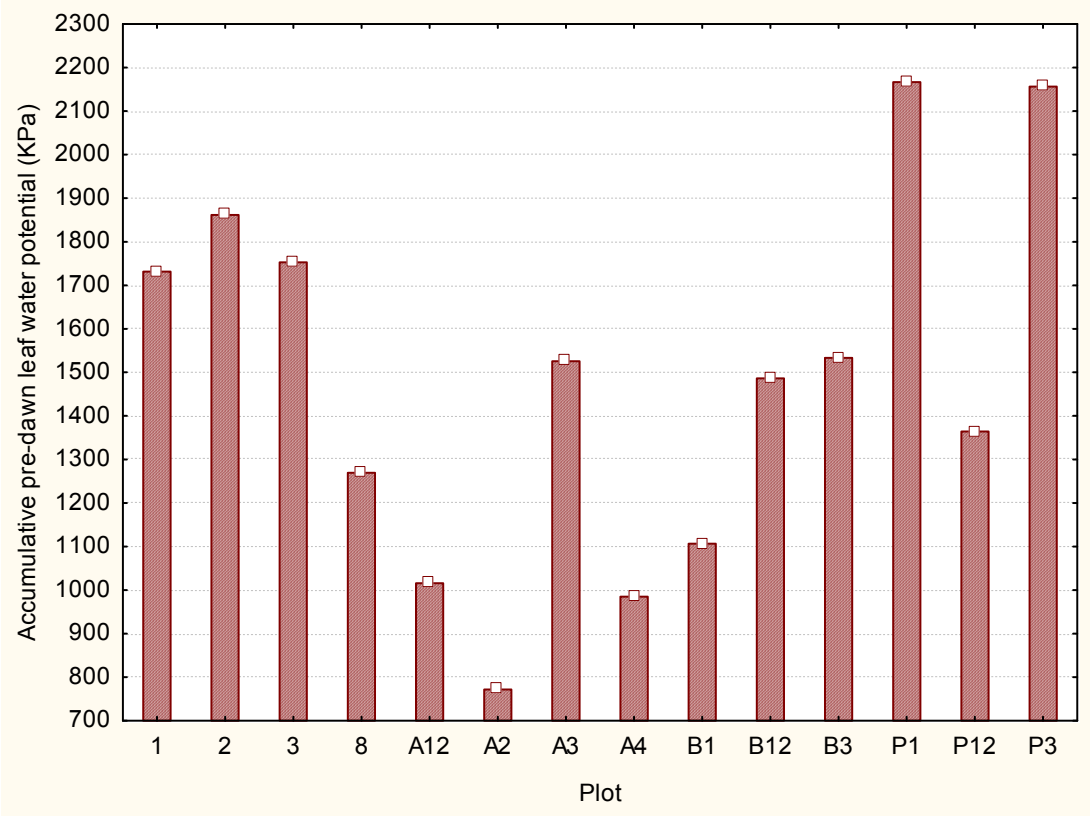

Figure 4.2 Accumulative mean pre-dawn water potential (KPa) during the season for the plots used during the reclassification of the treatments.

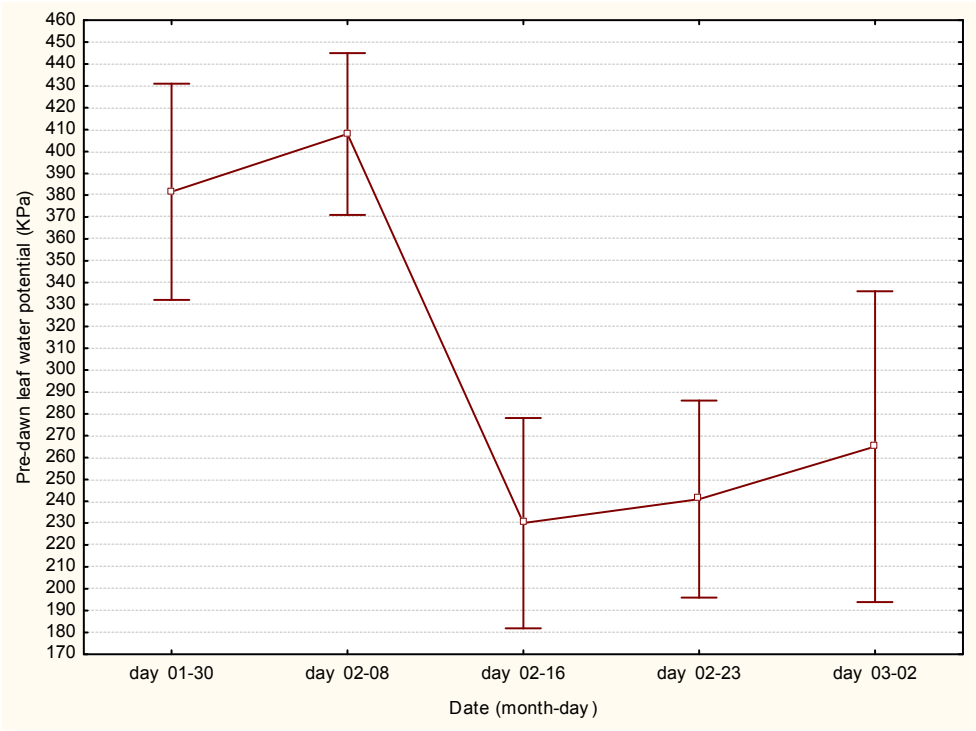

Figure 4.3 Means with error plot of the pre-dawn water potential (KPa) of plot A3 during the season (Vertical bars denote 0.95 confidence intervals).

Table 4.1 Summary of the plots classified as wet- or dry according to accumulative mean pre-dawn water potential (KPa).

Classified Treatments							
Classification	**Treatment Plots**						
Wet (pre-dawn Ψ)	8	A2	A3	A4	A12	B1	B3
Wet	Plots reclassified as:						
	W1	W2	W3	W4	W5	W6	W7
Classification	**Treatment Plots**						
Dry (pre-dawn Ψ)	1	2	3	B12	P1	P3	P12
Dry	Plots reclassified as:						
	D1	D2	D3	D4	D5	D6	D7

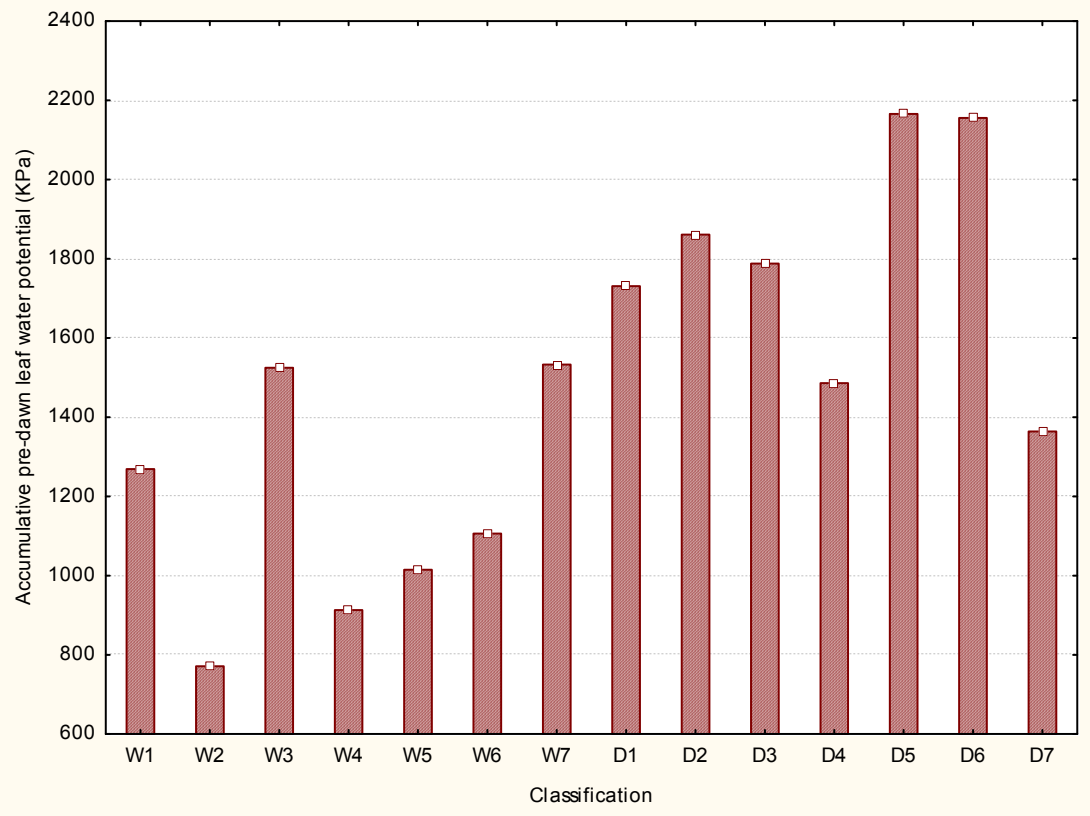

Figure 4.4 Accumulative mean pre-dawn water potential (KPa) during the season of the reclassified plots.

To study the interaction between grapevine vigour and water status, the vigour of each plot were quantified and incorporated into the statistical analyses. Pruning mass has been used throughout literature as a parameter to quantify the vigour level of a grapevine (Smart *et al.*, 1985, Myburgh, 2005). From an ANOVA of pruning mass for the different plots (Fig 4.5) it is possible to see the large and mostly significant vigour differences between the various plots. Pruning mass was therefore used as a covariate during statistical analyses in order to show the effect of vigour differences on the measured parameters. When discussing this project's results, the treatment effect was first evaluated and then the combined effect of vigour along with the treatments, via the incorporation of the covariate. The analysis performed without the covariate therefore still incorporates the inherent vigour differences shown in Fig 4.5 into the analysis, while the analysis with the covariate incorporated removes the effects of vigour differences from the analysis, in effect making clear the possible initial effects that vigour had on the analysis.

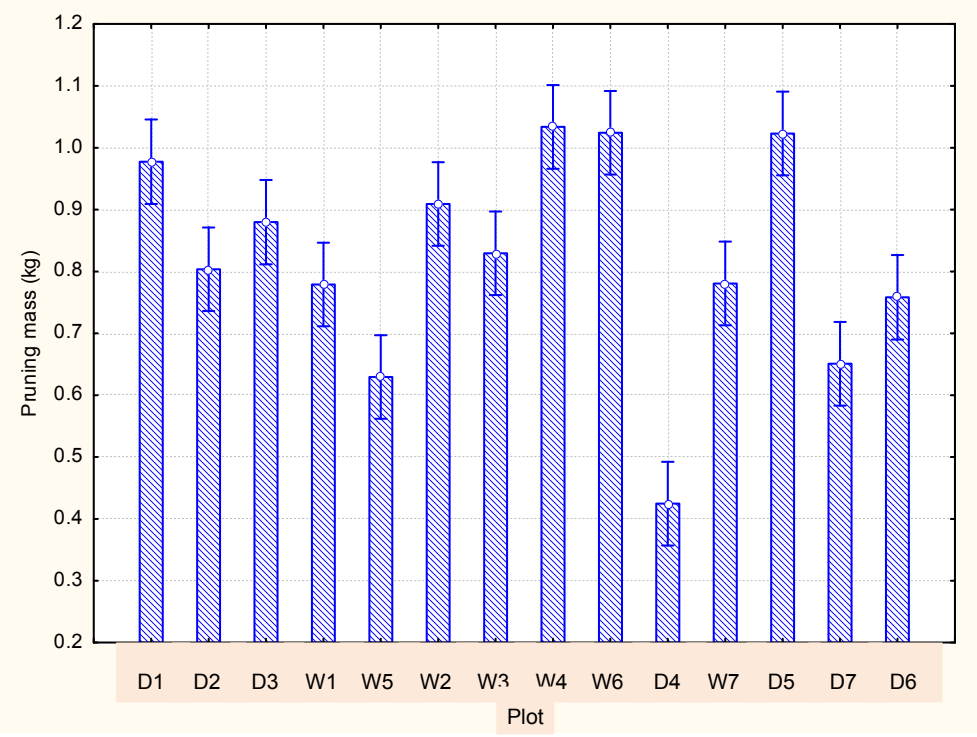

Figure 4.5 One way ANOVA of the pruning mass for the different plots during the 2007 season (Vertical bars denote 0.95 confidence intervals) (P≤0.01).

4.2 SOIL CHARACTERISTICS

4.2.1 SOIL WATER CONTENT

The count ratios of the soil were determined at 0.3 m depth intervals to a depth of 1.0 m at the fourteen plots that were used to establish the reclassification in Table 4.1. The count ratio of the whole profile was measured. An increase in the count ratio is mostly an indication of an increase in volumetric soil moisture, should soil texture and bulk density not differ significantly (Mc Dougall *et al*., accessed 2008). The variability in count ratios of the various treatment plots over the season were discussed in section 4.1 and this variability were the reason for reclassification of the treatments according to pre-dawn Ψ. After reclassification the data shown that there was no significant difference in count ratios between the wet and dry classifications at the end of the season. Count ratios at the three depths during the season and between classifications also did not indicate any differences (Table 4.2). The combined count ratios for each of the classifications at the three depths measured however showed a possible trend of increased soil wetness over depth (Fig. 4.6). The soil profile for all classifications was significantly wetter at a depth of 0.9 m than at 0.6 m for both the wet and the dry classification. A higher percentage of clay at a depth of 0.9 m is seen as the reason for this outcome (Table 4, Appendix) as explained by White (2003).

Table 4.2 ANOVA of count ratio of the plots after reclassification.

	DF	F	p
Pruning mass (kg)	117	9.08	$p < 0.01$
Depth	18	15.45	$p < 0.01$
Classifications	9	0.66	$p > 0.05$
Date*Depth	117	1.03	$p > 0.05$
Depth*Classifications	18	0.34	$p > 0.05$

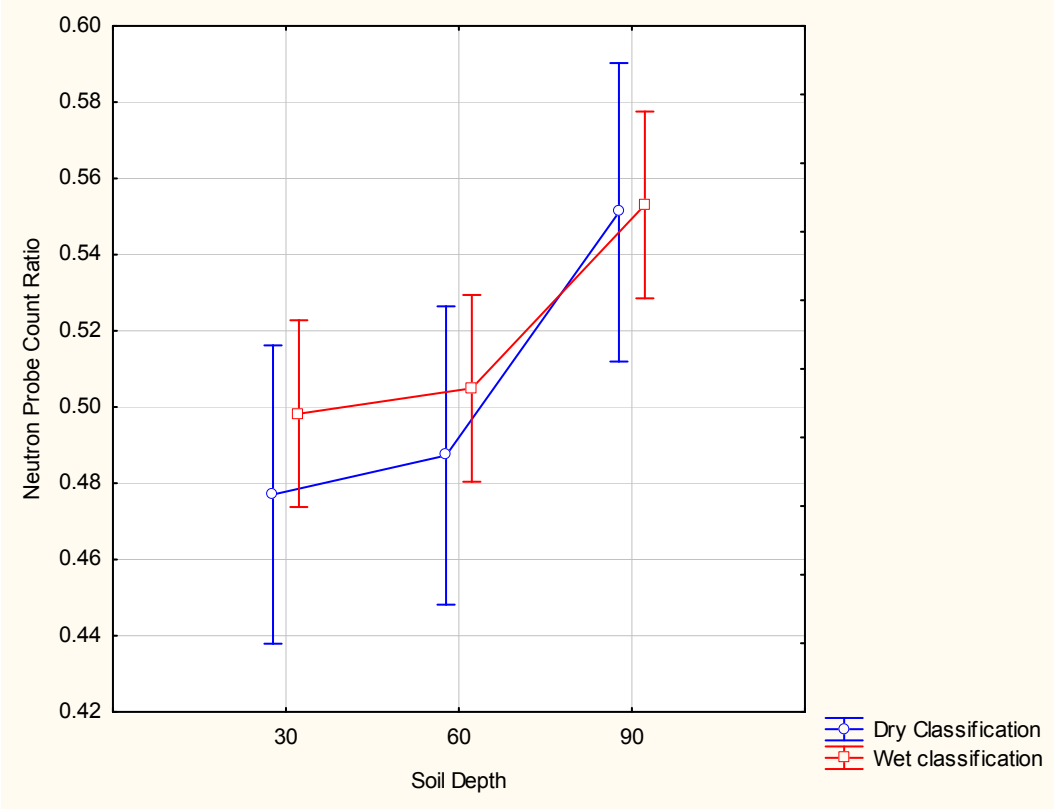

Figure 4.6 Graph showing least squares (LS) means of the count ratios of soil water content for the wet and dry classifications for 30, 60 and 90cm soil depths (Vertical bars denote 0.95 confidence intervals).

4.2.2 ROOT PENETRATION AND DISTRIBUTION

Root penetration and distribution were evaluated after the profile wall was prepared, roots were divided in to size classes, counted and then photos were taken in the various profile pits Figs. 1 to 5 (see Appendix).

Plot D2, Dry classification (Fig. 1): The colour hue differences throughout the profile give the impression of red "tongues" coming in from the left. It is evident here that the roots are predominantly found in the dark brown parts of the profile. The darker parts had a lower clay percentage that the red zones, and a higher coarse sand and stone fraction. This "tongue" effect of soil coloration may be caused by soil preparation procedures, stressing the importance of judicious soil preparation techniques, and the potential detrimental effects of bad soil preparation (Van Huyssteen, 1987). The pH (KCl) of the profile is relatively higher than what is optimum for root growth.

Plot D3, Dry classification (Fig. 2): The most important observation here is the low total number of roots throughout the face of the wall. Roots were mainly found in the top left hand side of the profile and the soil zones where the least amount of roots was found were redder in colour.

The low root density can be ascribed to a low pH (KCl) of 4.5 throughout the profile. Conradie (1994) indicated that a soil pH (KCl) of at least 5.5 is optimal for grapevine root penetration and growth.

Plot W1, Wet classification (Fig. 3): In this profile a high quantity of large stones were found that did not allow for easy root penetration; however the soil had a high sand fraction that in turn may have stimulated it. It is also visible that the majority of roots were found at the 40 to 90 cm depth levels.

Plot A10, (Fig. 4): It was apparent in this profile that most of the roots were found in the layers from 50 to 90 cm. Root distribution was fairly homogenous throughout the profile, except for the top 20 cm, where only fine roots could be found. Larger roots were also lacking, seeing that almost all of the roots in the profile are 2 mm and smaller.

Plot B8, (Fig. 5): This profile is exemplary of optimal root distribution throughout the soil. Roots are present in all the layers of the soil and the ratio of thin and thick roots are also healthier than in the other profile pits. The colour hue are also very homogenous, more so than the previous profiles.

In Table 4.3 there is a summary of the size classification and root count found at different depths at each profile pit. The amount of roots counted and the distribution of the various root classes varied significantly among the plots, as seen in the profile photos. The root count indicated that the majority of the roots are between 0.5 and 2 mm in size and the bulk of all the roots are situated in the 30 cm to 70 cm depth range.

Table 4.3 Summary of the size classification and root counts found at different depths at each soil profile pit.

Plot	Root size (mm)	Soil depth										Total
		10 cm	20 cm	30 cm	40 cm	50 cm	60 cm	70 cm	80 cm	90 cm	100 cm	
2	< 0.5	1	1	2	4	14	5	5	7	10	6	**55**
	0.5 - 2	2	5	14	20	23	27	24	18	23	22	**178**
	2 - 5			2	1	1	2	3	3		5	**17**
	5 - 7						1			1	5	**7**
	> 7						1			1		**2**
3	< 0.5	1	4	9		1	2	2		1	1	**21**
	0.5 - 2	23	15	26	18	28	12	17	10	9	15	**173**
	2 - 5		3	2	3	1		2	1			**12**
	5 - 7					1				1		**2**
	> 7							1	1			**2**
4	< 0.5		11	1	1				1			**14**
	0.5 - 2	3	9	15	27	22	21	33	28	35	41	**234**
	2 - 5			4	2	1	2	3	5	4	10	**31**
	5 - 7					1	1		2			**4**
	> 7											**0**
8	< 0.5		16	14	16							**46**
	0.5 - 2	4	4	1	4	10	8	16	14	12	9	**82**
	2 - 5					3	2	5	5	1	1	**17**
	5 - 7											**0**
	> 7					1						**1**
A10	< 0.5											**0**
	0.5 - 2	3	20	20	21	23	25	24	31	24	16	**207**
	2 - 5		1	3	1	4	5	5	7	1	4	**31**
	5 - 7			1		1	1			1		**4**
	> 7						1	2				**3**
B1	< 0.5					3	1					**4**
	0.5 - 2		5	5	13	18	15	18	12	9	14	**109**
	2 - 5		1	1	2	1	3		1	2	1	**12**
	5 - 7					1					1	**2**
	> 7						1					**1**
B8	< 0.5		4					2				**6**
	0.5 - 2	2	16	23	25	27	34	22	35	25	24	**233**
	2 - 5			1	6	4	5	4	2	9	3	**34**
	5 - 7				3	1	1	1	1	2		**9**
	> 7										2	**2**
B11	< 0.5											**0**
	0.5 - 2	3	8	20	31	20	18	9	18	3	156	**286**
	2 - 5		1	5	6	4				1	2	**19**
	5 - 7			1						1		**2**
	> 7				1	1	1					**3**
B12	< 0.5											**0**
	0.5 - 2		3	14	9	16	5	15	10	13	24	**109**
	2 - 5		4		6	1	6	8	8	5	8	**46**
	5 - 7						2			1	2	**5**
	> 7					1	1	1				**3**

4.2.3 SOIL DESCRIPTIONS AND CHEMICAL ANALYSIS

A soil scientist classified each soil profile into soil form and soil family, the classification codes correspond to the Binomial System for Soil classification of MacVicar *et al*. (1977), which is indicated in Table 1 (see Appendix). All of the plots except for one (B1) consisted of three horizons, and the first two horizons out of the three are exactly the same for all of the plots. The parent material of plot 8 was classified as granite with sandstone as additional material, but the parent material of all the other plots were classified as predominantly granite. All the plots were classified as an Oakleaf soil form belonging to the 2110 soil family. No significant variation in description was found between the various plots in wetness class and soil vigour potential.

A review of all the results obtained from soil analysis is summarised in Tables 2, 3 and 4 (see Appendix). General soil analyses, base saturation and mechanical analyses were conducted. The bulk density and porosity of the soil were also analysed to be used for a companion study (data not shown).

In general the soil composition is indicative of the area and type of soil (Mr P. Raath, personal communication, 2008). There are however some aspects that have to be addressed. By comparing the pH (KCl) of the plots to a norm of 5.5 – 7.5 (Conradie, 1994) it becomes apparent that the pH (KCl) of plot 3 is relatively low and can be classified as an acidic soil. The low pH (KCl) also corresponds with the higher H^+ values encountered at this plot. Plot B11 and B12 also show low pH values in the 60-90 and 90 cm depth levels respectively. The phosphate content, that should be in the range of 25 mg/kg for this specific soil with its measured clay content (Conradie, 1994), is definitely too low at the depths of 60 cm and deeper. This could indicate that the soil phosphate content was not successfully rectified during soil preparation. The high phosphate levels in the topsoil (30cm) are mainly due to fertilisers applied to rectify the phosphate shortage. The potassium (K) content of the soil is quite controversial when it comes to wine grapes, seeing that K is absorbed by the grapevine and could cause an increase in grape juice pH (Strever, 2003). As a norm K were usually supplemented until it amounted up to about 4% of the CEC, but in recent years a concentration of 70-80 mg/kg is deemed sufficient (Conradie, 1994). The K content in the profile is therefore at an optimum level. The levels of K at 30 cm depth is definitely too high, especially at plots B1, B8 and B11. The K would eventually leach into the profile, but this does not mean that it would be easily absorbed by the grapevine roots as many factors affect its absorption. The bulk of the roots is also situated between a depth of 30 - 70 cm and would not be affected by this high levels of K in the topsoil. The organic material (C%) content is seemingly at an optimum range for the type of soil, with optimal ranges indicated by Conradie (1994) as 0.6-0.9 (%).

4.3 PLANT WATER STATUS

4.3.1 PRE-DAWN LEAF WATER POTENTIAL

Pre-dawn leaf water potential (pre-dawn Ψ) was initially measured to provide a reference value for irrigation scheduling. However, these measurements performed at various dates during the season also gave a clear indication of the water status of the grapevines. The treatment effect and vigour influence on the grapevine water status were evaluated at the various dates and at the end of the season. The combined pre-dawn Ψ for both classifications, as measured at five different dates during the season is shown in Fig. 4.7. It is clear that the water status of the grapevines varied considerable during the season and that the pre-dawn Ψ became less negative as the season progressed, thus the wet and dry classification ended up with a relative lower grapevine water deficit at the end of the season. However, the total seasonal pre-dawn Ψ of the classifications showed that there was a significant difference in water deficit between the classifications (Fig. 4.8) (Table 4.4). The seasonal pre-dawn Ψ of the dry classification plots was significantly more negative than that of the wet classification plots. This indicates that the treatment plots were correctly classified as wet or dry, and that the grapevine water status would be accounted for in all the analyses incorporating the classification.

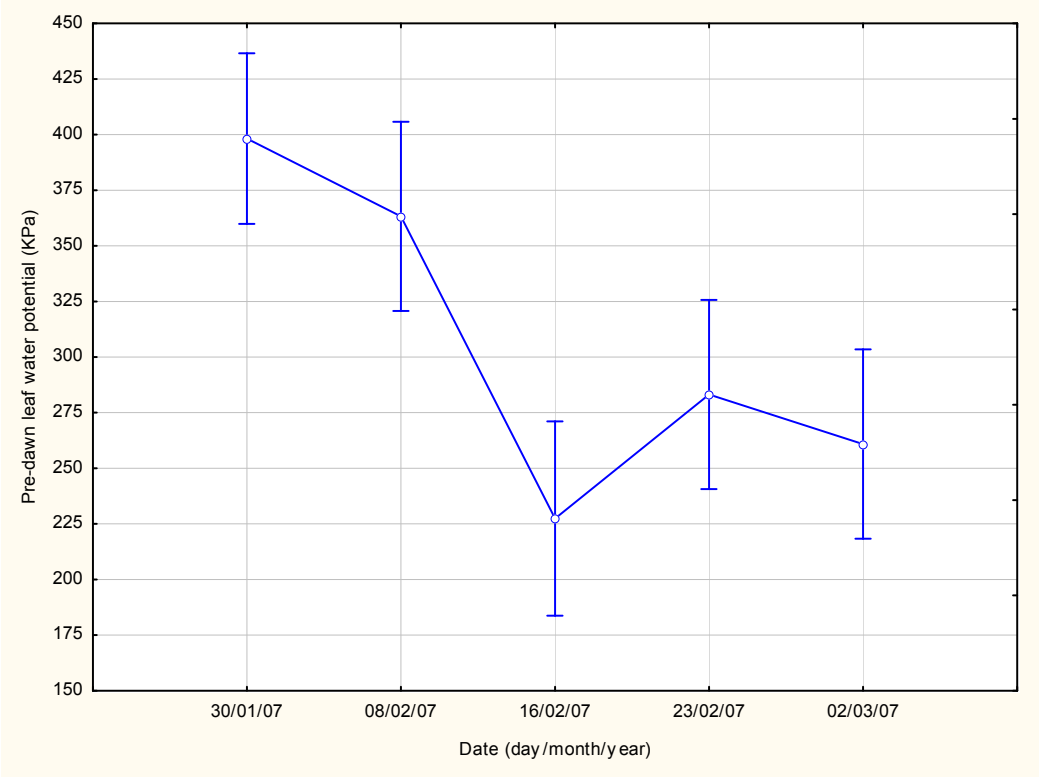

Figure 4.7 Graph showing least squares (LS) means of the combined pre-dawn Ψ for both classifications at the various measurement dates (Vertical bars denote 0.95 confidence intervals) (P≤0.01).

This variation in pre-dawn Ψ might be a result of the amount of water present in root zones of the classifications. As according to Choné *et al.* (2001) pre-dawn Ψ measure plant water status when the vine is in equilibrium with the soil's water potential, therefore providing information on the root zone soil water potential. However in the scope of this study the count ratio did not show the same trend exhibited here. In section 4.2.1 it was apparent that there was no significant difference in count ratio between the wet and dry classification plots, probably due to the high levels of variability in count ratios between plots in this study, specifically regarding soil physical properties (Table 4, appendix).

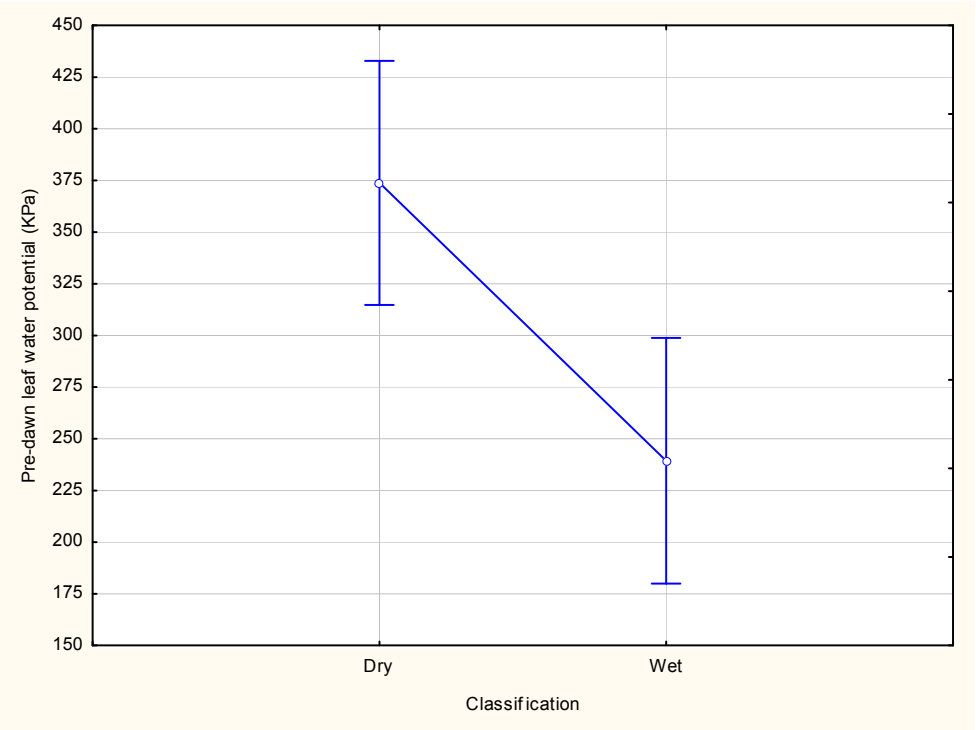

Figure 4.8 Graph showing least squares (LS) means of the total seasonal pre-dawn Ψ for the two classifications established (Vertical bars denote 0.95 confidence intervals) (P≤0.01).

Vine vigour as covariate was included in the statistical analyses to evaluate the effect thereof on the seasonal pre-dawn Ψ. The analyses indicated that the vigour of the vines did not have an effect on the variance in pre-dawn Ψ of the vines as indicated by a P value >0.05 (Table 4.4). The significant difference in pre-dawn Ψ is thus mainly a factor of the treatments implemented as irrigation regimes. The availability of water and not the vigour of the grapevines resulted in the grapevine water status exhibited. This corresponds with Van Zyl and Weber (1981) which found that vine water status is strongly correlated with the amount of available soil moisture. Even though Table 4.4 indicates that the classifications does not vary significantly by date the specific graph is indicative of the variation seen if Fig. 4.8. The pre-dawn Ψ of the two classifications over the season is shown individually in Fig. 4.9.

Table 4.4 ANOVA of the effect of water deficit and vigour on pre-dawn leaf water potential.

	DF	F	p
Pruning mass (kg)	43	1.53	p >0.05
Classifications	12	16.56	p < 0.01
Date*Classifications	43	0.67	p >0.05

It is clear that the individual pre-dawn Ψ trends throughout the season correspond exactly with the trend in Fig. 4.7 and the trends of the classifications also match each other. Both classifications had a lower water deficit (less negative pre-dawn Ψ values) at the end of the season. Figure 4.9 also indicates that the dry classification started off with the highest water deficit and the wet classification with the lowest, however, these vines experienced only a moderate water deficit throughout the season as the pre-dawn Ψ never exceeded -600 KPa. This is when measurement values of this study are compared with the reference values supplied by Deloire *et al.* (2004), as described in Table 2.2.

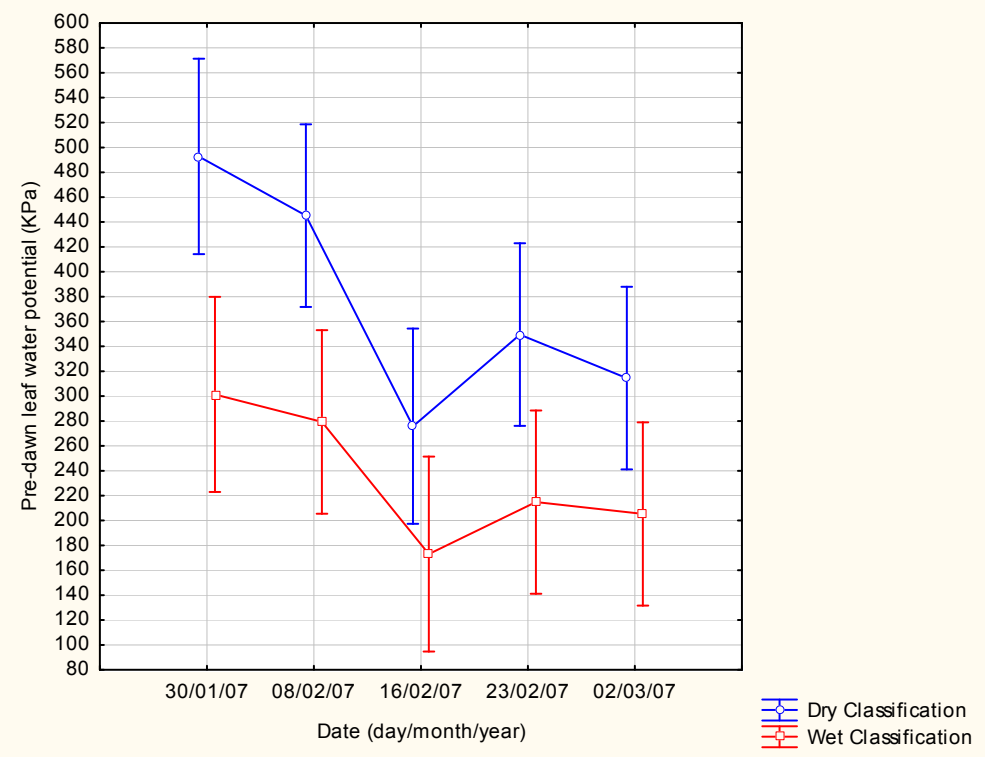

Figure 4.9 Graph showing least squares (LS) means of the individual pre-dawn Ψ for both classifications at the various measurement dates (Vertical bars denote 0.95 confidence intervals) (P≥0.05).

4.3.2 STEM WATER POTENTIAL

Stem water potential (stem Ψ) measured during the season acted as an additional aid for irrigation scheduling. However stem Ψ were not measured throughout the whole period of grape ripening. Stem Ψ measurements were already conducted at the end of 2006 even though pre-dawn Ψ measurements started end of January 2007. The early measurements were used to evaluate the grapevine water status before implementing the irrigation regimes. The combined stem Ψ for the classifications, as measured at the various dates during the season are shown in Fig. 4.10. The first three dates on the graph shows how grapevine water status became more negative until it reached the potential target at which the irrigation regimes were started. The second half of the graph (Fig. 4.10) can be compared with the pre-dawn Ψ graph (Fig. 4.7) to evaluate the same time of grape ripening. Stem Ψ showed the same trend and decrease in grapevine water potential as pre-dawn Ψ during the middle part of the season. However, the stem Ψ of the dry classification was not significantly more negative than that of the wet classification for the period of measurement (Table 4.5). This outcome is mainly due to the fact that the stem Ψ was not measured during the latter part of grape ripening. During this stage it was apparent that the wet and dry classification plots had a significant difference in grapevine water status, as indicated by pre-dawn Ψ. Also, the various classification plots did not differ significantly during the first period of measurement before irrigation was applied and pre-dawn Ψ measured. The result is significantly different when the stem Ψ is evaluated for the post irrigation implementation period. It can be observed that the stem Ψ of the dry classification is significantly more negative than that of the wet classification, especially at the last measuring date (Fig. 4.11). Further measurement of stem Ψ, in line with pre-dawn Ψ, would probably have shown the same significant difference as pre-dawn Ψ.

Grapevine vigour as a covariant did not have any significant effect on the stem Ψ of the classifications ($P>0.05$), as with pre-dawn Ψ.

Table 4.5 ANOVA of the effect of water deficit and vigour on stem water potential.

	DF	F	p
Pruning mass (kg)	14	0.02	p >0.05
Classifications	10	2.88	p >0.05
Date*Classifications	14	2.22	p >0.05

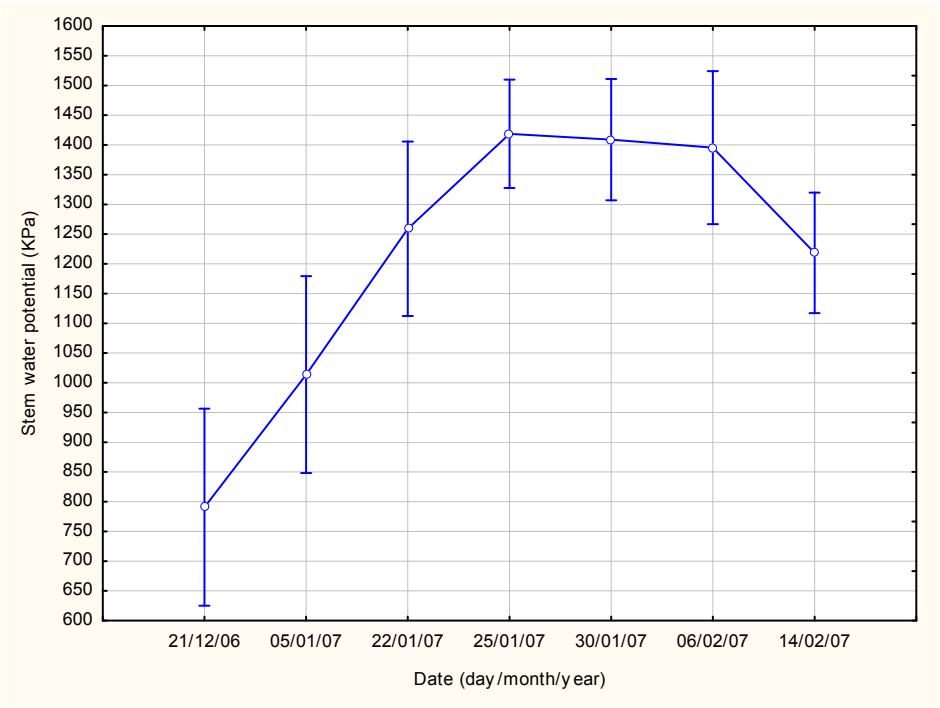

Figure 4.10 Graph showing least squares (LS) means of the combined stem Ψ for both classifications at the various measurement dates (Vertical bars denote 0.95 confidence intervals) (P≤0.01).

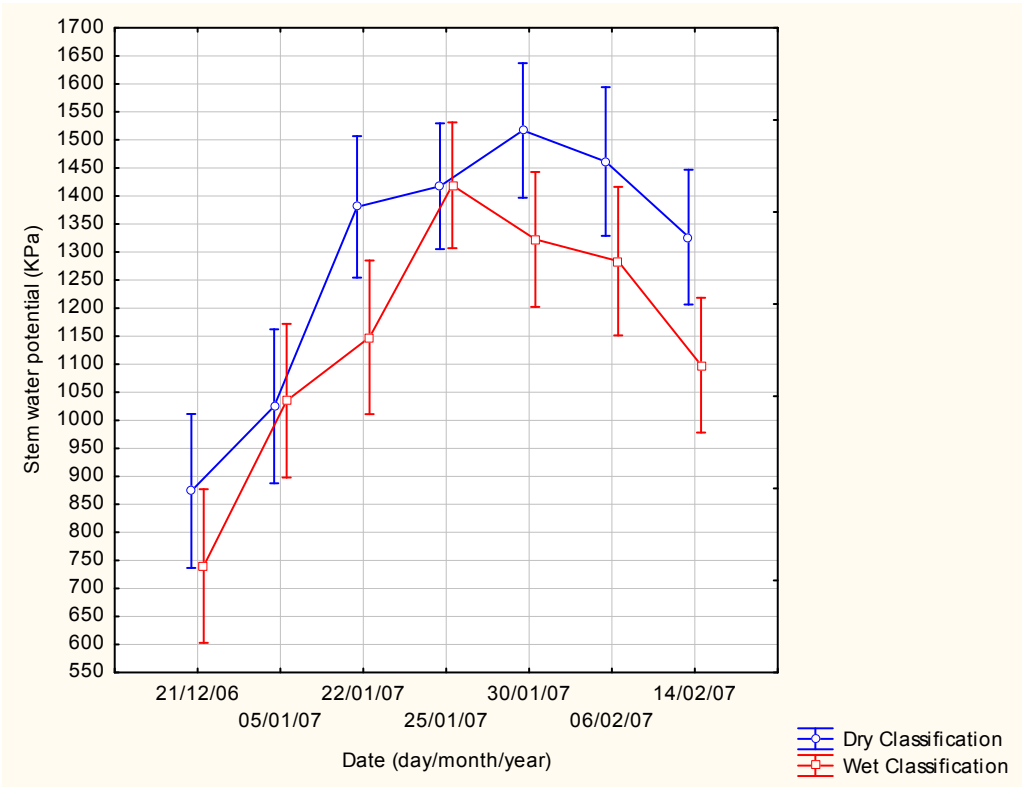

Figure 4.11 Graph showing least squares (LS) means of the individual stem Ψ for the two classifications at the various measurement dates (Vertical bars denote 0.95 confidence intervals) (P≥0.05).

4.4 VEGETATIVE CHARACTERISTICS

4.4.1 LEAF AREA MEASUREMENTS

Leaf area measurements were conducted at various plots, at the end of the vegetative growth cycle, throughout the vineyard. The selection of these plots were based on the multispectral aerial image, which were used in the beginning of the season to differentiate between three relative vigour zones, high-, medium- and low vigour. The aim of leaf area measurements was mainly to collect ground truth data, to be used to calibrate the NDVI image and to quantify vigour variation at the end of vegetative growth. Thus, to establish the degree of vigour variation during the season as opposed to later in the season when pruning mass measurements at dormancy are used to indicate vigour variability. However, the vineyard was mechanically topped before leaf area could be measured, which could have an effect on the outcome of leaf measurements. The topping actions were also not conducted throughout the whole vineyard by the producer, as it was mainly focused on the areas with relative higher vigour that has overgrown the trellising system.

Statistical analyses showed that the canopy management had no significant effect on the number of laterals and the total lateral length measured on the canes during pruning, but it did have the obvious effect on the main cane length and total cane weight (main plus lateral canes)(data shown later). However after reclassification Table 4.6 shows that the outcome of the classification effect on the parameters measured was not influenced by the canopy management. This explain why there were still a correlation between pruning mass and total main leaf area (r^2=0.3876 and r=0.6226, P≤0.1) as well as pruning mass and total lateral leaf area (r^2=0.4239 and r=0.6511, P≤0.1) despite the topping action.

If only plot 1 and plot 8 is assessed (reclassified as plot D1 and plot W1 respectively in Table 4.1), which are laid out in acutely differing vigour areas it becomes apparent that ground truth data do validate the trends exhibited by the NDVI aerial image. On the aerial image plot 1 is classified as high vigour and plot 8 as low vigour. An ANOVA of pruning mass for these two plots corresponds with the image classification (Fig. 4.12). The same result was obtained in a study by Dobrowski *et al*. (2003) where aerial image analysis was utilised to predict dormant pruning weights.

Table 4.6 ANOVA of the effect of canopy management on the outcome of the classifications on cane mass , cane length, total internodes, total laterals and total lateral length.

		MS	F	p
Classification*Canopy management	Cane mass	0.01	0.35	p >0.05
	Cane Length	40.14	0.21	p >0.05
	Total Internodes	0.99	0.16	p >0.05
	Total Laterals	0.14	1.57	p >0.05
	Total Lateral Length	0.06	0.01	p >0.05

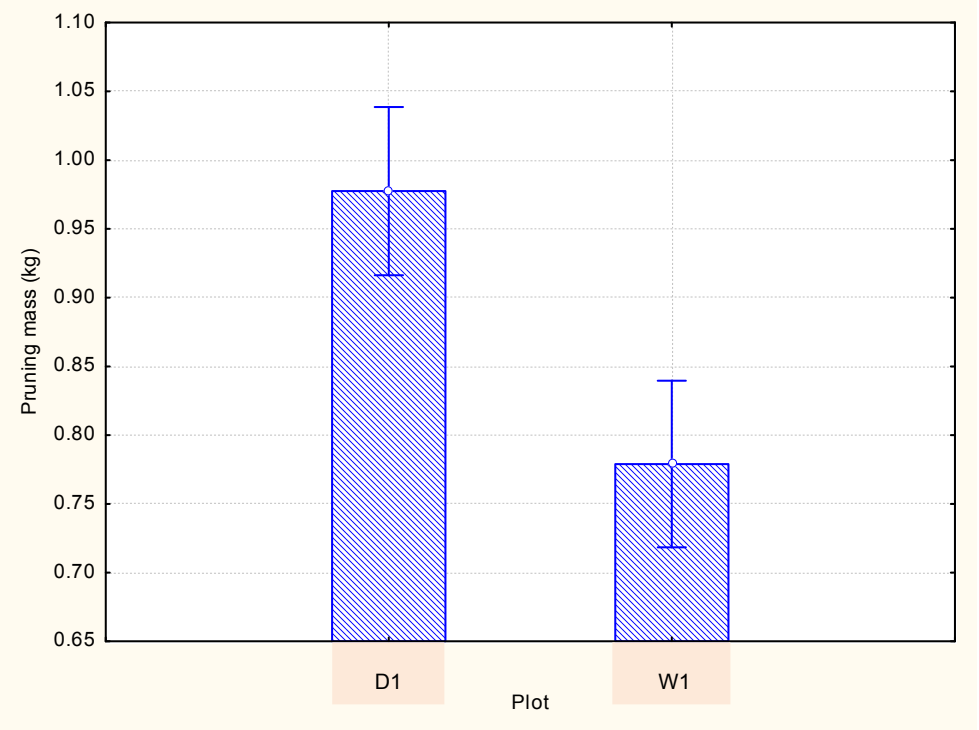

Figure 4.12 One way ANOVA of the pruning mass for plot D1 and plot W1 (Vertical bars denote 0.95 confidence intervals) (P≤0.01).

Total leaf area also corresponded to the pruning mass (Fig. 4.13) and this support the theory that vigour can already be differentiated during or at the end of vegetative growth, it is however not clearly visible where the vigour differences are less significant.

Total leaf area by definition is made up out of multiple components which are associated with the grapevine, its shoots and leaves, and its arrangement in space, as provided by the trellising system. The various components of leaf area do not always complement each other and must therefore also be individually evaluated. In Fig. 4.14 it is evident that the average main leaf area (leaf size) per shoot confirms the trend previous seen, however Fig. 4.15 shows the opposite outcome than expected. The larger lateral leaves of plot W1 did not have a substantial effect on the lateral leaf area per shoot (Fig. 4.16). This is due to the fact that plot D1 had a lot of small lateral leaves, compared to plot W1 which had a fewer but larger leaves. The total main and lateral leaf area per grapevine for plot D1 and plot W1 is shown in Fig. 4.17. As with pruning mass, the leaf area of plot D1 and plot W1 corresponds with the multispectral image.

Leaf area per grapevine also indicates a possible correlation with the NDVI values taken for these plots. Derived as the ratio of canopy leaf surface area to vineyard ground surface area, leaf area index (LAI) has previously been directly correlated to NDVI values (Hall *et al*., 2008).

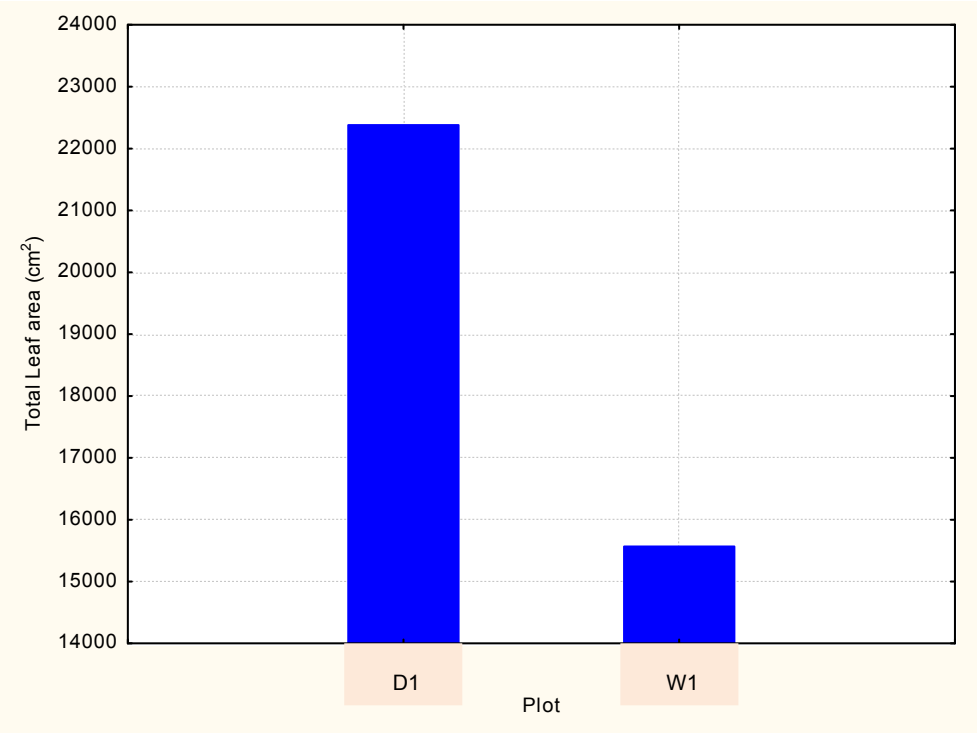

Figure 4.13 One way ANOVA of the total leaf area for plot D1 and plot W1.

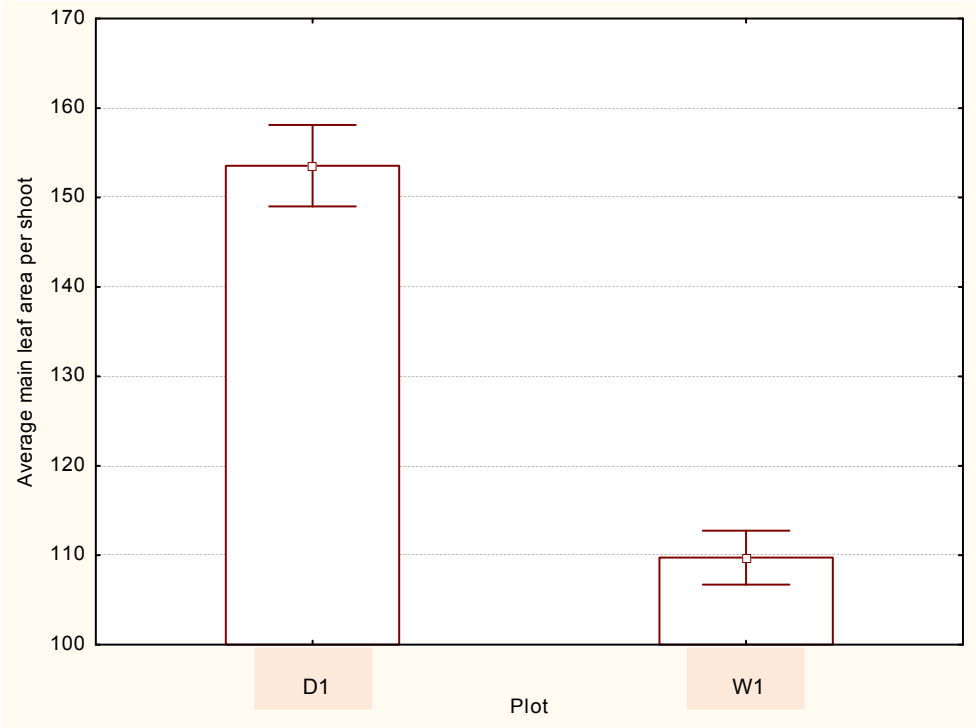

Figure 4.14 Means with error plot of the average main leaf area per shoot for plots D1 and W1 (Vertical bars denote 0.95 confidence intervals).

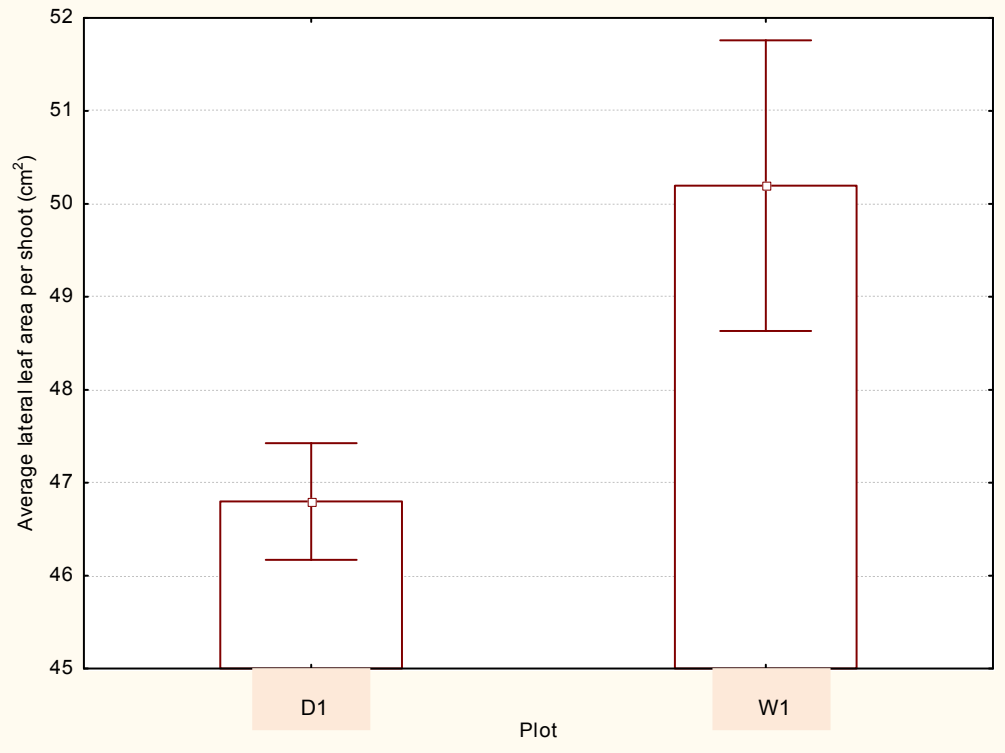

Figure 4.15 Means with error plot of the average lateral leaf area per shoot for plot D1 and plot W1 (Vertical bars denote 0.95 confidence intervals).

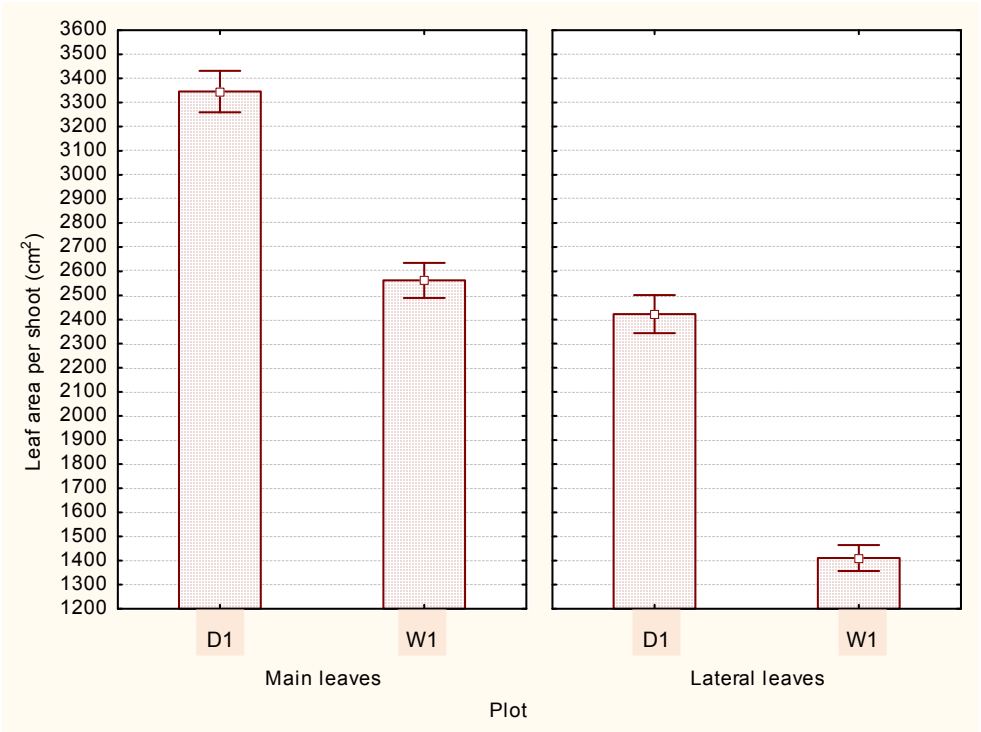

Figure 4.16 Means with error plot of the total main leaf area and total lateral leaf area per shoot for plot D1 and plot W1 (Vertical bars denote 0.95 confidence intervals).

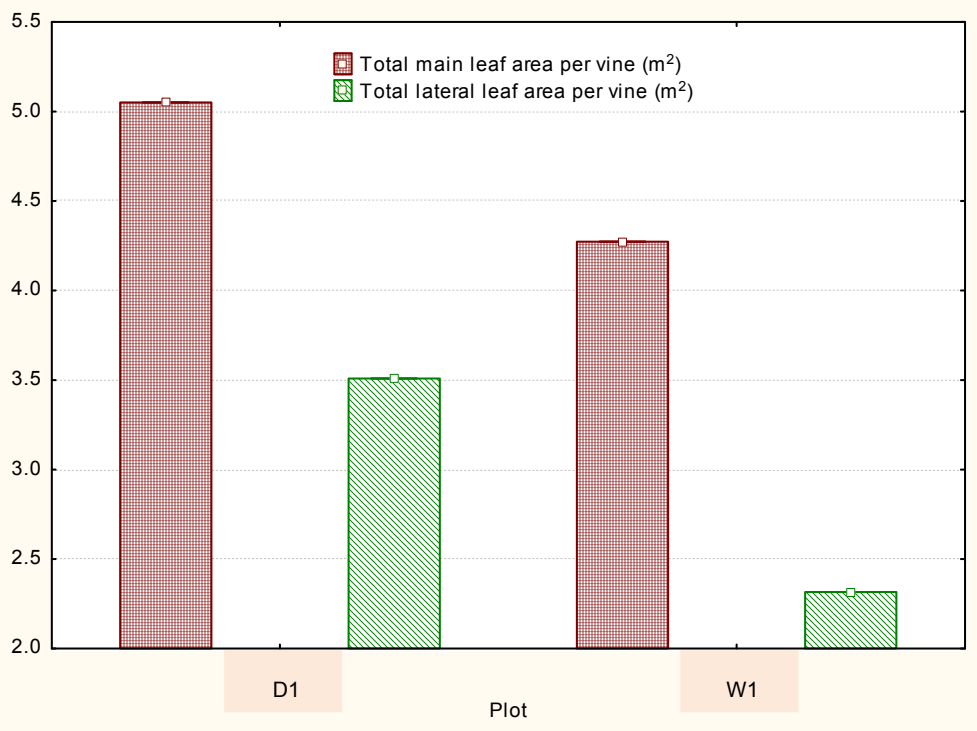

Figure 4.17 The total main leaf area and total lateral leaf area per grapevine for plot D1 and plot W1.

4.4.2 CANE MEASUREMENTS

The pruning mass of each grapevine at every plot were determined to establish the within vineyard variation at the end of the season. During these measurements canes were sampled and cane weight, length (main and lateral), internode length, node number and diameter were determined. After reclassification the total cane weight of the wet classification were significantly higher than that of the dry classification (Table 4.7). This trend was also seen when the average weight per cane were evaluated (Fig. 4.18). Consequently the total pruning mass of the plots that make up the wet and dry classifications were also significantly different. This ANOVA could imply that the irrigation applied as treatments could have affected grapevine vigour, in that a decreased water deficit led to a higher cane/pruning mass. However, Table 4.7 indicates that grapevine vigour as a covariate had an effect on the measured cane weight and length. But vigour was not influential on the outcome of the lateral canes. The wet classification did also have significantly more and longer lateral canes than the dry classification (Table 4.7). These higher numbers of lateral canes measured at the wet classification plots were also a complementing factor to the variance exhibited in pruning mass. The measurements of total number of internodes and the cane diameter at the top, middle and bottom did not show any significant difference between the classifications.

Table 4.7 ANOVA of the effect of water deficit and vigour on cane mass, cane length, total internodes, total laterals and total lateral length.

		MS	F	p
Pruning mass (kg)	Total Cane Mass	0.50	17.33	p < 0.01
	Total Cane Length	1178.98	6.28	p < 0.05
	Total Internodes	7.69	1.27	p >0.05
	Total Laterals	0.09	1.07	p >0.05
	Total Lateral Length	10.90	1.24	p >0.05
Classifications	Total Cane Mass	0.29	10.14	p < 0.05
	Total Cane Length	475.91	2.53	p >0.05
	Total Internodes	5.04	0.83	p >0.05
	Total Laterals	0.62	7.15	p < 0.05
	Total Lateral Length	69.43	7.88	p < 0.05

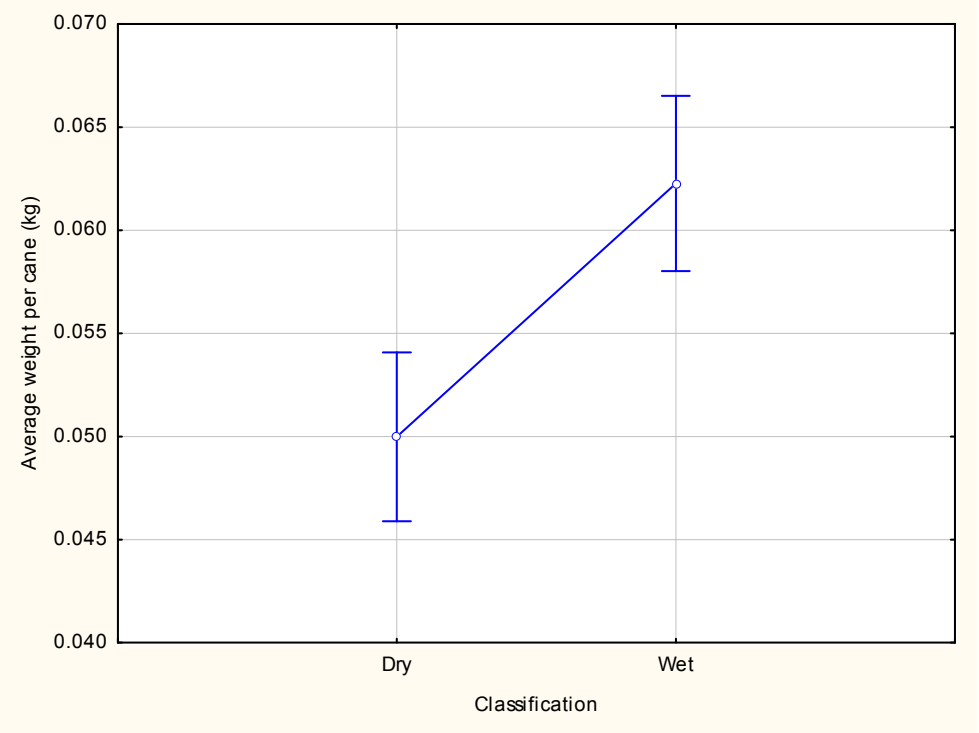

Figure 4.18 Graph showing least squares (LS) means of the average weight per cane for both classifications (Vertical bars denote 0.95 confidence intervals) (P≤0.01).

4.5 REPRODUCTIVE CHARACTERISTICS

4.5.1 BERRY ANALYSIS

4.5.1.1 Berry development

The classification (treatment effect) and vigour influence on berry development were evaluated at various dates during the season. The combined average berry weight for both classifications, as measured during the season is shown in Fig. 4.19.

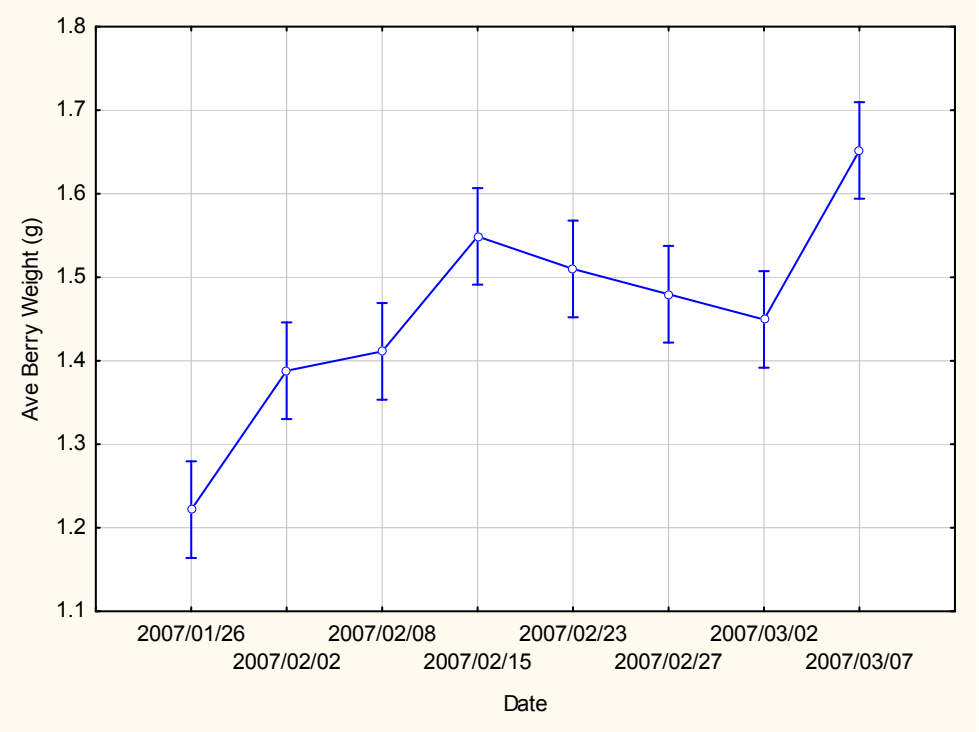

Figure 4.19 Graph showing least squares (LS) means of the combined average berry weight for the two classifications at the various measurement dates (Vertical bars denote 0.95 confidence intervals) (P≤0.01).

The total seasonal average berry weight for each of the classifications showed that there was a significant increase in berry weight from the dry classification to the wet classification (Table 4.8). Berry volume responded the same as berry weight but was not significant according Table 4.8. However, the graph of berry volume (Fig. 4.20) showed that the variation was high between the wet and dry classification. These outcomes in berry parameters are as expected, seeing that an increase in plant available water (PAW) and a decrease in plant water deficit contributes to larger grape berries. In the Breede River valley, irrigation at 75% PAW depletion throughout the season significantly reduced berry mass of Colombar grapevines in loamy soil compared to 30% and 50% PAW depletion (Van Zyl, 1984).The correlation between the classifications and average berry weight (r^2=0.2006 and r=0.4479, P≤0.01), and the correlation between berry volume (r^2=0.1855 and r=0.4307, P≤0.01) and the classifications corresponded well to the correlation found between berry weight at harvest and the average pre-dawn Ψ during the

season for the various classification plots (r^2=0.2839 and r=-0.5328, P≤0.01) (correlation data not shown).

However, when vine vigour as covariate was included in the statistical analyses it became apparent that the variation in average berry size is mainly a factor of grapevine vigour (Table 4.8). This indicates that vigour was the main cause of the variation, but it does not mean that influence of the plant water status of the grapevines should be ignored.

Table 4.8 ANOVA of the effect of water deficit and vigour on average berry weight and berry volume.

		DF	F	p
Pruning mass (kg)	Ave berry weight	83	11.77	p < 0.01
	Berry volume	83	11.58	p < 0.01
Classifications	Ave berry weight	12	4.94	p < 0.05
	Berry volume	12	3.81	p >0.05
Date*Classifications	Ave berry weight	83	0.64	p >0.05
	Berry volume	83	0.43	p >0.05

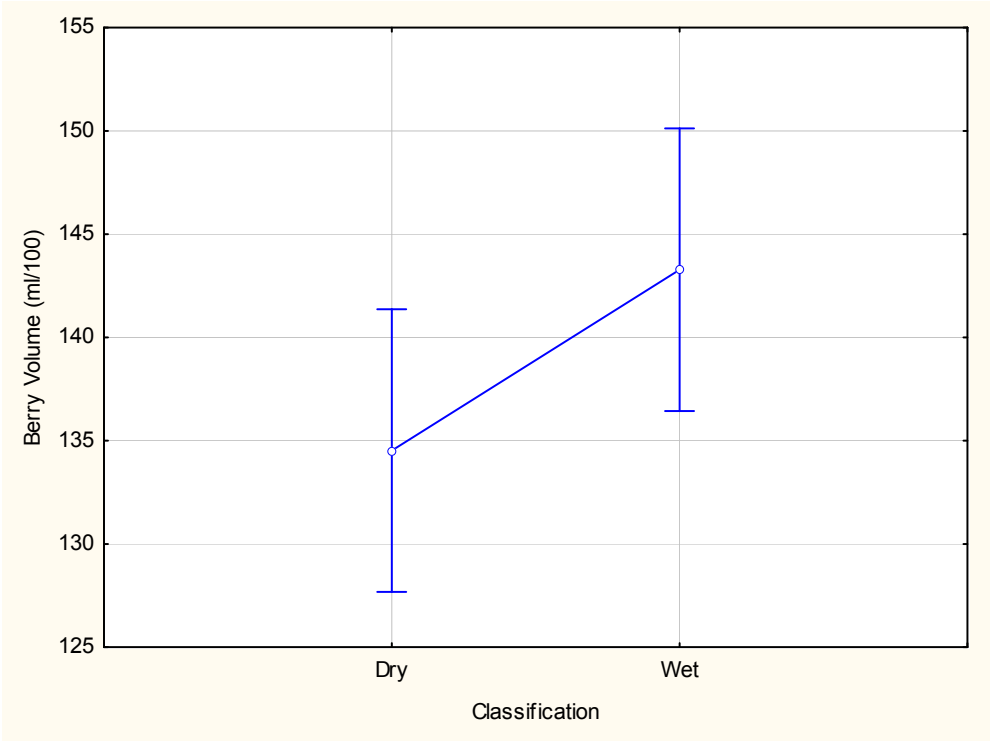

Figure 4.20 Graph showing least squares (LS) means of berry volume for the classifications established (Vertical bars denote 0.95 confidence intervals) (P≥0.05).

4.5.1.2 Berry composition

Grape ripening analysis was done on the grape samples collected throughout the season. Grape juice from these samples were also analysed with the FOSS® grapescan. The seasonal total soluble solid content of the classifications showed a slight trend of lower TSS content for dry classification compared to the wet classification. However, it was only at one measuring date that the classifications showed a significant difference. The slight trend at the end of the season could be ascribed to the fact that the berries of the dry classification were smaller with less juice (Table 4.8). The berries of the dry classification could also have lost water through transpiration during the latter part of the season as the water deficit of the grapevines increased, while the wet classification berries were supplied with sufficient water. A relative measurement was used to compensate for the differences in berry mass, namely the sugar per berry. The trend of this measurement was the opposite of the TSS content, as the wet classification tended to have higher sugar content per berry weight than the dry classification (Fig. 4.21). According to Myburgh (2009) severe water deficits can inhibit sugar accumulation. The measurement compensated for the variation in berry size, seeing that it is indicative of the amount of sugar actually loaded into the berries. The grapevines of the wet classification that did not experience mild water deficits possibly induced better sugar loading into the berries, seeing that the leaves could have had a better physiological efficiency (Kliewer and Dokoozlian, 2005). In Table 4.9 it is shown that vigour also had a significant effect on the sugar per berry measured. The generally higher vigour of the wet classification grapevines would be the main cause. The possible combined effect of larger berries and the higher sugar content per berry found at the wet classification should also result in a higher degree of balling at harvest. Van Zyl (1984) also found that the sugar content of berries increased with continued irrigations at limited quantities during the ripening period.

There was a significant difference in juice pH between the classifications ($P<0.05$), the low water deficit of the wet classification had a positive (decreasing) effect on berry pH. This resulted in the berry pH of the dry classification to be significantly higher than that of the wet classification (Fig. 4.22). The lower pH of the wet classification was visible as from 8 February 2007 until the end of the season. The vigour of the grapevines did not contribute to the pH effect (Table 4.9). It is recognized that a high water deficit may affect the chemical breakdown or formation of important berry acids that contribute to berry pH (Sivilotti *et al*., 2005).

The total acidity (TA) differences were not significant. It was expected that the wet classification would have a higher TA content in the berries, as was found by Esteban et al. (1999) and Smart and Coombe (1983). Vigour did however have a significant influence on the total acid (TA) of the berries (Table 4.9). This can be due to the shading-induced increase in TA in high vigour grapevines.

The FOSS® data in Table 4.10 also indicated that the berries of the dry classification had a higher pH than the berries of the wet classification. The FOSS® measurement of malic acid showed a significant difference, with the wet classification having a higher amount. Carbonneau (1995) also found that excess shade in higher vigour vines decrease the levels of tartaric acid and increase that of malic acid in grape berries. As shown earlier the higher vigour (shaded canopies) were encountered at the grapevines of the wet classification. Tartaric acid tended to be lower in the berries of the wet classification but it was not significant. Pruning mass as a covariate however showed that vigour affected the measurement. The significantly higher total phenols (OD 280) and total red pigment content (OD 520) of the dry classification berries could be due to the smaller berries of this classification at harvest. It also seems that the berries of the dry classification had a higher nitrogen contents in the form of ammonium and alpha amino nitrogen. Myburgh (2006) also found that the nitrogen concentration in grape juice decreased with irrigation applied continuously during grape ripening.

Table 4.9 ANOVA of the effect of water deficit and vigour on sugar per berry, pH and total acid per berry.

		DF	F	p
Pruning mass (kg)	Sugar per berry	83	6.73	$p < 0.05$
	pH	83	0.04	$p > 0.05$
	Total acid (TA)	83	20.53	$p < 0.01$
Classifications	Sugar per berry	12	2.79	$p > 0.05$
	pH	12	7.28	$p < 0.05$
	Total acid (TA)	12	0.53	$p > 0.05$
Date*Classifications	Sugar per berry	83	0.88	$p > 0.05$
	pH	83	1.19	$p > 0.05$
	Total acid (TA)	83	0.71	$p > 0.05$

Table 4.10 ANOVA of the effect of water deficit and vigour on FOSS grape parameters.

		DF	F	p
Pruning mass (kg)	Glucose-Fructose	71	3.53	p >0.05
	Density	71	1.96	p >0.05
	Total Acid	71	35.73	p < 0.01
	pH	71	0.17	p >0.05
	Tartaric Acid	71	4.83	p < 0.05
	Malic Acid	71	86.07	p < 0.01
	Volatile Acid	71	4.70	p < 0.05
	Folin C index	71	1.72	p >0.05
	OD 280	71	1.80	p >0.05
	OD 520	71	0.17	p >0.05
	Colour Intensity	71	0.11	p >0.05
	Anthocyanins	71	7.23	p < 0.01
	Ammonia	71	1.54	p >0.05
	Alpha Amino Nitrogen	71	0.13	p >0.05
Classifications	Glucose-Fructose	12	0.05	p >0.05
	Density	12	0.01	p >0.05
	Total Acid	12	2.59	p >0.05
	pH	12	16.82	p < 0.05
	Tartaric Acid	12	1.49	p >0.05
	Malic Acid	12	14.94	p < 0.01
	Volatile Acid	12	21.70	p < 0.01
	Folin C index	12	13.41	p < 0.01
	OD 280	12	20.00	p < 0.01
	OD 520	12	13.27	p < 0.01
	Colour Intensity	12	2.02	p >0.05
	Anthocyanins	12	0.20	p >0.05
	Ammonia	12	5.24	p < 0.05
	Alpha Amino Nitrogen	12	14.34	p < 0.01
Date*Classifications	Glucose-Fructose	71	0.21	p >0.05
	Density	71	0.25	p >0.05
	Total Acid	71	0.54	p >0.05
	pH	71	0.95	p >0.05
	Tartaric Acid	71	1.44	p >0.05
	Malic Acid	71	0.38	p >0.05
	Volatile Acid	71	2.57	p < 0.05
	Folin C index	71	0.17	p >0.05
	OD 280	71	0.41	p >0.05
	OD 520	71	0.51	p >0.05
	Colour Intensity	71	0.76	p >0.05
	Anthocyanins	71	1.73	p >0.05
	Ammonia	71	0.29	p >0.05
	Alpha Amino Nitrogen	71	0.14	p >0.05

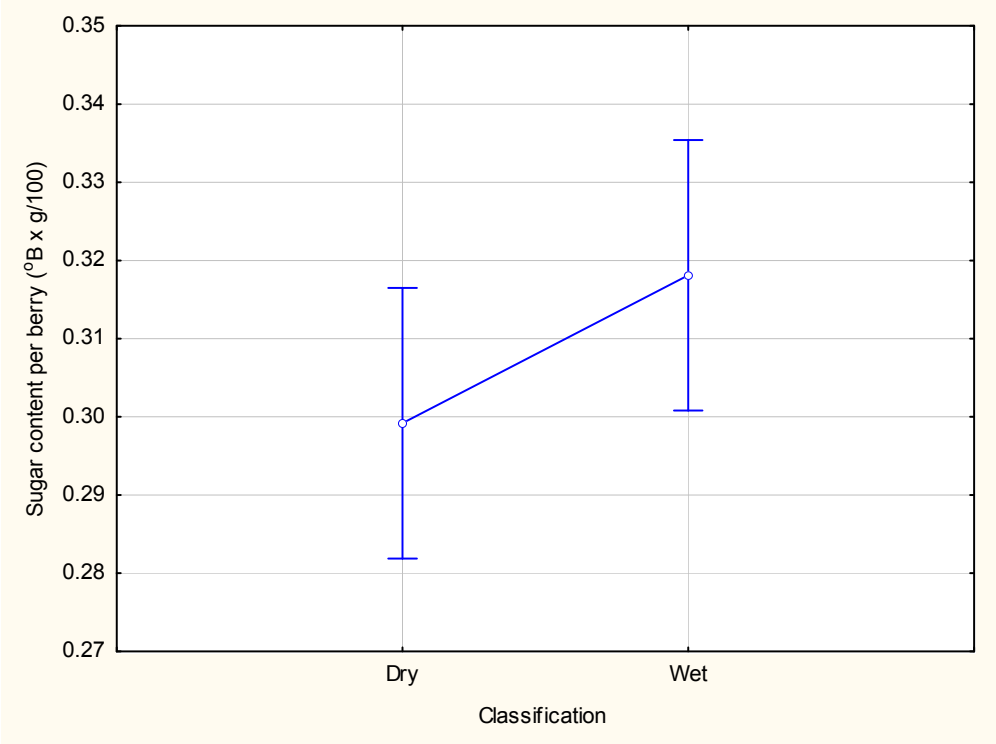

Figure 4.21 Graph showing least squares (LS) means of sugar content per berry for the classifications established (Vertical bars denote 0.95 confidence intervals) (P≥0.05).

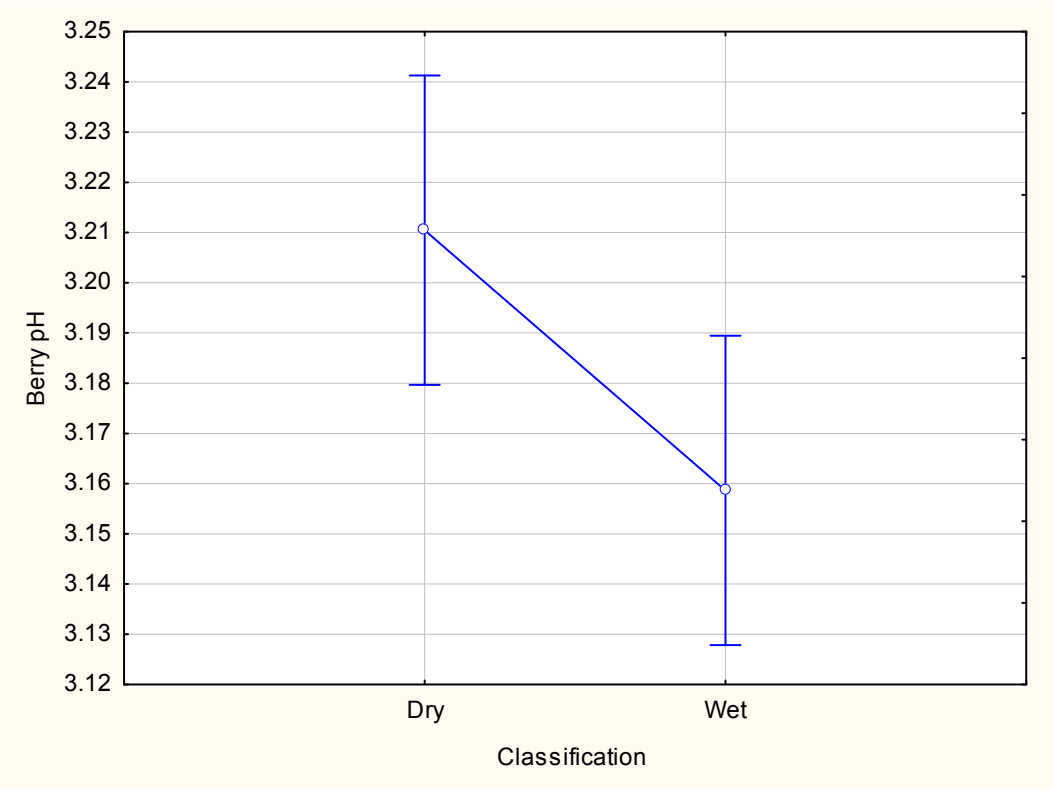

Figure 4.22 Graph showing least squares (LS) means of berry pH for the classifications established (Vertical bars denote 0.95 confidence intervals) (P≤0.05).

4.5.2 HARVEST MEASUREMENTS

Measurements of yield, bunch weight and average berry size at harvest gave an indication of how the plant water status and vigour variation affected the reproductive growth of the grapevines. The total seasonal effect on the grapes can be evaluated from these results. The yield measurements (Fig. 4.21) indicated that the grapevines of the wet classification had the highest yield per grapevine. The measurement of yield is a combination of bunch number per grapevine and the weight of these bunches. The average bunch weight at harvest of the classifications showed the same tendency as yield per grapevine, but the significance between classifications was increased. The number of berries and consequent bunch weights of the wet classification were significantly more/higher than the dry classification. The average weight per berry was also significantly higher for the wet classification (Table 4.11). The grapevine vigour (covariate) contributed significantly to the outcome of each of these yield parameters. Berry weight and volume has been shown to increase with an increase in grapevine vigour (Smart *et al.*, 1985), as was the case during this study. The number of bunches per grapevine were not different for the classifications (Table 4.12). Even though all the mentioned parameters showed significant differences the end difference in yield was not significant between classifications (Fig. 4.21).

The classification of the plots indicates that plant water status did also have an effect on the outcome. The increase in yield from the wet- to dry classification can be linked to possible higher soil water content and lower grapevine water deficits in the wet classification grapevines, compared to the dry classification grapevines. Grapevine water status as a factor of average bunch weight was evaluated by using the average seasonal stem water potential (SWP). Average bunch weight are definitely affected by the water status of the grapevine, as seen by a correlation between average SWP and bunch weight (r^2=0.2496 and r=-0.4996, P≤0.1) (data not shown). Myburgh (2005) also mentioned that yield can be affected by soil moisture content (irrigation) and grapevine water status. However, correlations between grapevine pruning mass and yield (r^2=0.4943 and r=0.7030, P≤0.01) (data not shown) indicated that vigour also had an effect on the mass of grapes produced by the grapevines. The more vigorous grapevines correlated strongly with a higher yield, which confirms observations by Smart *et al.* (1985a). These correlations are in line with the results shown in Table 4.11.

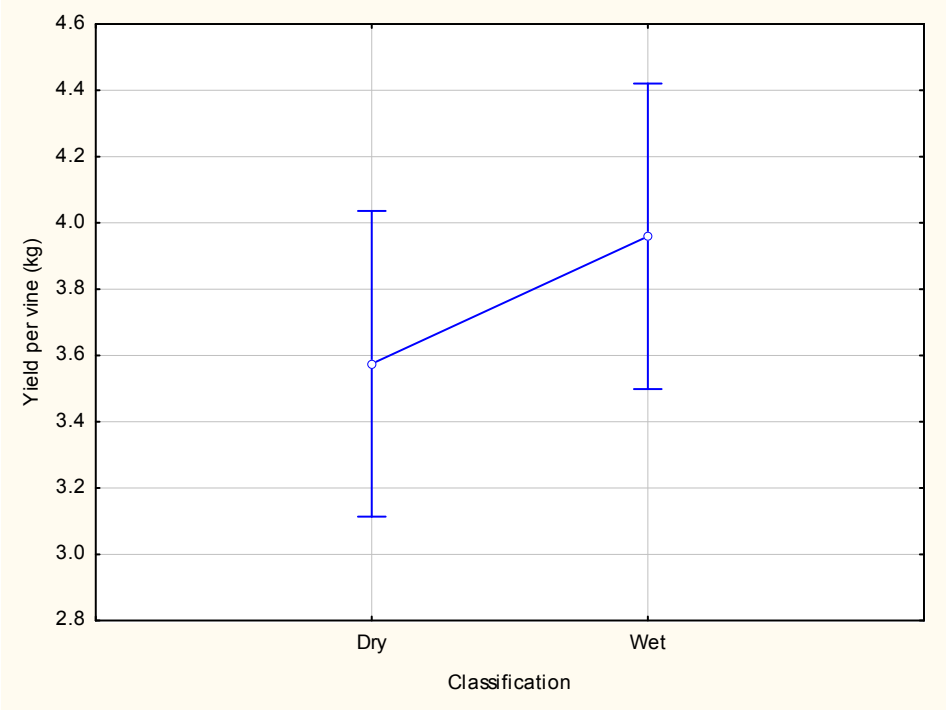

Figure 4.23 Graph showing least squares (LS) means of yield per vine for the classifications established (Vertical bars denote 0.95 confidence intervals) (P≥0.05).

Table 4.11 ANOVA of the effect of water deficit and vigour on bunch weight, total number of berries per vine, total berry weight and average berry weight.

		MS	F	p
Pruning mass (kg)	Bunch weight	5178.80	15.89	p < 0.01
	Berry count	749.69	7.01	p < 0.05
	Total berry weight	5057.08	15.84	p < 0.01
	Average berry weight	0.13	22.46	p < 0.01
Classifications	Bunch weight	2914.20	8.94	p < 0.05
	Berry count	553.60	5.18	p < 0.05
	Total berry weight	2729.93	8.55	p < 0.05
	Average berry weight	0.04	7.75	p < 0.05

Table 4.12 ANOVA of the effect of water deficit and vigour on the total number of bunches per vine.

	MS	F	p
Pruning mass (kg)	178.22	21.41	p < 0.01
Classifications	0.18	0.02	p >0.05

4.6 MICROVINIFICATION

4.6.1 WINE CHEMICAL ANALYSES

FOSS® wine scan (FT-IR spectroscopy) and gas chromatography-flame ionisation detector (GC-FID) analyses were performed on all the wines produced from microvinification. The significance between the classifications for the parameters analysed were evaluated with and without the covariant and the influence of the covariant is also indicated. The FOSS® data is calibrated for routine analyses performed by winemakers to evaluate the final product or to make adaptations. The analysis showed no large differences between most of the parameters analysed, except for pH, total acid and malic acid (Table 4.13). The outcomes of the other parameters measured are not shown. Wine pH showed the same significant outcome as seen during the berry analyses (Fig. 4.24). The pH of the wet classification wines was significantly lower than that of the dry classification wines. The FOSS® wine scan also indicated that there is a significant tendency for malic acid to be higher in the wet classification wines than in the dry classification wines (Fig. 4.25). This outcome is also in line with the results found during berry composition analysis. The expected outcome of Total acid (TA) as discussed under berry composition was seen during wine analyses. The wines of the wet classification had a significantly higher TA concentration than the wines of the dry classification (Fig. 4.27). The significantly higher total phenols (OD 280) and total red pigment content (OD 520), as persieved via the grapescan, of the dry classification was not reflected during wine chemical analyses.

Table 4.13 ANOVA of the effect of water deficit and vigour on FOSS wine parameters.

		MS	F	p
Pruning mass (kg)	pH	0.02	15.39	$p < 0.01$
	Total acid	0.24	18.89	$p < 0.01$
	Malic acid	0.04	1.99	$p > 0.05$
Classification	pH	0.01	9.17	$p < 0.05$
	Total acid	0.07	5.23	$p < 0.05$
	Malic acid	0.12	5.24	$p < 0.05$

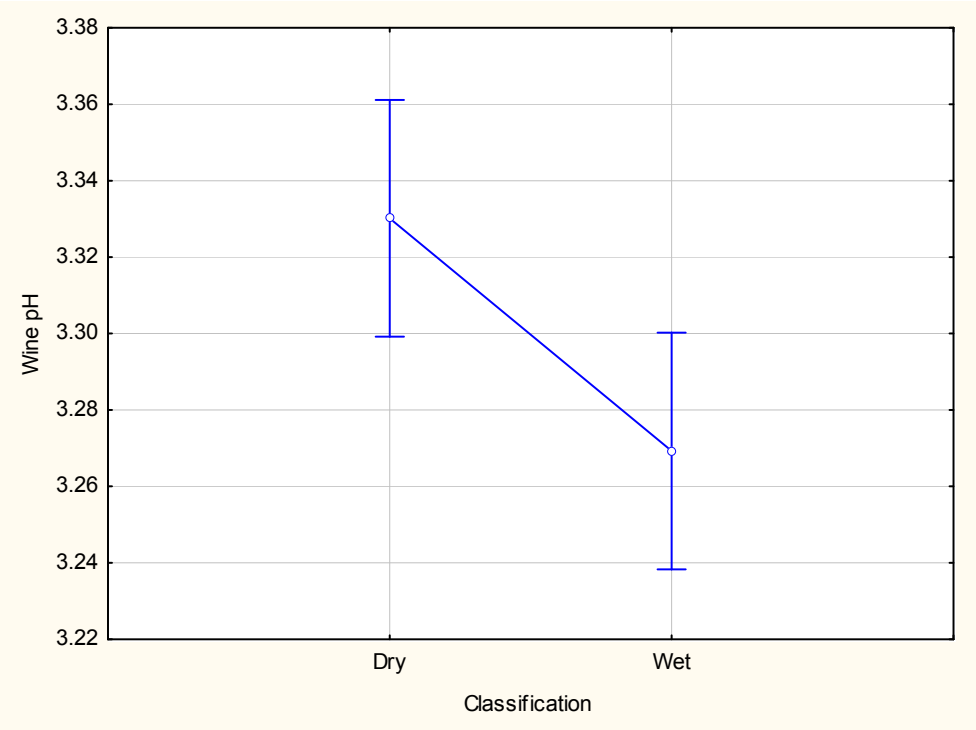

Figure 4.24 Graph showing least squares (LS) means of wine pH for the classifications established (Vertical bars denote 0.95 confidence intervals) (P≤0.05).

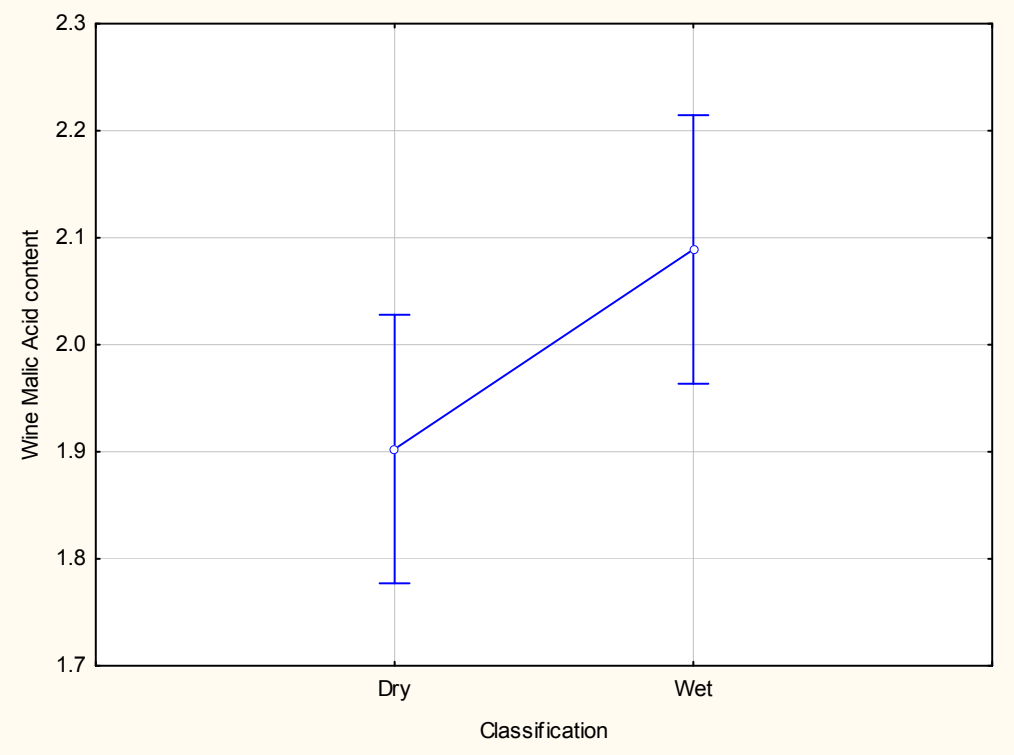

Figure 4.25 Graph showing least squares (LS) means of wine pH for the classifications established (Vertical bars denote 0.95 confidence intervals) (P≤0.05).

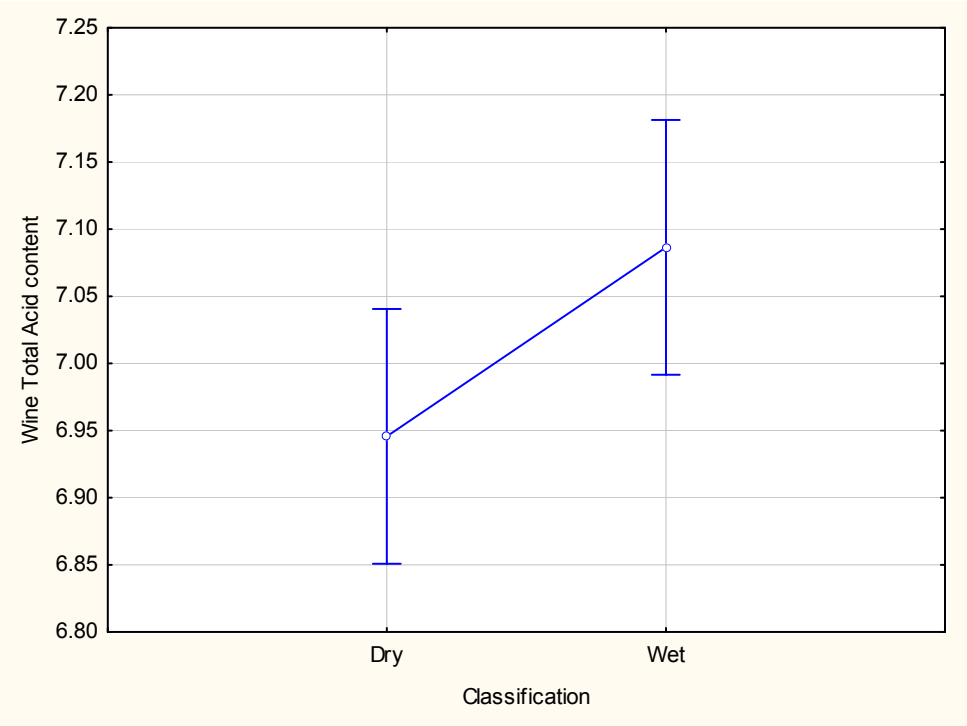

Figure 4.26 Graph showing least squares (LS) means of wine pH for the classifications established (Vertical bars denote 0.95 confidence intervals) (P≤0.05).

Wine volatile components present in the wine are quantified with GC-FID analyses. As with some of the the FOSS® data the volatile components present in the wines showed no great variance among classifications. The odour active values of each component were also compared to see if the threshold values of each component would be influential, but the results were similar (Tao *et al*., 2008). Only the components that showed a significant variation between the classifications and there corresponding aroma compounds are summarised in Table 4.14. The Ethyl Acetate, Butanol, Propionic Acid and Valeric Acid concentration in the dry classification wines were significantly higher than in the wet classification wines. The concentrations of Ethyl Lactate and Iso-Butyric Acid were significantly higher in the wet classification wines.

Table 4.14 ANOVA of the effect of water deficit and vigour on GC-FID wine parameters.

		MS	F	p
Pruning mass (kg)	Ethyl Acetate	16.48	0.09	p >0.05
	Butanol	0.00	0.00	p >0.05
	Ethyl Lactate	32.24	14.50	p < 0.01
	Propionic Acid	0.40	0.59	p >0.05
	Iso-Butyric Acid	0.00	0.02	p >0.05
	Valeric Acid	0.00	3.91	p >0.05
Classification 2	Ethyl Acetate	992.69	5.70	p < 0.05
	Butanol	0.10	6.18	p < 0.05
	Ethyl Lactate	26.96	12.13	p < 0.01
	Propionic Acid	3.65	5.42	p < 0.05
	Iso-Butyric Acid	0.24	7.49	p < 0.05
	Valeric Acid	0.00	7.57	p < 0.05

Componets	Aroma compound
Ethyl Acetate	apple, pineapple
Butanol	pharmaceutical
Ethyl Lactate	butter
Propionic Acid	rancid, slight pungent
Iso-Butyric Acid	rancid, butter, cheese
Valeric Acid	no reverence

4.6.2 WINE SENSORY ANALYSIS

In spite of the restrictions found during sensorial assessment, it is regarded as the ultimate test to evaluate the success of a particular irrigation strategy. According to Myburgh (2009) wine sensory analysis should be preferred to indirect quality assessments based only on berry size or the chemical composition of juice or wine. Regrettably the results obtained during this study from the tasting panel did not differentiate the wines of the various classifications before or after reclassification. The classifications showed no indication of difference in any of the components selected for sensory analysis of Merlot. This however, does not mean that the plant water status or vigour did not have an effect on the wine subsequently produced. Various factors were influential during the tasting that could have possibly skewed this data. The sensory evaluation of wine showed to be a more complex exercise than anticipated. The tasters showed high variation among each other, regarding the evaluation of the wine components, even though they seemed to show little variation between own tasting replications. Not even the wine volatile components quantified with GC-FID analyses that were above their threshold values corresponded with remarks made by the tasters. The unstructured line scales used could be the main cause of this, not the training (which was performed in separate sessions with examples of typical sensory attributes before the tasting) or tasting

ability of the panel. The variation in component evaluation among tasters is seen in Fig. 4.27. The graph indicates how each of the tasters evaluated the specific component for all the wines he or she tasted. It is important to note that the tasters all perceive the component in a personal (subjective) range as indicated via the confidence intervals on the graph (vertical bars denote 0.95 confidence intervals). Taster 2 indicated that a high range for this component is around 30% and a low range of 24%, where as taster 5 has a high range of 19% and a low range of 13% for the same component. These two tasters are relatively in the same evaluation range, but if taster 7 with the lowest range is compared to taster 6 with the highest range the variation becomes extensive.

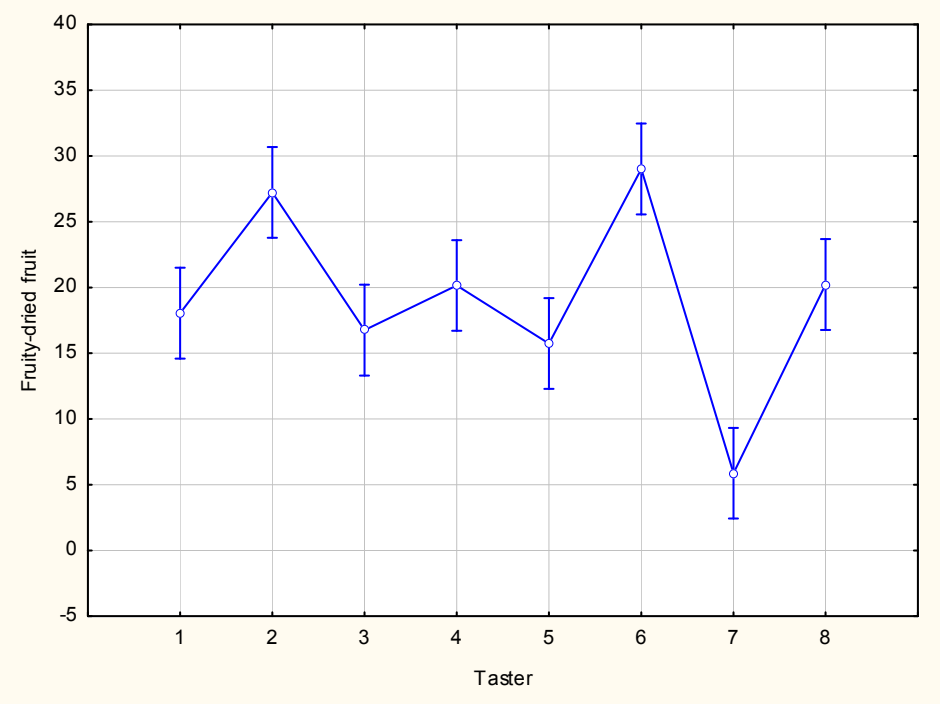

Figure 4.27 ANOVA computed for covariates at their means of the component: fruity-dried fruit evaluated on all the wines and differentiated among tasters (Vertical bars denote 0.95 confidence intervals) (P≥0.05).

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Chapter 5

GENERAL DISCUSSION AND CONCLUSION

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5.1 GENERAL DISCUSSION AND CONCLUSION

To study the interaction between grapevine vigour and grapevine water status, as this study set out to do, there must be a measurable variation in vigour within the vineyard. The variation must also be quantified to identify the zones where the water status of the grapevines must be altered and consequently validated. Only then it is possible to study the interaction between these two variables. Therefore the first action performed during this study was the collection of multispectral images in January 2006 which were classified using a normalised difference vegetation index (NDVI). These multispectral images were used to define and characterise grapevine vigour variation within the vineyard block. The experimental design was almost completely dependent on the vigour classification obtained from the multispectral images even though visual observations of grapevine vigour at block level were also performed throughout the 2006 season. The multispectral images taken in 2007 after the plots were laid out were used as the main vigour reference at the start of experimentation, seeing that the irrigation regimes were implemented in 2007. The first aim of this study was fully reached with the leaf area and pruning mass measurements at the end of 2007 that corresponded with the arbitrary classifications of the NDVI classification of multispectral images collected during the 2007 growing season. Thus, the relative vigour zones chosen at the hand of the multispectral images corresponded to the vigour data gathered at vineyard level.

The irrigation regimes established in the experimental vineyard were based on plant water status measurements, as it was proposed during the aims. The soil water content and plant water status in reaction to the established irrigation regimes were measured during the season. During the gathering and evaluation of this data it became apparent that the irrigation applied could not be used directly to classify the classifications, as mentioned during the results discussion. Reclassification of the classifications was therefore done to encapsulate the global effect encountered in the vineyard during the experiment. By doing this it was possible to evaluate the response of the grapevines on actual growing conditions, as some complications arose from only considering soil water status by way of neutron count ratios as a factor interacting with vigour. Even though the classifications of the various plots were re-evaluated, the vigour level of each plot were quantified at the end of the season and incorporated into the statistical analyses. The pruning mass was used to quantify the vigour of each plot and it was therefore possible to study the interaction of vigour by using the pruning mass as a covariate during statistical analyses.

The various methods used to establish the vigour of the grapevines corresponded very well with each other. The pruning mass measured at the end of the season correlated well with the leaf

area (main leaves and lateral leaves) of the grapevines during vegetative growth, and it corresponded just as well with the NDVI images taken of vineyard. The pruning mass trend exhibited among the classifications was expected, seeing that a decrease in grapevine water deficit coincides with vigorous growth. However, the classifications did not exactly mimic the vigour variability measured between classifications, probably strongly related to the built-in survival and adaptive mechanisms in the grapevine.

Variation in berry weight and volume signified the response of the grapevine's reproductive growth towards the various classifications. An increase in wetness from one classification to a next correlated with the increase in berry weight and volume. The variation in yield per grapevine and the trend in yield among classifications were indicative of the berry weight and volume. The water status of the grapevine regulated berry development to an extent, as shown by a correlation between berry weight at harvest and average pre-dawn Ψ for the various plots during the season. However, yield also correlated with grapevine vigour (pruning mass). The combining effect of vigour and grapevine water status was responsible for the size of the harvest.

Analyses of the berry composition throughout the season showed statistical variance among the classifications. The wet classification showed a higher sugar content per berry weight than the dry classification, with the covariate (vigour) having a significant influence on the sugar per berry measured. A significant differences was found in juice pH between the classifications ($P<0.05$), the berry pH of the dry classification was higher than that of the wet classification. The FOSS® data (grape scan) also indicated this significance in berry pH. The statistical analyses indicated that vigour did not contribute to the pH of the grapevines. The total acid (TA) content of the grapes showed no variation among the classifications. The grape scan measurement of malic acid showed a significant difference, with the wet classification having a higher amount present in the berries. The same analyse also showed a significantly higher total phenols (OD 280) and total red pigment content (OD 520) in the grapes of the dry classification. It also seems that the berries of the dry classification had a higher nitrogen contents in the form of ammonium and alpha amino nitrogen.

Wine pH showed the same significant outcome as seen during the berry analyses with the wet classification wines having a significantly lower pH than that of the dry classification wines. The FOSS® wine scan indicated that there is a significant tendency for malic acid to be higher in the dry classification wines than in the wet classification wines. This outcome was also in line with the results found during berry composition analysis. The expected outcome of Total acid (TA) as discussed under berry composition was seen during wine analyses. The wines of the wet classification had a significantly higher TA concentration than the wines of the dry classification.

None of the variations found during wine chemical analyses could be differentiated during wine sensory analyses. The classifications also showed no indication of difference in any of the components selected for sensory analysis of Merlot.

Assessment of grapevine vigour, grapevine water status, berry growth and composition within the course of a season, clearly shows maxima and low values at different parts of the season for the various parameters. Since it has been proven that irrigation can affect each of these parameters individually, it can be anticipated that judicious irrigation management could be used as a powerful tool to contain unnecessary and even detrimental grapevine growth and to improve growth of fruit and quality aspects.

The information gathered during this study does not give rise to the practical irrigation strategies necessary to enable wine quality to be optimised for varying combinations of grapevine water status, soil type and vineyard vigour. However, within the scope of this study it became apparent that sub-block irrigation can be used to manipulate areas (grapevines) of a vineyard block, and considering effects on berry size and some grape and wine chemical composition aspects could potentially be used to negate wine style. Differences in grapevine vigour and plant water status due to possible variability in soil water status could be either reduced or deliberately accentuated if irrigation is applied in sub-vineyard block areas. Sub-block irrigation should even be more beneficial if it is implemented during the establishing of a new vineyard block, after analysing soil differences and possible long-term effects on grapevine vigour. However, altering an irrigation system to introduce sub-block irrigation would not always be economical viable for smaller blocks especially if the main viticultural outcome is focused on bulk- rather than quality wine production.

APPENDIX

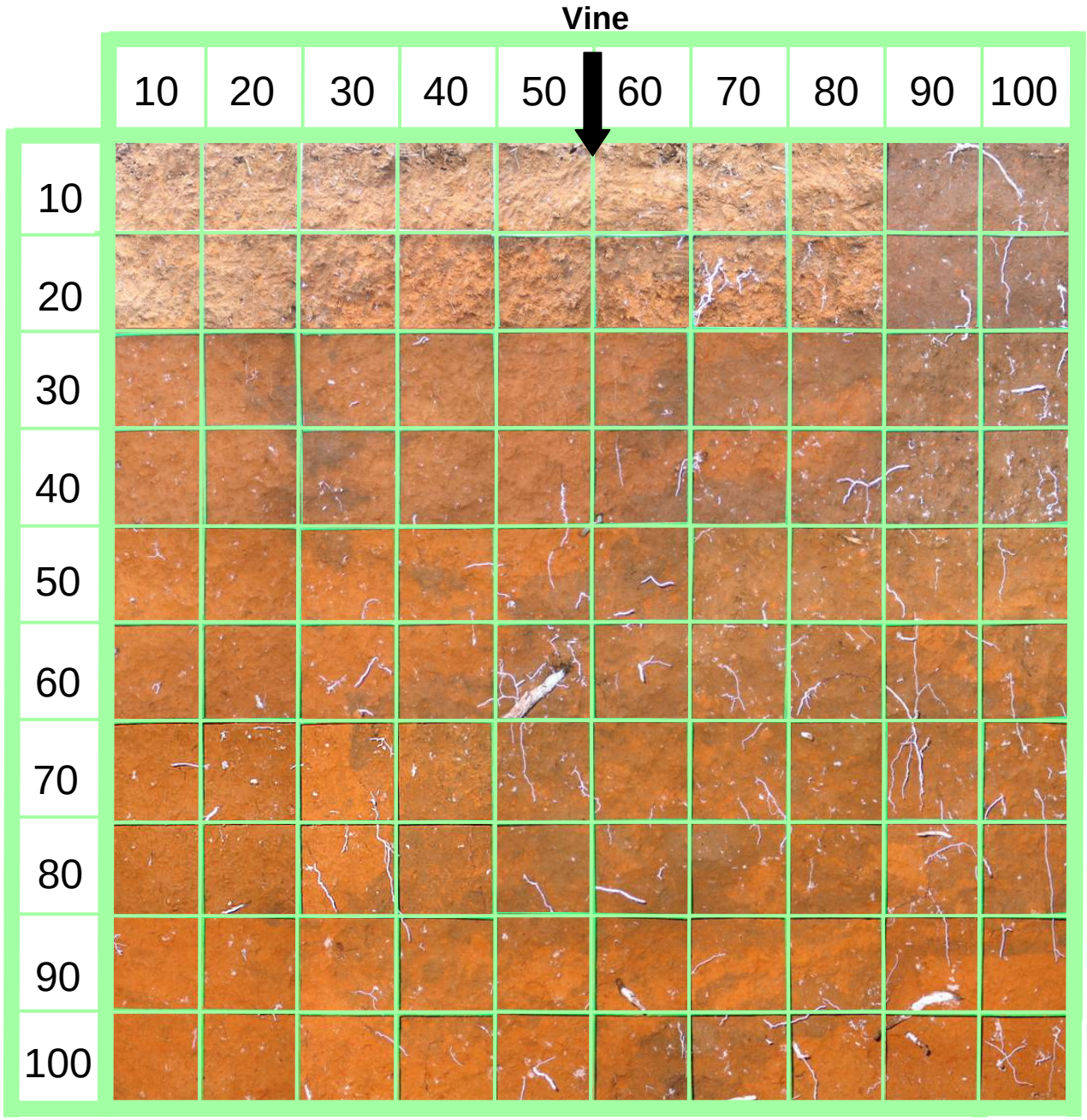

Fig.1 Soil profile pit with a grid indicating root penetration and distribution of Plot D2, Dryland treatment, Dry classification.
Merlot noir/Richter 110 on Oakleaf 2110

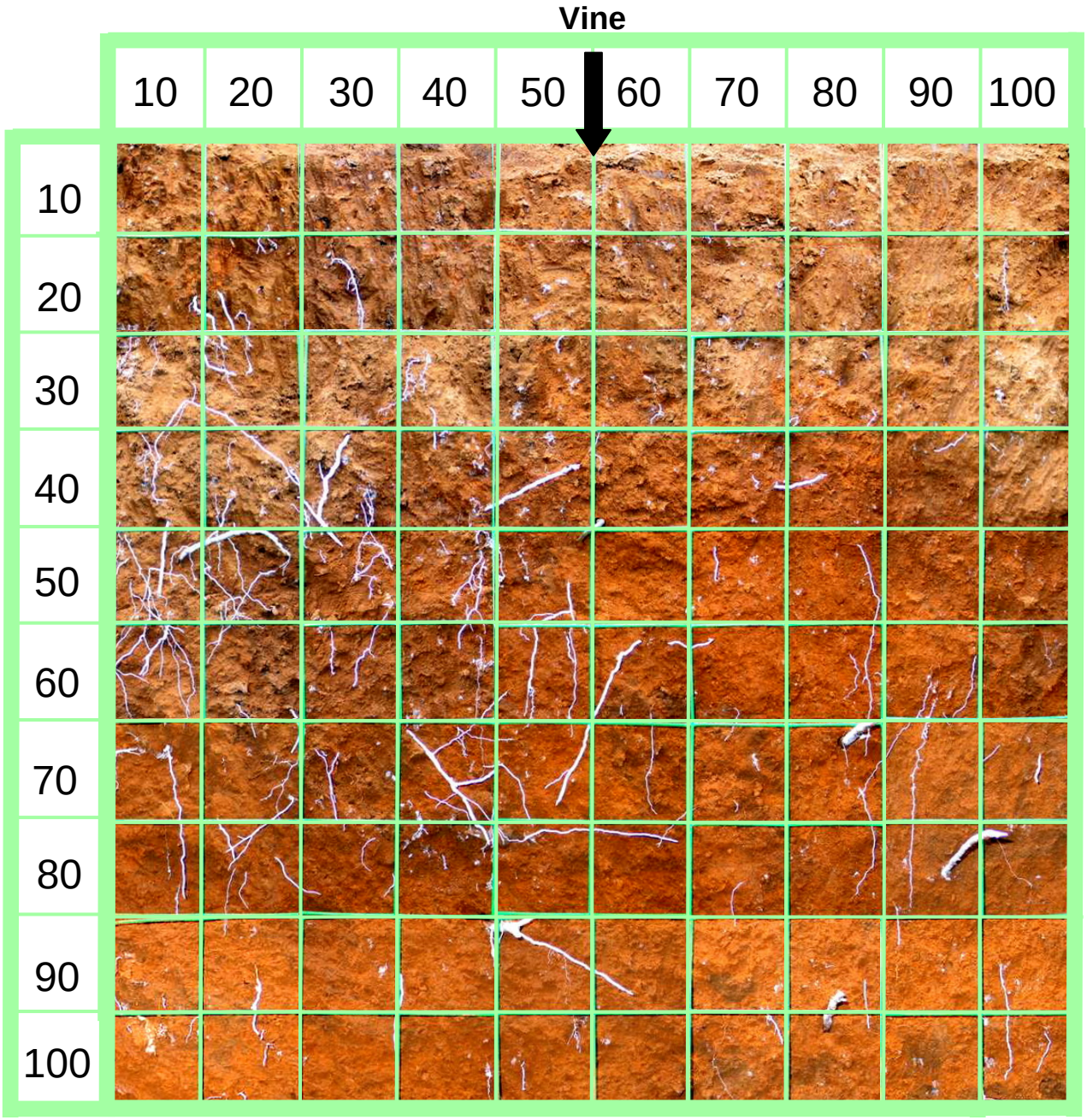

Fig.2 Soil profile pit with a grid indicating root penetration and distribution of Plot D3, Dryland Treatment, Dry classification.
Merlot noir/Richter 110 on Oakleaf 2110

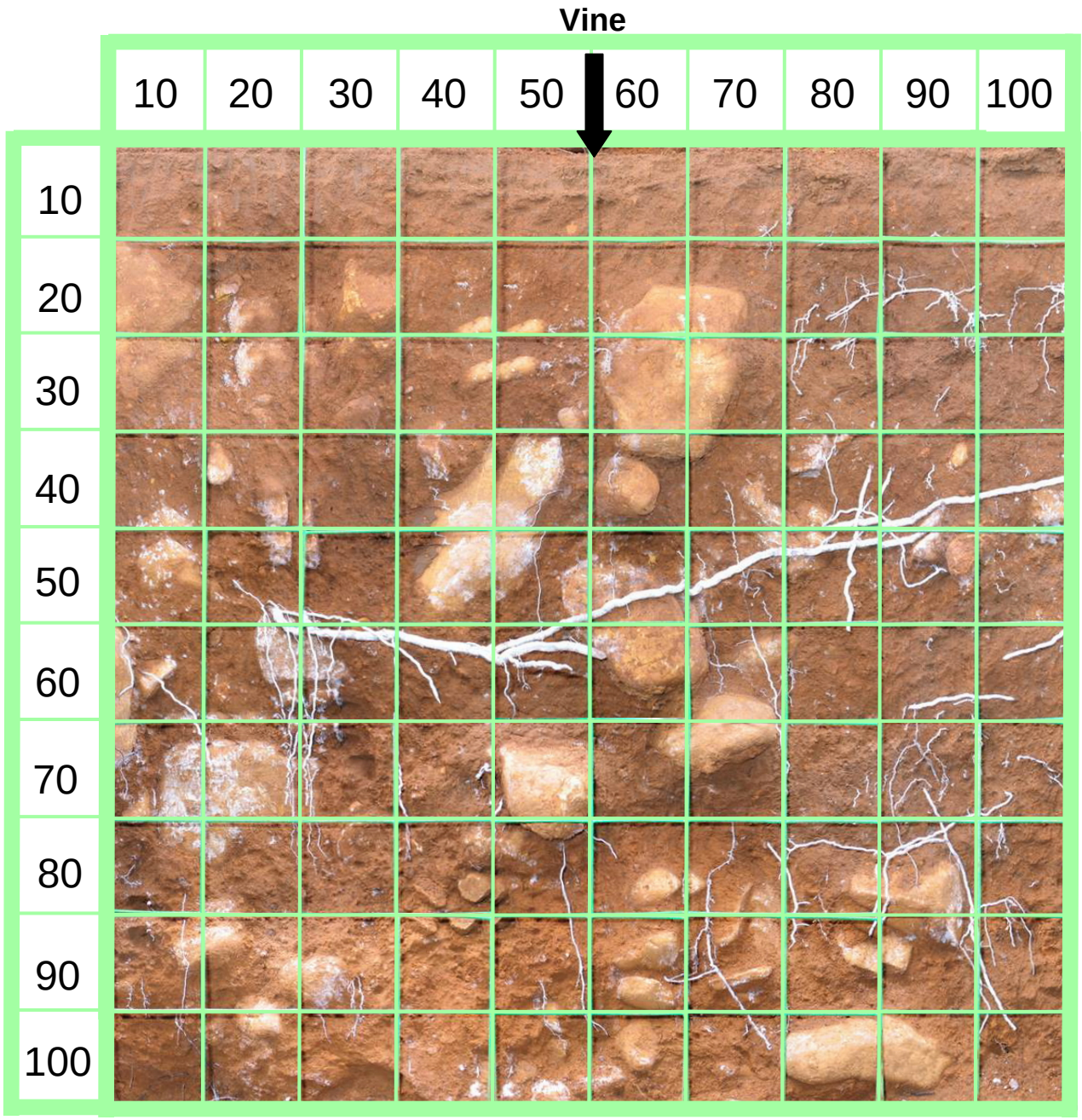

Fig.3 Soil profile pit with a grid indicating root penetration and distribution of Plot W1, Dryland Treatment, Wet classification.
Merlot noir/Richter 110 on Oakleaf 2110

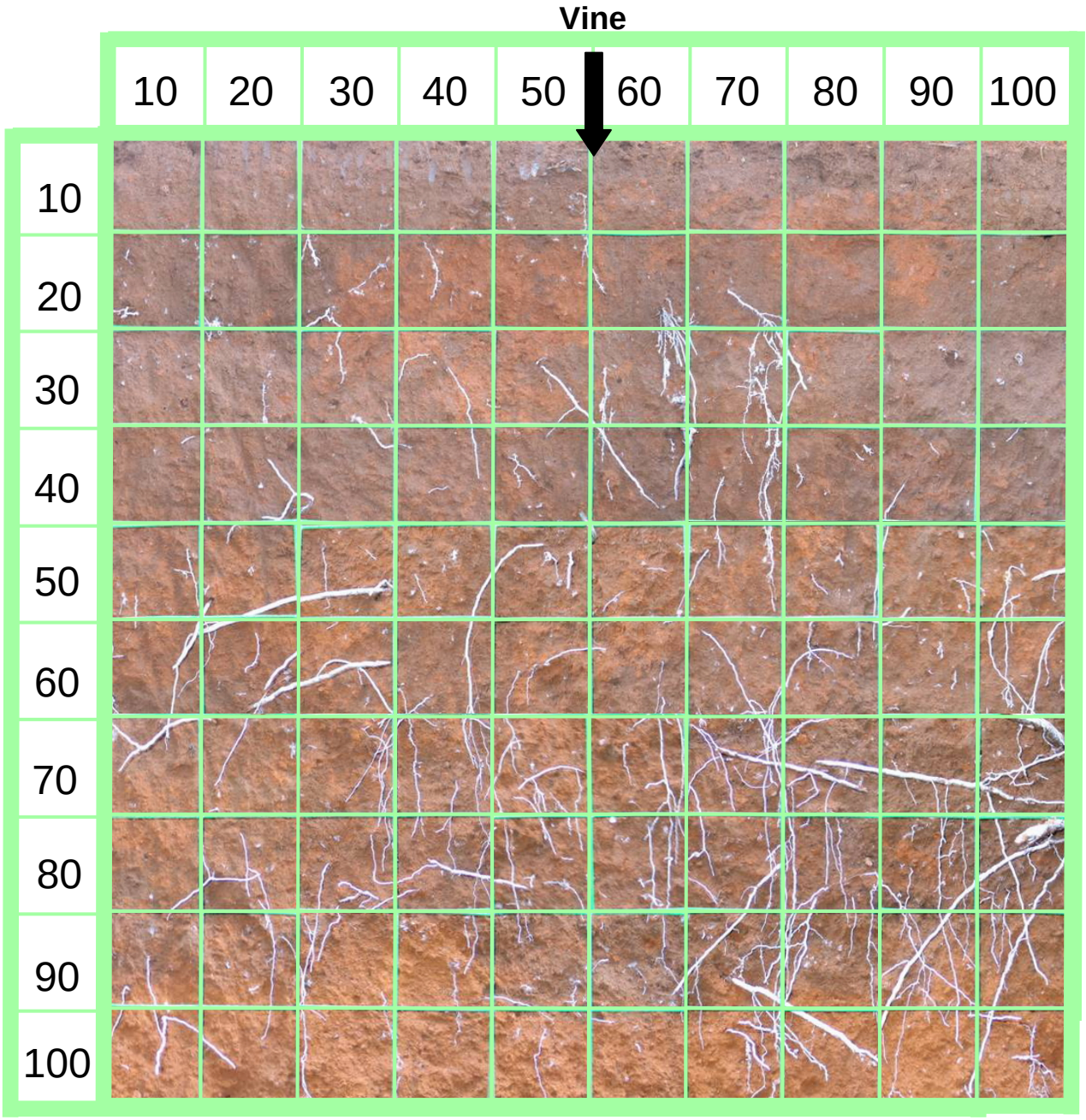

Fig.4 Soil profile pit with a grid indicating root penetration and distribution of Plot A10, Low deficit irrigation Treatment (no classification).
Merlot noir/Richter 110 on Oakleaf 2110

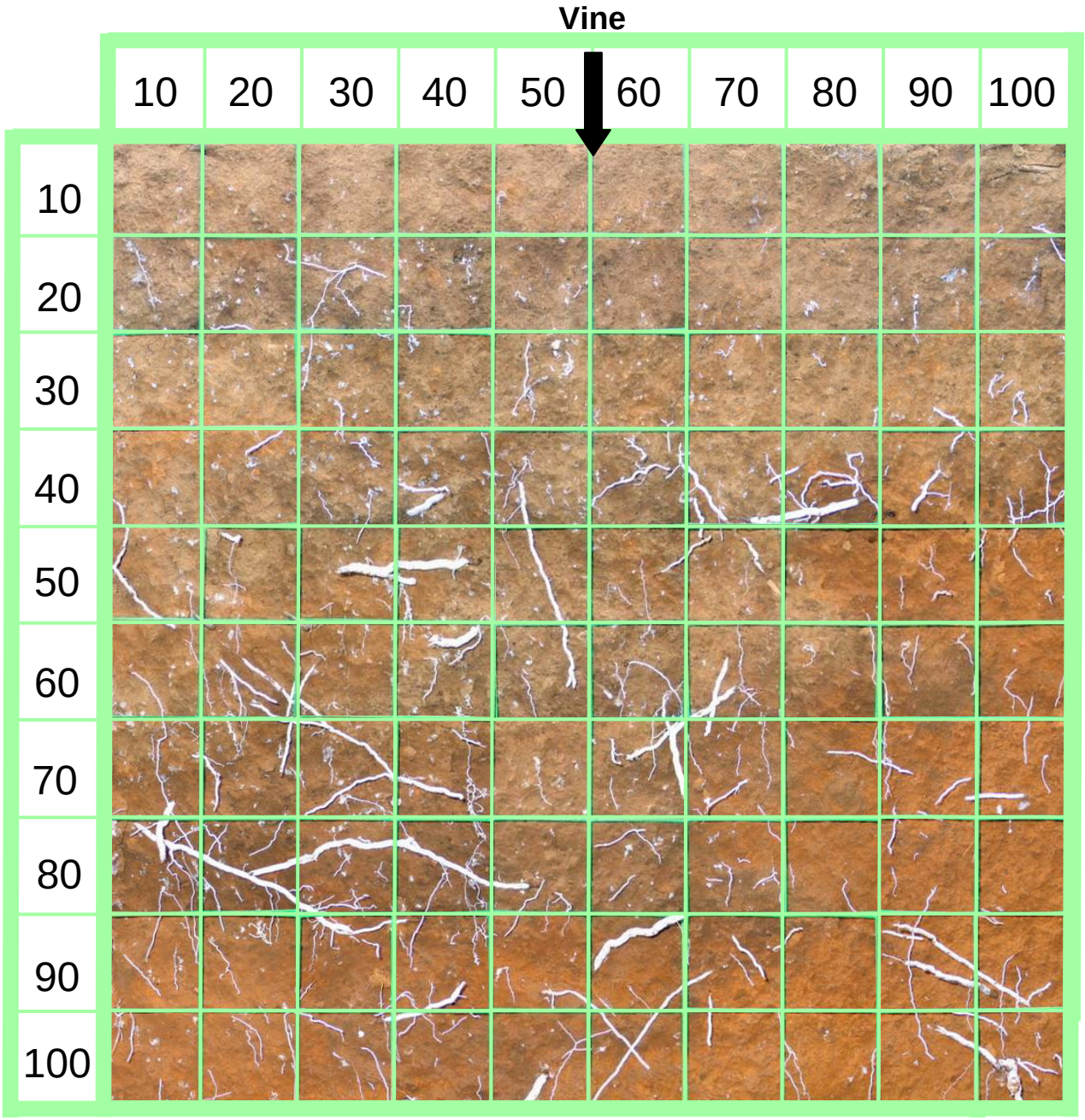

Fig.5 Soil profile pit with a grid indicating root penetration and distribution of Plot B8, Moderate deficit irrigation Treatment (no classification).
Merlot noir/Richter 110 on Oakleaf 2110

Table 1: Soil survey providing soil descriptors and classification for the different profile pits. See extra table for legend.

Plot	Horizon classification	Lower depth of horizon	Sand grade	Munsell colour			Parent geology	Soil form name	Soil family	Wetness class	Soil vigour potential
				Hue	Value	Chroma					
2	A	40 cm	fi/co	7.5YR	3	4	GR	Oa	2110	1	7.75
	ne/ye	90 cm	fi/co	7.5YR	5	8	GR				
	ne/sp	+	fi/co	7.5YR	5	8	GR				
3	A	40 cm	fi/co	7.5YR	3	4	GR	Oa	2110	1	7.75
	ne/ye	90 cm	fi/co	7.5YR	5	8	GR				
	ne/sp	+	fi/co	7.5YR	5	8	GR				
4	A	40 cm	fi/co	7.5YR	3	4	GR	Oa	2110	1	7.75
	ne/ye	90 cm	fi/co	7.5YR	5	8	GR				
	ne/sp	+	fi/co	7.5YR	5	8	GR				
8	A	35 cm	fi/co	10YR	3	6	GR, SN	Oa	2110	1	7
	ne/ye	85 cm	fi/co	7.5YR	4	6	GR, SN				
	ne/ye	+	fi/co	10YR	4	6	GR, SN				
A10	A	40 cm	fi/co	10YR	3	6	GR	Oa	2110	1	7.5
	ne/ye	95 cm	fi/co	7.5YR	5	8	GR				
	ne/ye	+	fi/co	7.5YR	6	8	GR				
B1	A	40 cm	fi/co	10YR	3	4	GR	Oa	2110	1	7.75
	ne/ye	+	fi/co	7.5YR	5	8	GR				
B8	A	40 cm	fi/co	10YR	3	4	GR	Oa	2110	2	7.75
	ne/ye	95 cm	fi/co	7.5YR	5	6	GR				
	ne/sp	+	fi/co	7.5YR	6	8	GR				
B11	A	40 cm	fi/co	10YR	3	4	GR	Oa	2110	1	7.7
	ne/ye	95 cm	fi/co	5YR	5	8	GR				
	ne/ye	+	fi/co	7.5YR	5	6	GR				
B12	A	45 cm	fi/co	10YR	3	4	GR	Oa	2110	2	7.75
	ne/ye	95 cm	fi/co	10YR	4	6	GR				
	ne/ye	+	fi/co	10YR	5	6	GR				

**Legend follows in next table*

Horizon classification	Identification of type of horizon using symbols of soil description code.
Lower depth of horizon	Lower depth of each horizon in centimetres from the soil surface. "+" indicates that the horizon extends to an unknown depth below the profile hole depth.
Sand grade	co = course; fi = fine; Combinations indicate a finer categorization. The first category given is the category it tends towards.
Parent geology	GR = granite; Sn = sandstone
Wetness class	A number between 1 and 9 indicating wetness class based on the depth at which saturation occurs in the profile and the length of time for which the soil remains saturated. 1 indicates that no signs of wetness are present
Soil vigour potential	An estimated rating out of 10 of the soil vigour potential for grapevines, based on the system used by Western Cape soil scientists

Table 2: Results of the soil analyses from sampling done in the different profile pits.

Plot	Depth	Soil	pH	Resist.	H^+	Stone	P Bray II	K	Exchangeable cations (cmol(+)/kg)				C	CEC (pH 7)
	(cm)		(KCl)	(Ohm)	(cmol/kg)	(Vol%)	mg/kg		Na	K	Ca	Mg	%	cmol(+)/kg
2	30	Sand	6.1	2170		2	25	133	0.04	0.34	4.62	0.90	0.84	5.11
	60	Sand	6.4	2520		3	7	46	0.05	0.12	3.57	0.62	0.33	4.06
	90	Sand	6.4	2250		2	6	38	0.06	0.10	3.54	0.63	0.46	3.92
3	30	Sand	4.6	3970	1.23	1	6	82	0.05	0.21	1.53	0.51	0.75	4.25
	60	Sand	4.4	4130	1.44	1	6	42	0.07	0.11	1.25	0.45	0.66	3.92
	90	Sand	4.6	3150	1.18	1	5	39	0.06	0.10	1.35	0.55	0.54	3.54
4	30	Sand	5.9	2890	0.46	2	22	97	0.06	0.25	4.78	1.08	0.98	5.22
	60	Sand	5.7	3000	0.51	2	7	34	0.06	0.09	2.89	0.88	0.40	4.47
	90	Sand	5.8	3130	0.41	2	8	24	0.06	0.06	2.67	0.82	0.36	4.14
8	30	Sand	5.5	3370	0.51	6	13	123	0.04	0.31	3.26	0.78	0.77	4.69
	60	Sand	6.1	3020		6	12	56	0.05	0.14	4.31	1.06	0.17	4.85
	90	Sand	5.8	3170	0.41	10	7	37	0.04	0.09	2.72	0.69	0.47	4.55
A10	30	Sand	5.6	3050	0.57	3	13	69	0.13	0.18	3.10	0.70	0.75	4.50
	60	Sand	5.6	3680	0.46	2	4	29	0.12	0.07	2.40	0.55	0.40	4.18
	90	Sand	5.4	2560	0.51	3	3	33	0.13	0.08	2.03	0.65	0.48	3.71
B1	30	Sand	6.3	1790		2	28	206	0.03	0.53	5.44	1.22	0.85	5.47
	60	Sand	6.1	2170		2	6	67	0.04	0.17	3.61	0.95	0.37	4.25
	90	Sand	5.3	1160	0.62	2	3	43	0.07	0.11	2.17	0.43	0.12	3.39
B8	30	Sand	5.8	2230	0.51	2	40	222	0.06	0.57	4.93	0.94	0.95	5.39
	60	Sand	5.8	2950	0.46	2	18	94	0.10	0.24	4.18	0.81	0.73	5.20
	90	Sand	5.3	3770	0.62	3	2	82	0.06	0.21	2.14	0.57	0.26	3.35
B11	30	Sand	6.1	1540		2	29	261	0.04	0.67	4.29	1.63	1.10	6.76
	60	Sand	4.5	3910	1.13	3	3	48	0.04	0.12	1.45	0.62	0.39	4.76
	90	Sand	4.8	3340	0.93	3	4	32	0.06	0.08	1.50	0.77	0.42	4.81
B12	30	Sand	5.8	2840	0.51	2	60	134	0.07	0.34	5.09	1.13	1.07	6.82
	60	Sand	5.1	3340	0.72	2	19	45	0.07	0.11	2.91	0.88	0.81	5.39
	90	Sand	4.4	4540	1.49	1	6	34	0.04	0.09	0.83	0.30	0.68	4.94

Table 3: Base saturation results of the soil analyses from sampling done in the different profile pits.

Plot	Depth	Na %	K %	Ca %	Mg %	T value cmol/kg
2	30	0.68	5.79	78.32	15.20	5.89
	60	1.11	2.69	81.93	14.27	4.36
	90	1.33	2.27	81.85	14.54	4.32
3	30	1.49	5.91	43.25	14.55	3.53
	60	2.05	3.21	37.76	13.63	3.32
	90	1.86	3.08	41.68	16.92	3.24
4	30	0.94	3.75	72.08	16.28	6.63
	60	1.34	1.97	65.26	19.91	4.42
	90	1.50	1.50	66.46	20.34	4.02
8	30	0.74	6.43	66.54	15.87	4.89
	60	0.87	2.56	77.54	19.03	5.55
	90	1.06	2.38	68.78	17.43	3.96
A10	30	2.82	3.75	66.28	14.96	4.68
	60	3.34	2.03	66.61	15.23	3.60
	90	3.83	2.47	59.65	19.09	3.41
B1	30	0.43	7.28	75.34	16.95	7.23
	60	0.86	3.58	75.69	19.86	4.77
	90	1.95	3.22	63.90	12.69	3.40
B8	30	0.88	8.11	70.33	13.40	7.01
	60	1.81	4.16	72.15	13.95	5.79
	90	1.65	5.85	59.33	15.96	3.60
B11	30	0.58	10.08	64.71	24.63	6.63
	60	1.28	3.64	43.01	18.46	3.36
	90	1.73	2.44	44.89	23.03	3.33
B12	30	0.95	4.79	71.29	15.84	7.14
	60	1.40	2.44	62.09	18.70	4.68
	90	1.48	3.16	30.24	10.91	2.75

Table 4: Mechanical analysis results from soil sampling done in the different profile pits.

Plot	Depth	Clay %	Silt %	Fine sand %	Medium sand %	Coarse sand %	Classification
2	30	8.4	13.6	48.3	15.1	14.6	SaLm
	60	13.8	12.2	40.3	13.2	20.5	SaLm
	90	14.4	12.6	44.4	13.3	15.3	SaLm
3	30	7.4	13.4	50.1	15.4	13.7	LmSa
	60	9	11.8	50.4	15.4	13.4	LmSa
	90	12	12.8	46.2	14.4	14.6	SaLm
4	30	6.8	15.4	46.6	15.7	15.5	LmSa
	60	13.6	12.2	42.9	14.8	16.5	SaLm
	90	15.6	12.8	39.3	14	18.3	SaLm
8	30	10	15.2	39.6	17.3	17.9	SaLm
	60	8.4	14.6	42.3	17.4	17.3	SaLm
	90	11.4	13.8	41.1	17	16.7	SaLm
A10	30	8	15	43.1	17.8	16.1	SaLm
	60	12.4	13.4	41.4	15.6	17.2	SaLm
	90	12	3.4	42.9	15.3	16.4	SaLm
B1	30	5.8	16	47.6	15.2	15.4	LmSa
	60	10.2	11.8	45.5	14.6	17.9	SaLm
	90	13.6	10.6	43.4	13.8	18.6	SaLm
B8	30	7.6	19.4	44.7	15.8	12.5	SaLm
	60	11.6	16.8	41.5	14.8	15.3	SaLm
	90	19.4	12.8	35.8	14	18	SaLm
B11	30	2.6	15.6	52.6	17.1	12.1	LmSa
	60	12.6	14.4	41.8	15.6	15.6	SaLm
	90	13	12.6	43.5	16.2	14.7	SaLm
B12	30	2.4	13.6	53.3	19.3	11.4	LmSa
	60	1.6	12.4	54.1	20.3	11.6	LmSa
	90	2	12.4	56.3	20.8	8.5	LmSa