A study of within-vineyard variability with conventional and remote sensing technology

By

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DECLARATION

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that I have not previously in its entirety or in part submitted it at any university for a degree.

AE Strever **Date**

SUMMARY

In the past it was very difficult to visualise the extent and distribution of variability in growth vigour within vineyards. The advancement of remote sensing technology has changed this however, establishing new methods to assess and manage variability. Even though the causes and effects of within-vineyard variability in growth vigour are complex, new technologies offer better ways of monitoring, researching and managing these factors. In addition to the possible benefits of aerial or satellite remote sensing, new methods of mapping soil spatial variability as well as advances in georeferencing technologies supply precision tools to both researchers and producers. The scientific advancement of the technology, however, is currently the most important aspect needed. This is crucial to answer and explore fundamental questions regarding the use of the technology and the interpretation of results within the framework of the plant's observed reaction. Only then can the possible applications in vineyard management be optimised to address the management problems of extensive within-vineyard variation in growth vigour. The choice will always be to use the technology to manage the observed variability in order to limit the negative impacts of a heterogeneous harvest, or to identify the variability and its causes for the implementation of management practices aimed at a more homogenous vineyard and harvest. Whatever the case, extensive research is needed to provide tight correlations between information gathered with new technologies to assess variability and plant status, such as multi- and hyperspectral analysis, and ground-truthed results in the vineyard. Only then will it become evident which methods and analyses would be useful in the drive towards in-depth analysis and management of vineyards within the concept of precision viticulture and its derived advantages.

With this in mind, the aim of this study was to establish an experimental model to use remote sensing technologies to identify and classify within vineyard variability with a subsequent analysis of the causes of variability and the effects on the plants. The targeted experimental model was a vineyard with highly heterogeneous above-ground growth. An aerial photograph of the vineyard was studied and manipulated to yield image pixel values used to quantify the degree of variability for different plots, which were chosen according to different plot layouts. Soil conditions were assessed on both a global and plot level, with extremely high pH and low resistance values in the soil in combination with erratic soil preparation practices found to be the main cause of variability. Soil physicochemical condition was also assessed during a soil profile pit study. Significant differences were found between several soil-related parameters measured for the higher and lower vigour levels and a strong correlation was also found between the resistance of a saturated soil paste and the image pixel values.

Vegetative measurements also yielded highly significant differences between the vigour levels and confirmed the suitability of the vineyard to study within-vineyard

variability. Some of these measurements were also strongly correlated with soil conditions as well as image pixel values. Trunk circumference proved to be an excellent measure for the level of variability, being linked strongly to canopy characteristics, soil conditions as well as the image pixel values. Leaf water potential measurements also yielded significant differences between the vigour levels.

Harvest data and wine analyses showed the effect that vigour differences can have on grape composition and wine quality, even though the differences found here were much less than expected. Even though no clear preference was shown between the wines made from the different vigour levels, the lower vigour wine was considered fruitier. The overall quality of both experimental wines was however very high, considering that experimental winemaking techniques has been used.

Hyperspectral measurements also confirmed differences between the vigour levels through a narrow-band NDVI (normalised difference vegetation index). It was also possible to show differences in certain biochemical compounds between the vigour levels on both a leaf and canopy level. Wavelength regions corresponding to carotenoid, chlorophyll a and chlorophyll b showed different spectral reactions in the leaves of more stressed (lower vigour) canopies, indicating possibilities for further studies.

This study and its results is the first of its kind in the South African wine industry and paves the way for more focussed and in-depth analyses of the use of specifically multi- and hyperspectral data to accurately assess within-vineyard vigour variability and the management thereof to yield optimum quality grapes for a specific wine target. Moreover, the approach adopted in this study is also echoed in other international research programs in prominent wine countries. The availability of scientific research regarding the optimal use and limitations of these technologies has the potential to revolutionise production management practices in the next few years in the viticultural industry.

OPSOMMING

In die verlede was dit baie moeilik om die omvang en verspreiding van groeikragvariasie binne 'n wingerd te visualiseer. Die vordering gemaak op die gebied van afstandswaarneming-tegnologie het egter nuwe metodes beskikbaar gestel waardeur hierdie variasie in wingerde gemonitor en bestuur kan word. Selfs al is die oorsake en invloede van binne-wingerd-groeikragvariasie kompleks, verskaf nuwe tegnologieë verbeterde metodes om hierdie variasie te monitor, te bestuur en na te vors. Saam met die moontlike voordele wat lugfoto's en satelliet-afstandswaarneming teweegbring, verskaf nuwe metodes om ruimtelike variasie in grondfaktore te karteer, asook vordering in geo-verwysingstegnologie, presisiehulpmiddels aan produsente én navorsers. Die wetenskaplike vordering van dié tegnologie is tans van groot belang. Die belang daarvan is om fundamentele vrae te ondersoek en te beantwoord rakende die gebruik van die tegnologie en die interpretasie van resultate binne die raamwerk van die waargeneemde reaksie in die plant. Dit sal die weg baan vir optimale toepassing van die tegnologie in wingerdbestuur om sodoende die bestuursprobleme wat deur binne-wingerd-groeikragvariasie teweeggebring word, aan te spreek. Die voorkeurkeuse is om dié tegnologie aan te wend om hierdie variasie te bestuur sodat die negatiewe impak van 'n heterogene oes teengewerk kan word, of om die variasie te identifiseer vir die implementering van bestuurspraktyke gemik op die skep van 'n meer homogene wingerd en oes. Dit is noodsaaklik dat uitgebreide navorsing gedoen word om noue verwantskappe vas te stel tussen inligting wat ingewin is met behulp van nuwe tegnologieë wat die variasie in plantstatus monitor, soos multi- en hiperspektrale analise, en inligting wat op grondvlak ingewin is. Hieruit sal dit duidelik wees watter metodes en analises die doeltreffendste is vir in-diepte analises en die bestuur van wingerde binne die konsep van presisie-wingerdkunde.

Met inagneming van hierdie aspekte, was die doel van hierdie studie om 'n eksperimentele model daar te stel waardeur afstandswaarneming-tegnologie gebruik kan word om variasie binne wingerde te identifiseer en te klassifiseer deur analises van die oorsake van hierdie variasie en invloede op die plant. Die geteikende eksperimentele model was 'n wingerd met hoogs heterogene bogrondse groei. 'n Lugfoto van die wingerd is bestudeer en gemanipuleer om pixelwaardes te verskaf wat die graad van variasie vir verskillende eksperimentele plotte, wat aan die hand van verskillende plotuitlegte gekies is, te kwantifiseer. Grondtoestande is bestudeer op 'n globale én plotvlak, met uiters hoë pH en lae weerstande in kombinasie met verkeerde grondvoorbereidingspraktyke, wat geïdentifiseer is as die hoofoorsake vir die hoë vlakke van variasie. Grondfisiese en -chemiese toestand is ook tydens profielgatstudies bestudeer. Betekenisvolle verskille is gevind tussen verskeie grondverwante parameters gemeet vir plotte met onderskeidelik

laer en hoër groeikrag, en 'n sterk verwantskap is gevind tussen grondweerstand en pixelwaardes, soos vanaf die lugfoto bepaal.

Vegetatiewe metings het ook betekenisvolle verskille tussen die hoër en laer groeikragvlakke opgelewer, wat die geskiktheid van die wingerd vir die studie van binne-wingerdvariasie in groeikrag bevestig het. Van hierdie metings was ook nou verwant aan grondtoestande, asook beeldpixelwaardes. Stamomtrek was 'n uitstekende maatstaf vir die vlakke van variasie, aangesien dit nou verwant was aan lowertoestande, grondtoestande, asook beeldpixelwaardes. Blaarwaterpotensiaal-metings het ook betekenisvolle verskille tussen die hoër en laer groeikragvlakke opgelewer.

Oesdata en wynanalise het die uitwerking van groekragverskille op druifsamestelling en wynkwaliteit uitgewys, selfs al was die verskille wat gevind is minder as wat verwag is. Hoewel geen duidelike voorkeur tussen die wyne afkomstig van verskillende groeikragvlakke uitgewys kon word nie, was die wyn wat van die laer-groeikrag stokke gemaak was, meer vrugtig. Die algemene kwaliteit van beide wyne was egter baie hoog as in ag geneem word dat eksperimentele wynmaakprosedures gevolg is.

Hiperspektrale metings het ook die verskille tussen groeikragvlakke bevestig deur 'n nou-bandwydte NDVI ("normalised difference vegetation index"). Dit was ook moontlik om verskille in sekere biochemiese komponente tussen die groeikragvlakke op 'n blaar- én lowervlak uit te wys. Golflengte-areas ooreenstemmend met karotenoïed, chlorofil a en chlorofil b het verskillende spektrale reaksies in die blare met hoër stresvlak (laer groeikrag) lowers ten toon gestel. Dit het moontlikhede vir verdere navorsing uitgewys.

Hierdie studie en die resultate wat verkry is, is die eerste van sy soort in die Suid-Afrikaanse wynbedryf. Dit baan die weg vir meer gefokusde en in-diepte analise van die gebruik van spesifiek multispektrale en hiperspektrale data om binne-wingerd-groekragvariasie akkuraat te monitor en te bestuur met die oog op optimum wynkwaliteit vir 'n spesifieke produkdoelwit. Die aanslag van hierdie navorsing is ook sigbaar in ander prominente wynproduserende lande. Beskikbaarheid van wetenskaplike navorsing rakende die optimale gebruik en tekortkominge van hierdie tegnologieë het die potensiaal om produksiebestuurspraktyke in die wingerdbedryf in die komende jare te revolusionaliseer.

This thesis is dedicated to my wife, Elana

BIOGRAPHICAL SKETCH

Albert Strever was born in Pretoria on 5 October 1977. He matriculated at Groblershoop High School in 1995. Albert enrolled at Stellenbosch University in 1997 and obtained the degree BScAgric in Viticulture and Oenology in December of 2000. In 2001 he enrolled for the degree MScAgric in Viticulture, also at the Stellenbosch University.

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PREFACE

This thesis is presented as a compilation of five chapters. Each chapter is introduced separately, with the results presented in chapters three to four and concluded in chapter five.

Chapter 1	**GENERAL INTRODUCTION AND PROJECT AIMS**
Chapter 2	**LITERATURE REVIEW** The use of remote sensing techniques to manage spatial variability of vigour within vineyards to optimise wine quality
Chapter 3	**EXPERIMENTAL PLOT LAYOUT AND VALIDATION** Characterisation of a highly variable vineyard
Chapter 4	**RESEARCH RESULTS** Characterisation of above-ground vigour variability at Perdeberg with conventional and hyperspectral analyses
Chapter 5	**GENERAL DISCUSSION AND CONCLUSIONS**

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CHAPTER 1. GENERAL INTRODUCTION AND PROJECT AIMS

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CHAPTER 5. GENERAL DISCUSSION AND CONCLUSIONS

Chapter 1

GENERAL INTRODUCTION AND PROJECT AIMS

GENERAL INTRODUCTION AND PROJECT AIMS

1.1 INTRODUCTION

Spatial variability of vine vigour in vineyards can be either beneficial or detrimental to wine quality, depending on both the degree of variability as well as the specific contributing factors. These factors are of a complex nature, including aspects such as: i) soil and environmental properties; ii) intrinsic plant factors (genetic or physiological); and iii) other external factors, such as the management input made by the producer. A study of vineyard variability is therefore multidisciplinary in nature and if one discipline (e.g. soil science) is neglected, it may result in incorrect interpretations in other disciplines.

Recent advances in agriculture have focused on the management of spatial and temporal variability in production systems with the use of new technologies, such as geographical information systems (GIS) and remote sensing (Cook & Bramley, 1998) under the umbrella of precision agriculture. These technologies are also now being applied to the wine and grape industries. Within single vineyards, the monitoring and management of spatial variation in productivity and quality parameters have been described as precision viticulture (Lamb, 2001; Lamb & Bramley, 2001).

Due to the considerable variation in soil conditions found over relatively short distances in South Africa (Burger, 1977; Saayman, 1977; Conradie *et al.*, 2002), precision viticulture has recently attracted a great deal of attention, and several producers have already obtained high-resolution multispectral images of their vineyards. Yield monitoring technologies, incorporated in mechanical harvesters, have however not been available in South Africa, with the first adapted harvesters only scheduled to arrive in the near future.

International experience, however, seems to suggest that the adaptation of precision agriculture technology has been slower than was originally anticipated, mainly due to the fact that producers' capacity to acquire information about variability generally outweighs the capacity of researchers to explain it (Cook & Bramley, 2001). In addition to this, a danger exists with these technologies to extrapolate either too little or too much from the information acquired. Research can play a key role in changing the latter scenario.

While conventional management techniques were adapted in the past to compensate for the high levels of vigour variation found in many vineyards, these adaptations can be laborious and costly, as are the methods of determining the extent of this variation. New methods of determining the levels of spatial and temporal variation in vigour are under investigation, currently making the field of precision viticulture an actively researched field.

The increasing demand for higher quality grape products (Hall *et al.*, 2002) has played a major role in motivating the implementation of more precise management techniques in vineyard management and wine production. However, it has been a major concern of producers and commercial providers of these technologies in both Australia and the USA that research has been lagging behind them (Cook & Bramley, 2001). The rapid development of precision technologies such as global positioning technologies (GPS, and especially differential GPS), geographical information systems (GIS), yield monitoring, aerial imaging and electromagnetic or radar soil surveying, is paving the way for research to redefine current methods of managing vineyards for optimum grape quality. However, collaboration between researchers in different fields, commercial service providers and producers has to receive high priority if these technologies are to make a real contribution to the advancement of wine quality. The challenge posed to research in this field lies in creating models able to link remotely sensed canopy biophysical data with vine physiological properties that affect fruit composition (Arkun *et al.*, 2001).

1.2 SPECIFIC PROJECT AIMS

This study had the overriding goal of introducing research into the use of viticultural remote sensing technologies in South Africa, and to show how these technologies can aid in measuring vigour variation within vineyards.

Two main types of precision tools were used in this study, namely conventional aerial photography, as well as recently introduced hyperspectral field spectroscopy. In combination, these tools were used to investigate the causes and effects of spatial variation in vine vigour in a vineyard with high levels of this variation, and to highlight aspects that may be investigated in future research in this field.

In order to achieve these goals, the following primary (i and ii) and secondary (a,b,c. . .) approaches were followed:

(i) To identify and characterise a highly variable vineyard, producing high quality wine and to acquire general information on the possible causes of the high levels of vigour variation;

   a. To manipulate a colour aerial image of the vineyard to indicate vigour variation accurately when compared to the ground-truthed field data;
   b. To design different plot layouts capable of showing different levels of vigour variation within the vineyard by identifying differently sized areas of distinct higher and lower vigour, while also confirming the vigour assignment to these plots by extracting digital image pixel values for the different plots;
   c. To use the extracted image pixel values to investigate correlations with soil properties.

(ii) To characterise the aboveground vigour variation in the vineyard with conventional and hyperspectral analyses and to investigate its effect on yield and wine quality;

   a. To use different methods to measure vine and canopy vigour variation and to correlate these measurements with image- as well as soil characteristics;

b. To harvest grapes from different vigour levels, measure grape juice parameters and use microvinification for wine analysis and -evaluation;
c. To determine if narrow-band normalised difference vegetation index differences between vigour levels correspond to pixel values extracted from an aerial image;
d. To determine possible spectral signature changes in vine leaves and canopies between stressed and less stressed conditions for further research.

1.3 LITERATURE CITED

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Chapter 2

LITERATURE REVIEW

The use of remote sensing techniques to manage spatial variability of vigour within vineyards to optimise wine quality

LITERATURE REVIEW

2.1 INTRODUCTION

Vigour variation within vineyards is of a complex nature, and therefore so are the relationships between the factors that affect it. Bramley (2001a) showed some of the complexity of the viticultural system with a model indicating viticultural production as an input-output system (Fig. 2.1), consisting of relationships between inputs made into the system by the vineyard manager or winemaker, natural sources of variability and outputs from the system. One important factor is the "noise" introduced by components within the system, which are more difficult to control with management practices. Yield and quality maps produced with recently introduced technologies could be valuable in clarifying the relationships between inputs and outputs of the system through the spatial representation of data, potentially leading to improved and more targeted management practices in vineyards (Bramley, 2001a).

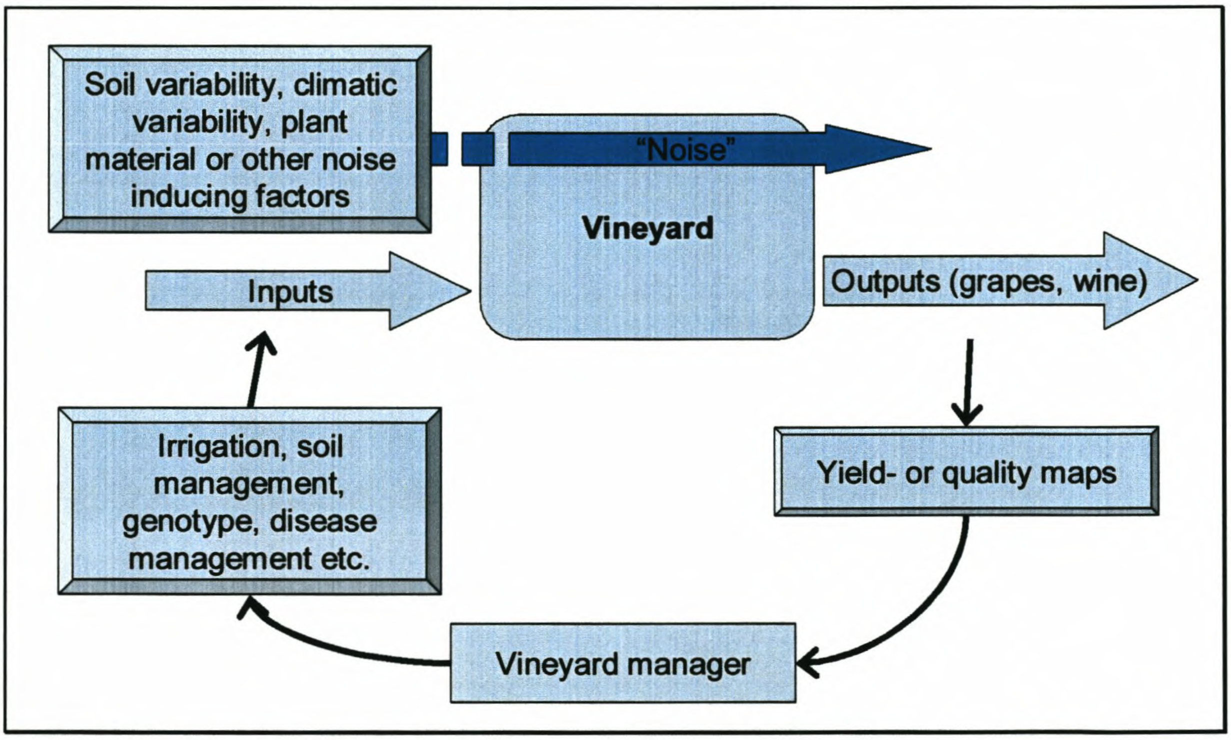

Figure 2.1 Viticultural production showed as an input-output process (Adapted from Bramley, 2001a).

The following are some characteristics of variability that are worth considering: i) it is often a function of size, with larger areas being more prone to environmental or managerial variability (Taylor, 2001); and ii) it may be of either a spatial or a temporal (time-related) nature. While the first type of variability mostly relates to aspects of the soil and environment, the second type relates to seasonal or within-season variability in plant reaction (V.A. Carey, University of Stellenbosch, personal communication, 2002).

The opposite of variability, namely uniformity in vineyards was considered by Long (1997) as very important for the achievement of better aroma and flavour concentration of grapes. Long (1997) addressed four types of uniformity of importance to vineyard management, namely: i) berry uniformity (equal ripeness levels of berries within a cluster); ii) cluster uniformity (equal ripeness levels of clusters within a vine); iii) vine uniformity (similar ripeness curve of vines within a vineyard); and iv) block uniformity, which she linked to the establishment of vineyard block boundaries based on soil variability. Recent observations by Archer (2001) added another type of uniformity to this list, namely shoot length uniformity, which was found to impact strongly on grape quality. The conclusion from the research done by Archer (2001) was that shoot length variability on a single grapevine originated from poor young vine training techniques, which emphasised the importance of using the correct vineyard establishment techniques.

In Table 2.1, a summary is presented of some of the management actions that have to be implemented in order to achieve uniformity in vineyards, and the possible outcomes of these actions.

2.2 CAUSES OF SPATIAL VARIABILITY IN VIGOUR WITHIN VINEYARDS

Several factors may lead to spatial variation of vigour within vineyards, but most literature sources discuss these factors as they differ between different vineyards, rather than within a single vineyard. For instance, the typical characteristics ascribed to high vigour vineyards are vines with longer shoots, larger leaves and more lateral shoots than vines in lower vigour vineyards (Smart *et al.*, 1985a). These characteristics can however differ within single vineyards if the factors leading to vigour variability show a high level of spatial variability within a vineyard.

It is important at this point to differentiate between the terms “vigour” and “capacity” in vineyards to form a better understanding of the concept of vine vigour. While vigour refers to the ability of parts of the vine to grow rapidly, capacity describes the ability of the vine or part of it concerning its total achievable production (Winkler *et al.*, 1974). The vigour of a vine with only a few shoots (which can then grow faster and longer) may be much higher than that of a vine with many shoots. The vine with more shoots, however, may have a considerably higher capacity, and be able to ripen more grapes (Fig. 2.2) (Archer, 1985). In a vineyard with variable vigour, it may therefore be possible to find vines for which the capacity either is under- or over-utilised. This may not only cause differences in yield, but also more importantly affect grape quality negatively if vines are over-stressed.

Although factors causing vigour variability within vineyards are reasonably well documented, there is still a lot of controversy surrounding the effect of these factors on wine quality. While some researchers stress the importance of management practices and winemaking techniques, others consider the effect of the environment to be dominant.

Table 2.1 Types of uniformity in vineyards and approaches to its management (Long, 1997; E. Archer, personal communication, University of Stellenbosch, 2002).

Type	Causes of poor uniformity	Actions	Outcomes	Comments
Berry	• Uneven cluster exposure • Weather at bloom and berry set • Tight clusters • Dense canopies	• Good spur/bud distribution • Canopy management, good shoot location: careful leaf removal • Avoid tight clusters • Select training system to allow best display of clusters and leaves • Monitor berry variability from vine size data, establish sample size	• Even ripeness at harvest • Greater success of ripeness prediction from fruit samples	• Some varieties tend to be less variable: Cabernet Sauvignon vs. Zinfandel • Weather impacts variability
Cluster	• Lack of vine balance • Excessive stress • Poor canopy structure • Disease (phylloxera) • Over-cropping	• Véraison green cluster removal • Well-managed canopies • Remove fruit on short shoots • Proper crop and vine balance • Crop adjustment on diseased vines	• Low ° Balling variability	• Cluster uniformity is less weather affected, more management dependent
Shoot	• Poor young vine training techniques • Poor summer canopy management	• Apply proper training techniques for young vines • Apply proper canopy management techniques	• Improved inter vine uniformity • Similar ripeness levels between vines	• Intensive training of labour essential
Vine	• Soil type variation • Irrigation • Disease • Irregular pruning • Varied vine age (after replacement of dead or poorly performing vines)	• Good block layout and design • Good initial stand (99 % +) • Disease control • Segmented block management • Vine removal • Good pruning techniques	• More flavour intensity	• Initial block layout very influential
Block	• Block layout not correlated to soil or topographic variability	• Initial layout critical to get manageable units for ease of working and to ensure optimal wine quality & flavour • Differential harvesting within blocks based on ripening pattern • Adapting vine spacing to soil variability • Wind breaks	• More efficient vineyard management • Less spatial variability of vigour/production	• Detailed soil map critical • Adapt in-row spacing according to soil variability

Johnson *et al.* (2001a) expressed the view that subtle differences in factors such as soil type, microclimate, slope, site exposure, soil water holding capacity and drainage predominantly affects grape quality and resulting wine quality.

Variability in vineyards may either originate from environmental or plant factors, or via the grower's contribution through management practices (Taylor, 2001). Some of these factors reduce vigour, while others may stimulate it. Smart *et al.* (1985a) considered high water and nutrient availability and freedom from pests and diseases to be important factors stimulating high vigour in vineyards. Factors that reduce vineyard vigour include, amongst others, water stress, higher crop load, poor nutrition, pests, diseases and limited root zones (Smart, 1985; Johnson *et al.,* 2001a). While many of these factors are discussed in literature, only a few have the potential to vary within vineyards.

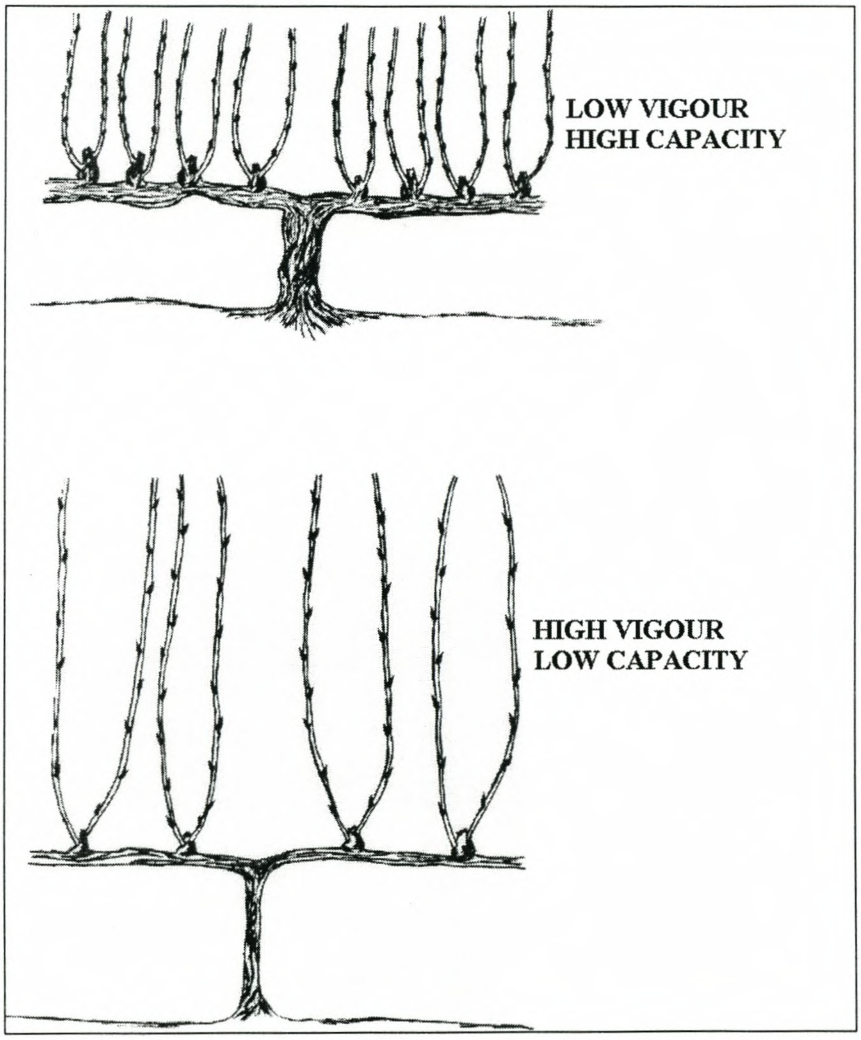

Figure 2.2 Vigour and capacity of vines (Archer, 1985).

To show how some of these factors affecting within-vineyard spatial variability in vigour are related to wine quality, a summary from research is presented in Fig. 2.3. This indicates possible sources of variability within a vineyard block that can have an effect on vine vigour, in turn leading to canopy density variability through its effect on the amount of foliage and foliage arrangement in space (Smart, 1985). This spatial arrangement of foliage determines canopy microclimate, which may play a dominant role in affecting wine quality.

The important concept contained in this model (mainly developed by Smart *et al.*, 1985a), is that environmental factors such as soil, climate and cultural decisions can have both direct and indirect effects on wine quality, with indirect effects predominantly brought about by canopy microclimate modification.

Early studies often recognised vigour variability within vineyards, but mostly did so owing to an experimental outlay that spanned over areas of differing vigour, and not because the study was primarily designed to investigate this variability. A good example of a study that was deliberately set up on different vigour levels in a vineyard, was the study by Smart *et al.* (1985a) conducted in a dryland Shiraz vineyard. 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 the water supply to the vine roots. Table 2.2 shows the effect of this soil depth variation on shoot growth, canopy dimensions and yield. A notable trend was the larger leaves, longer shoots and higher yield of the more vigorous vines, with a resulting increase in shading as indicated by the ratio leaf area (LA)/canopy surface area (SA). Even though leaf area showed a two-fold increase from low to high vigour experimental plots, the leaf area/fruit mass ratio was little affected. During the second part of the study, Smart *et al.* (1985b) found high must and wine pH and K content to be positively correlated with shading in the canopies, while the total and ionised anthocyanin and phenol concentrations were negatively correlated with shading.

2.2.1. SOIL VARIABILITY

Most of the factors that affect productivity-related variability within vineyards, with the exception of management practices and disease incidence, are in turn affected by soil type. In some countries (especially South Africa) soil type may vary considerably over short distances (Burger, 1977; Saayman, 1977; Conradie *et al.*, 2002), therefore making it a very important potential source of within-vineyard variability. Burger (1977) as well as Saayman (1977) pointed out that this variation in soil type over short distances may result in marked differences in vine performance, phenology and yield. Modern vineyard plantings may therefore often include more than one rootstock cultivar, within-row plant spacing and/or scion clone in a vineyard block with varying soil types (E. Archer, University of Stellenbosch, personal communication, 2002).

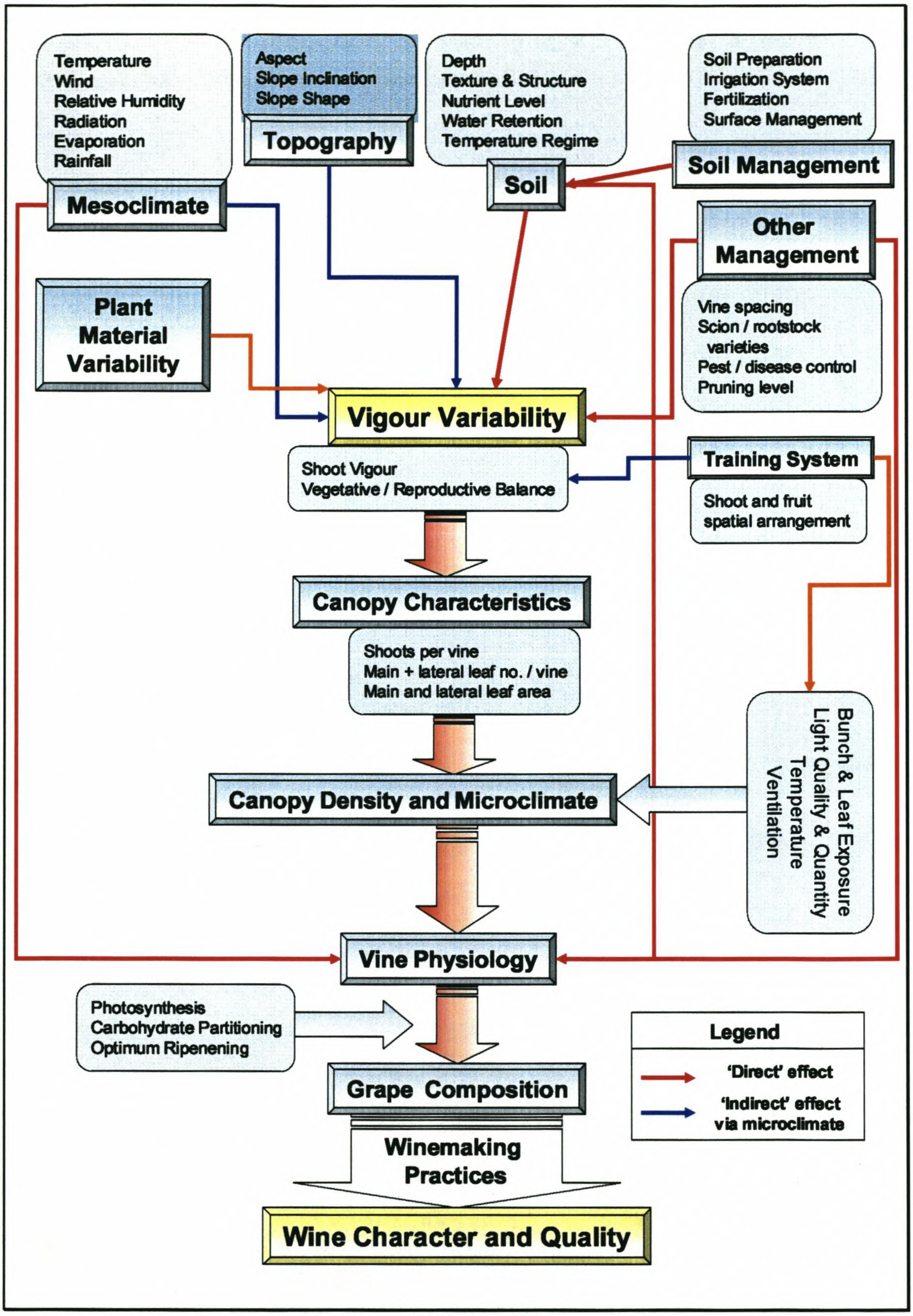

Figure 2.3 Interrelationship between spatial variability of environmental parameters, management practices, grapevine vigour and wine character/quality (Adapted from Smart, 1985; Smart *et al.*, 1985a; Jackson & Lombard, 1993; Zoecklein *et al.*, 1995; Carey, 2001).

Table 2.2 Effects of grapevine vigour on canopy dimensions, shoot growth and yield. Vigour increases from experimental plots 1 to 9, situated within a single vineyard block (Smart *et al.*, 1985a).

Canopy & vine characteristics	**Units**	**Experimental block**									**Signi-ficance**
		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	(1000m^2.ha^{-1})	13.2	14.3	15.1	18.0	15.6	19.5	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/vine	(kg)	11.5	14.7	15.4	16.5	16.1	17.2	15.5	22.5	24.7	*
Clusters/vine		225	257	241	269	294	236	300	308	307	NS
Mean cluster mass	(g)	51	58	65	60	53	73	54	72	82	**
Shoots/ vine		135	132	133	141	133	126	145	154	151	NS
Pruning mass / vine	(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	**
Leaf area / fruit mass	(cm^2.g^{-1})	11.2	9.2	9.9	10.7	10.4	10.2	13.4	10.2	11.5	NS
Canopy surface area / fruit mass	(cm^2.g^{-1})	7.4	5.5	5.9	5.4	6.6	5.4	5.9	4.3	4.0	NS
Nodes with periderm		5.3	4.6	6.4	5.7	6.2	5.2	7.2	5.8	4.5	NS

Significance levels:

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

Although it is mostly recognised that soils can vary within vineyards, the effect of soils on grape composition and wine quality has always been a subject of controversy. Some earlier writers recognised that different soils could produce organoleptically different wines (Fregoni, 1977). Other researchers related wine properties to soil chemistry or judged soil moisture retention capacity to be of principal importance, whereas in some cases the importance of soils was seen as important only as cofactor to cultivar and climate attributes (Saayman, 1981a). Most modern scientific writers tend to minimise the effect of soil on wine quality, but they do not deny the effect it may exert through vine vigour and moisture relations (Gladstones, 1992). Saayman (1977) also noted this much earlier, by stating that although soil properties might not have a significant direct effect on wine quality, it may influence the vegetative performance of the vine and therefore canopy microclimate. Jackson & Lombard (1993) discussed the complexity of the effect soils may have on wine quality by stating that it can affect the moisture and nutrient availability to the plant, the microclimate via heat-retaining and light-reflecting capacity, and root growth due to its penetrability and water availability.

Research in America (Winkler *et al.,* 1974) and Australia (Rankine *et al.,* 1971) tend to show a subordinate role of soil to that of climate in warmer regions when considering affected wine quality. This view can only be supported if soils are generally uniform and favourable, as is indeed the case in most Californian vineyards (Saayman, 1977). According to Saayman (1977), the experimental layout used by Rankine *et al.* (1971) could have lead to a confounding effect of soil and climate. Even though Rankine et al. (1971) found no wine quality differences, they did find that soil type affected the concentration of certain constituents in grapes and wine. The observed differences were ascribed to factors such as soil depth, water holding capacity and drainage, rather than soil chemical composition.

In South Africa, Saayman (1977) found Chenin blanc as well as Cinsaut wine quality to be affected considerably by soil conditions. The effect of soil on wine quality, however, was not consistent over vintage years, with opposite results found during the second season. Saayman (1977) ascribed this to a possible interrelationship between soils and climate, which was found by Conradie (1998) for Sauvignon blanc under dryland conditions in South Africa. Choné et al. (2001) also conducted a study on the effect of soil variation between vineyards on vine water- as well as nitrogen status in the Medoc area (Bordeaux, France). Choné *et al.* (2001) claimed soil to be the only variable in their survey and found distinct differences in wine quality from some of the different soils studied. Studies of the effect of soil on wine quality are further complicated by the modification of these effects through the intervention of man (Fregoni, 1977).

2.2.1.1 Physical soil properties

According to Conradie *et al.* (2002), it is mainly the physical properties of a soil that affect wine quality by determining drainage, soil temperature, water supply and water reserves, therefore also controlling the growth pattern of the vine. Northcote (2000) noted that the physical properties of a soil could affect tillage operations, entry and passage of water through the soil, aeration, growth of plant roots and the liability of the soil to erosion. A selected few of these physical properties will be discussed in the following paragraphs:

Soil depth variation: A key feature for a good vineyard site is efficient root penetration into deeper soil layers, as well as adequate exploitation of the topsoil by finer roots (Jackson & Lombard, 1993). When this is limited at some locations in the vineyard through root impeding layers, it will lead to reduced quantities of water and essential nutrients available to the vine (Saayman, 1981a; Van Huyssteen, 1988) and subsequent reduction in vigour. Root impeding layers can therefore be seen as a very important source of vigour variability in the vineyard. These impeding layers can be the result of physical factors such as high bulk density, a fluctuating free water table, solid or weathering bedrock, alternating texture layers or chemical factors such as low soil pH (potentially resulting in aluminium toxicity) (Burger, 1977; Van Zyl & Van Huyssteen, 1979).

Soil Texture/Structure: Soil texture and structure may affect factors such as soil erodibility, available water capacity and nutrient status and availability (Northcote, 2000). Rocky soils are generally less fertile than non-rocky soils (Gladstones, 1992), which can lead to variability in vegetative growth in vineyards with alternating rocky and less rocky parts. However, it must also be considered that stony surfaces capture moisture better and are more shielded against surface evaporation (Gladstones, 1992). Areas in the vineyard with higher rock content also conduct more heat deeper into the soil, resulting in lower surface temperatures (Gladstones, 1992). This may in turn lead to less heat re-radiated to the bunch zone during the day. In cool climates, stony soils also warm faster in spring, causing earlier root growth, better root absorption, earlier and more even budburst and greater fruitfulness (Fregoni, 1977). It can therefore be concluded that even though rocky parts in vineyards may be less vigorous than less rocky parts, this does not necessarily mean the vines will be more stressed or lower yielding. In spite of all the positive effects mentioned, the higher reflection of radiation on stony surfaces may be detrimental to wine quality where high temperatures near the soil can lead to destruction of acids, aroma and polyphenols in fruit, resulting in “flat” wines (Fregoni, 1977). According to Seguin (1983), as well as Robinson (1994), neither geological origin nor soil texture could explain Bordeaux and Burgundy’s best terroirs as judged from wine quality. In these terroirs, they described extremely variable soil textures, with highly variable gravel and pebble (0-50%) and clay contents (negligible to 60%), as well as variable chemical properties. The former author, however, named two general aspects of the good vineyard soils that could be distinguished, namely: i) none of the soils were very fertile, but neither did vines show mineral deficiencies; and ii) vine water supply was regulated by soils to be only moderately sufficient through a combination of good drainage and water storing capacity.

Soil Colour: A soil's colour mainly depends on the parent material from which the soil was formed, as well as soil forming factors (Saayman, 1981a). It may therefore vary considerably within vineyards, if more than one type of parent material is present, which is a common phenomenon in South Africa (Conradie *et al.*, 2002). Within-vineyard differences in soil colour may affect the air temperature closest to the ground, as well as the temperature of the soil itself, potentially affecting leaf physiology through the quality and quantity of the light reflected from it (Carey, 2001). Fregoni (1977) even considered the vines to be "between two suns", therefore considering soil reflection to be a very important factor. According to Van Zyl & Van Huyssteen (1979), very high soil temperatures may also decrease carbohydrate storage in roots.

Saayman (1981a) considered the soil characteristics associated with a certain soil colour to be more important than the colour itself. Red soils in high rainfall regions can normally be associated with good soil drainage, whereas darker soils may imply average to poor internal drainage. Light coloured soils, on the other hand, may point to extreme leaching and therefore nutrient deficiencies.

Various researchers have experimented with artificially coloured soils, some of them suggesting an effect of soil colour on the above ground growth, yield and root growth, whereas others (according to Fregoni, 1977) related the effect of colour to its modification of soil temperature, influencing the onset of root activity. Carey (2001), however, suggested that while these observations may be applicable to the cooler viticultural regions, it might not necessarily be the case in the warmer areas. The particular significance of orange to red wavelengths in the ripening of red grapes has already been shown (Smart, 1987). Smart *et al.* (1988) also showed that red light supplementation could increase nitrate reductase activity in leaves of potted Cabernet Sauvignon vines. This resulted in earlier fruit colouration and higher grape glucose and fructose concentration. Phytochrome control over leaf nitrate reductase as well as grape invertase and phenylalanine ammonium lyase activity has also been demonstrated by Smart (1991). Soil colour may therefore play an important role in fruit ripening processes as well as the quantity and quality of light reflected by the soil. In vineyards with high levels of soil colour variation, this may therefore induce variability in fruit ripeness levels as well as fruit quality.

Soil Water Status: Johnson *et al.* (1996) reported that canopy differences observed in remote sensing images acquired of a Californian vineyard could be related to either variation in soil water holding capacity or phylloxera infestation. Factors that could potentially affect the available soil water include soil depth, soil texture and soil composition (Carey, 2001). Conradie (1998) found the effect of soil type differences on Sauvignon blanc aroma profiles to be season dependent, but also mentioned that it was closely related to soil water status.

According to Smart (1995), water stress can be considered the most common environmental stress affecting grapevines worldwide, considering that grapes are commonly grown in Mediterranean climates, where water stress increases after stored winter rainfall becomes depleted. Smart (1995) also showed shoot growth to be very sensitive to water stress, the result being canopies with reduced shoot growth, less shading and more fruitful buds. Whereas moderate water stress may be favourable during berry maturation, water saturation in soils during ripening can have a negative effect on must composition, resulting in reduced sugar content, higher total acidity, higher concentration of tartaric and especially malic acids, as well as lower anthocyanin concentration in wines (Fregoni, 1977). Waterlogging can also result in weakened roots, increasing the susceptibility to attack by root-rotting organisms with a subsequent loss of vigour (Northcote, 2000).

Irrigation systems also can be a potential source of variability within a vineyard. This was confirmed by Long (1997), proposing “irrigation in good working order, with no plugged or missing emitters and no broken lines” as a measure to achieve uniformity in vineyards.

It can therefore be concluded that variability in soil water status within a vineyard may contribute strongly to within-vineyard variability, leading to heterogeneous growth and performance of vines throughout the vineyard.

2.2.1.2 Chemical soil properties

The origin of the soil as well as management practices such as draining, liming and soil nutrition affects the chemical and physicochemical properties of soils (Seguin, 1986). Some of these factors may vary considerably within some vineyards, which may lead to soil chemical variability.

Nutrients: Jackson & Lombard (1993) concluded that high soil nutrient levels with adequate moisture and temperature generally increases vigour, which can lead to reduced wine quality (high must pH, lower phenolic and aroma compound concentration), whereas high levels of nitrogen may also increase berry susceptibility to rot. Nitrogen is also an element often associated with high vigour, altering leaf to fruit ratios, increasing humidity and reducing sunlight penetration to inner leaves and berries (Jackson & Lombard, 1993). Choné *et al.* (2001) linked total berry nitrogen content values to soil organic matter content, whereas Conradie *et al.* (2002) linked high cane masses obtained at certain localities within vineyards to soils containing relatively high amounts of organic material.

Soil pH and salinity: According to Saayman (1981b), pH (KCl) levels of between 5.0 and 7.5 are normally not limiting to vine growth and nutrition, with no resulting effects on wine quality expected between these levels. He noted however, that free lime, often associated with higher pH values in soils, might have an effect on wine character, whereas the high levels of alkali- and alkali-earth ions associated with high pH levels may lead to higher total cations in the must, resulting in an increase in must pH.

Conradie (1988) found root development in acidic soils to be restricted, probably because of unfavourable soil physical structure, as well as aluminium toxicity. Literature quoted in Fregoni (1977) suggest that a low pH can favour the absorption of micronutrients (with the exception of molybdenum), whereas higher pH in turn favours macronutrient absorption. In recent studies by Australian researchers, vigour and yield maps of vineyards were used to show that soil salinity was the underlying cause for poor productivity at some vineyard sites (Bramley *et al.,* 2001). The effect of salinity on the grapevine will be discussed in more detail in Chapter 3.

2.2.2 VINEYARD LAYOUT

Site selection as well as vineyard layout considerations will affect the growth, performance and quality potential of the vineyard over a long period. In theory, the size, shape and position of a vineyard block is normally chosen to form an economic unit consisting of a single scion cultivar, situated on a uniform soil type, therefore requiring mostly uniform vineyard practices (Boehm & Coombe, 1999). In practice, however, the latter is not always attainable, especially where large variability in soil types is found. In some cases, it is therefore inevitable to include several soil types within a vineyard during layout. This is why within-vineyard soil variability is managed in South Africa before planting through adaptation of long-term practices such as rootstock choice, trellis height, within row spacing and through the adaptation of soil preparation implements and methods (E. Archer, University of Stellenbosch, personal communication, 2002).

2.2.2.1 Soil type boundaries

French vintners used the knowledge they acquired regarding vineyard variability over a long period to establish vineyard block boundaries that minimised variability in the harvest (Johnson *et al.*, 2001a). In South Africa, however, the establishment of vineyard block boundaries based on soil type variability has only been practiced since the early 1990's, typically involving a detailed soil survey supplemented by topographical and environmental information (E. Archer, University of Stellenbosch, personal communication, 2002).

According to Saayman (1981a), vines show great adaptability to various soil types, theoretically making it possible to plant vineyards on a wide variety of soils, but with varying levels of success. If soil types therefore vary considerably within a vineyard, it is these "varying levels of success" attained that can lead to vigour differences within vineyards. Conradie *et al.* (2002) also reported the effect of soil type on several vegetative and reproductive parameters of the vine.

If a detailed soil survey is conducted before planting, vigour variability may be reduced through better block layout and/or adapted management practices, but the question has to be posed whether or not the 75 m grid system often used in these soil surveys is sufficient. According to R. Bramley (CSIRO, Australia, personal communication, 2003) precision viticulture studies in Australia are increasingly showing the benefits of not using a grid system for soil surveying at all, but rather targeting soil profile pit positions after collecting information on soil variability via other methods (such as EM38 surveys).

2.2.2.2 Mesoclimate variation

Saayman (1981a) defined mesoclimate as the climate in a specific vineyard, which is affected by its location. Carey (2001) referred to it as a "vineyard climate", "topoclimate" or "site climate" that has a strong interaction with the other environmental components of climate and soil. According to Smart & Robinson (1991), mesoclimate may vary over ten to hundreds of metres, or by several kilometres. The extent of this variation will, according to Smart (1982), depend on the topographic variability. Gladstones (1992) also confirmed this by referring to "site climate" as a term that could be used synonymously to mesoclimate, but also stated that it alternatively could be used to describe the climate within parts of vineyards. For instance, a large vineyard situated over a hillock might have aspects that face north in one section and south in another, leading to variable levels of sunlight interception and therefore differing canopy temperatures. Vineyard block layout therefore has to consider these factors, especially when having to consider a high level of topographic variation.

2.2.2.3 Topography

Schultz, as reported by Carey (2001) described topography as a static landscape feature that can be described by altitude and its rate of change over distance. Some of its elements can show considerable variation within vineyards, such as aspect, slope inclination and slope shape. According to Carey (2001), aspect can affect the prevailing temperature on a slope via sunlight interception as well as wind exposure. The effect of topography on temperature variation may be an important factor affecting grape and wine quality (Gladstones, 1992). Johnson *et al.* (2001a) also referred to topographically induced variability in drainage and microclimate contributing to the production of fair to poor wines in a three-hectare Chardonnay block situated on a very hilly terrain in the Napa Valley.

It can therefore be concluded that the combination of variation in soil, mesoclimate and topography can have important effects on the growth of the vine and, eventually, wine quality.

2.2.3 MANAGEMENT PRACTICES

Although vineyard management practices are aimed at creating more homogenous canopies, it may lead to variability in fruit quality if not performed correctly. These practices are also usually performed by teams or individuals with different levels of expertise or training. This may be very important to consider, especially with practices such as the making of planting holes at vineyard establishment, which can introduce huge variability in vine performance over the long term if not performed correctly.

Soil preparation before planting can also play a very important role in affecting variability within vineyards. The effects of soil preparation on vine performance can especially play an important role in non-irrigated vineyards, where effective deep soil tillage is necessary to promote root systems that can exploit subsoil moisture during drought periods (Van Huyssteen, 1988). Soil preparation on undulating landscapes may also lead to variable depth of tillage and resulting variation in rooting depth that can become a major cause of within-vineyard variability.

According to Berqvist *et al.* (2001), canopy management practices that provide high amounts of diffuse light in the fruiting zone, rather than direct light exposure, are best suited to warm regions. Injudicious canopy management practices can cause variability in fruit exposure levels (Berqvist *et al.,* 2001), potentially having a large effect on fruit quality. Management practices such as shoot thinning, vigour control and trellising can play an important role in modifying canopy microclimate (Smart, 1985), and may therefore also induce canopy microclimate variability if large vigour variability in vineyards is not considered in its application.

The application of different levels of fertilisation within the same block has been performed in South Africa in some vineyards to minimise the effects of soil variability within a block (E. Archer, University of Stellenbosch, personal communication, 2002). When this is not performed in vineyards with highly variable levels of soil nutrients, and fertilisation is performed on the block as a whole, the end-result may only be an increase in vigour variability.

2.2.4 BIOTIC COMPETITION

Next to soil variability, pest, disease and weed competition may be the most important reason for variation in vine vigour. Detail on the characteristics, distribution and potential effects of these types of competition can be found in several literature sources (Marais, 1981; Buchanan & Amos, 1999; Emmet *et al.*, 1999) and will not be presented in detail here. It is important to note, however, that the monitoring of disease in vineyards has been one of the most important objectives in the initial investigations launched into remote sensing in viticulture. One of the first major projects launched in California from 1993 was a project called Grapevine Remote Sensing Analysis of Phylloxera Early Stress (GRAPES) (Bell, 1995; DeBenedictis *et al.*, 1995; Baldy *et al.*, 1996a, 1996b; Johnson *et al.*, 1996; Lobitz *et al.*, 1997; Omer *et al.*, 1999; Peterson & Johnson, 2000). In this investigation, multispectral remote sensing was used to monitor reduced leaf chlorophyll levels, as well as reduced biomass of vines that were infected with phylloxera.

2.3 THE NECESSITY OF IMPROVED TECHNIQUES TO MEASURE VIGOUR VARIATION WITHIN VINEYARDS

The main problems with conventional techniques of vigour measurement used in viticultural management are amongst others: i) the limited scale of these measurements; ii) its labour intensiveness; iii) experimental error; and iv) the difficulty to quantify and explain differences between measurements. Some of these problems were named by Wolpert (1999) when referring to the measurement of canopy structure, but it can also apply to other measurements made (such as trunk circumference or pruning mass). For a vineyard management plan to be successful, improved techniques of vigour measurement are therefore needed that also account for variation in the vegetative and reproductive properties of vines within a vineyard. This is especially relevant when vineyard sampling for harvesting at optimum ripeness levels is considered.

The use of remote sensing and yield monitoring are examples of these techniques, which can be used to show the spatial distribution of conventionally measured parameters, if these parameters should be well correlated with the results from conventional measurement techniques.

The main goals with these improved measuring techniques are amongst others: i) to choose the best location for conventional sampling techniques, or in some cases to infer sampled values into other areas through the measurement of correlating factors ("targeted sampling" as referred to by Bramley, 2001b as well as Profitt & Hamilton, 2001); ii) to target areas of differing vigour and adapt management practices accordingly (Nemani *et al.*, 2001; Profitt & Hamilton, 2001); and iii) to determine through change monitoring technologies if these practices had the desired effect.

2.4 REMOTE SENSING CONCEPTS FOR VITICULTURE

With the establishment of new technologies that have the ability to capture images of spatial vigour variation and in addition overlay and analyse large amounts of supplemental data with Geographical Information Systems (GIS), it has become possible to analyse vigour variability in vineyards for more purposeful management. This approach, originally developed for perennial crops and pastures, is based on the monitoring of yield, growth, fertilizer application and other techniques and is termed "precision agriculture" (Cook & Bramley, 1998). Of these technologies, spatial information systems that may be used to give viticulturists a greater understanding of the vine's response to management practices under varying natural conditions (Smith, 1998). This could enable producers to differentiate their management techniques between different parts of the same block, rather than following a recipe approach for the whole block. The term "precision viticulture" is used to describe the concept of monitoring and managing spatial variability in yield and quality factors within single vineyards (Lamb & Bramley, 2001; Lamb, 2001b).

Geographic information is important in viticulture because of the inherent spatial nature of many of the variables affecting grape quality (Smith, 1998). It can therefore offer a spatial perspective into vineyard management, giving the viticulturist an idea of the extent (spatial distribution) and intensity of vigour variability in vineyards (De Blij, 1983).

Several studies in remote sensing have already shown the potential it has in the qualitative analysis of several crop types. Though this in itself has great value, the goal should still be to extract quantitative information if the full potential of remote sensing is to be realised (Nemani *et al.*, 2001). It is therefore important that ground truth data measuring vigour variation should be used to establish strong links between quantitative measurements and image data, allowing for both spatial and temporal comparison of data between vineyards.

2.4.1 GENERAL CONCEPTS

Remote sensing may be defined as the ability to measure an object's properties without touching it (USWCL, 2001). The sun's energy covers a broad region of the electromagnetic spectrum (Fig. 2.4). Each region of the spectrum can be defined by a unique waveform, which is characterised by its wavelength. The wavelength of a wave can be defined as the distance between two successive wave-peaks or –troughs, which is measured in micrometers (1 µm = 10^{-6} m) or nanometers (1 nm = 10^{-9} m) (Fig. 2.5).

Objects appear to display different colours owing to pigments that absorb and reflect different wavelengths in the electromagnetic spectrum. Passive sensors can detect regions of the electromagnetic spectrum not visible to man, providing much additional information on an object and its reflectance (Servilla, 1998).

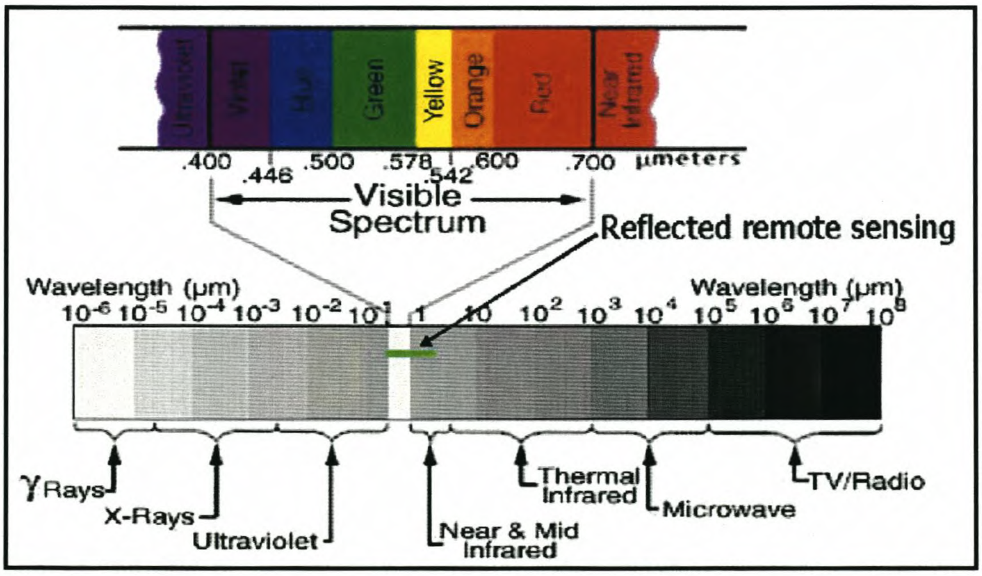

Figure 2.4 The electromagnetic spectrum (De Jong & Sluiter, 2001).

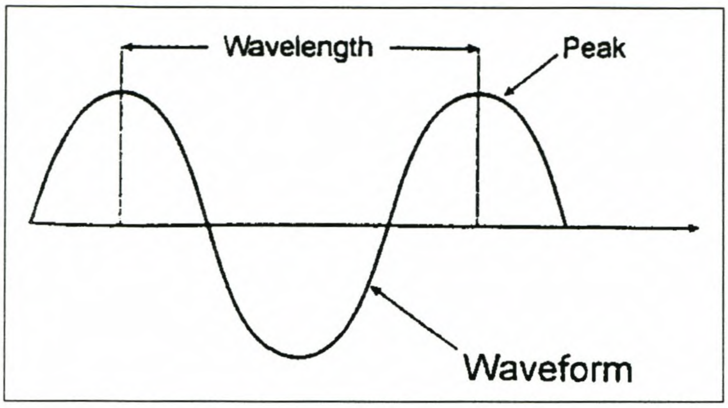

Figure 2.5 Typical waveform for electromagnetic energy (illustration from Servilla, 1998).

Remote sensing in agriculture commonly utilises the visible, near infrared (NIR) and thermal infrared parts of the spectrum (USWCL, 2001), whereas new applications in the microwave region are under development. Spectral regions within the electromagnetic spectrum are shown in Table 2.3.

Table 2.3 Spectral regions within the visible and infrared spectrum (USWCL, 2001).

Visible		Infrared	
400-450 nm	Violet	700 – 3000 nm	Near infrared
450-500 nm	Blue	3000 – 14 000 nm	Thermal infrared
500-550 nm	Green	14000 nm – 1 mm	Far infrared
550-600 nm	Yellow	~400 – 1000 nm	Visible near infrared
600-650 nm	Orange	1000 –2500 nm	Shortwave infrared
650-700 nm	Red		

Two sensor types are generally used in agricultural remote sensing. The most common type is a passive sensor that measures reflected light from the object's surface. Active sensors, on the other hand, use an energy source within themselves to transmit and receive their own signal (such as radio detecting and RADAR systems) (Servilla, 1998). A radiometer is an instrument used to measure the amount of energy radiating from a surface (radiance, or radiant energy) in a particular part of the electromagnetic spectrum. Considering that the radiation arriving at an object (irradiance) can vary by time of day and atmospheric conditions when the sun is the source, radiance has been found to be suboptimal as an indication of an object's physical properties (USWCL, 2001). Apparent reflectance (the ratio of radiance to irradiance) is therefore calculated instead. Aspects that complicate the measurement of reflectance include the instrument's viewing angle and the angle of the sun, complicating its accurate determination (USWCL, 2001).

2.4.2 SPECTRAL PROPERTIES OF VEGETATION

A model describing the possible reactions of light reaching a leaf's surface is shown in Fig. 2.6. Although this may differ between cultivars and growing conditions, a vine leaf generally reflects (R) about 10% of incident radiation (I), while transmitting (T) only 9%. Of the 81% absorbed by the leaf, 20% is re-radiated, 60% is used in transpiration and convection and only about 1% is used in photosynthesis (Champagnol, 1984). While only 10% of visible light is reflected, infrared light is reflected to a much higher degree (40 to 50%).

Remote sensing generally aims to measure either the presence of reflected green or infrared light, or the absence of blue and red light absorbed by chlorophyll. The two primary components of solar energy interacting with vegetation therefore include visible and infrared energy. This interaction largely takes place within the leaves of plants. A vine leaf (Fig. 2.7) consists of chlorophyll rich tissue (mesophyll tissue) with two structurally different layers, namely the palisade and spongy parenchyma layers.

The palisade chlorophyll absorbs most incoming visible energy for use in photosynthesis, with better absorption of red and blue energy than green energy, causing the green appearance of vegetation (Fig. 2.8). Infrared energy is not affected by chlorophyll, but the longer wavelengths interact directly with the leaf cell structure. Palisade cells are vertically aligned, causing infrared energy to pass through unchanged, while being met by an open cell structure in the spongy layer, causing about half of it to be reflected back through the leaf. Nemani *et al.* (2001) referred to the red wavelength band as the chlorophyll absorption band and to the near-infrared band as the internal leaf scattering band.

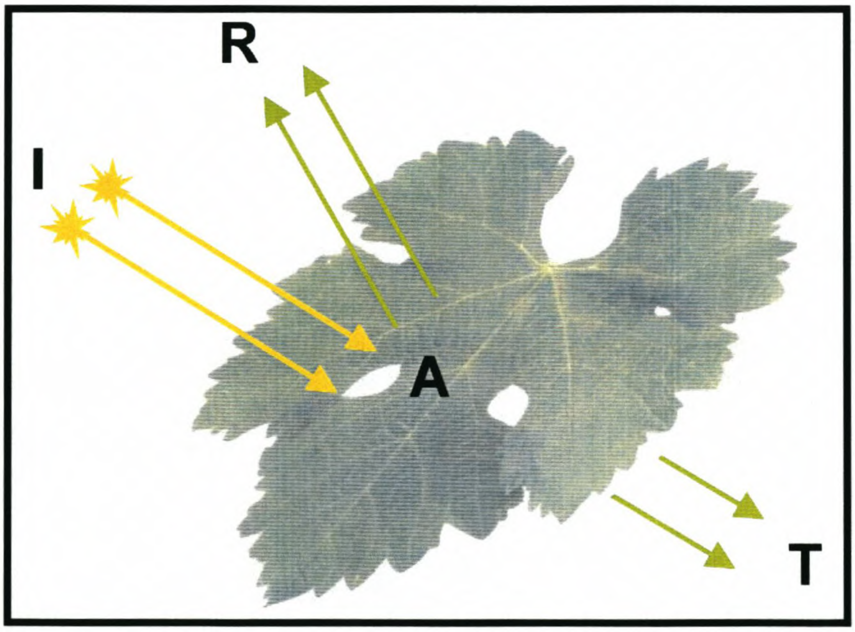

Figure 2.6 Absorption (A), reflection (R) and transmission (T) of incident radiation (I) for a grapevine leaf (adapted from Champagnol, 1984).

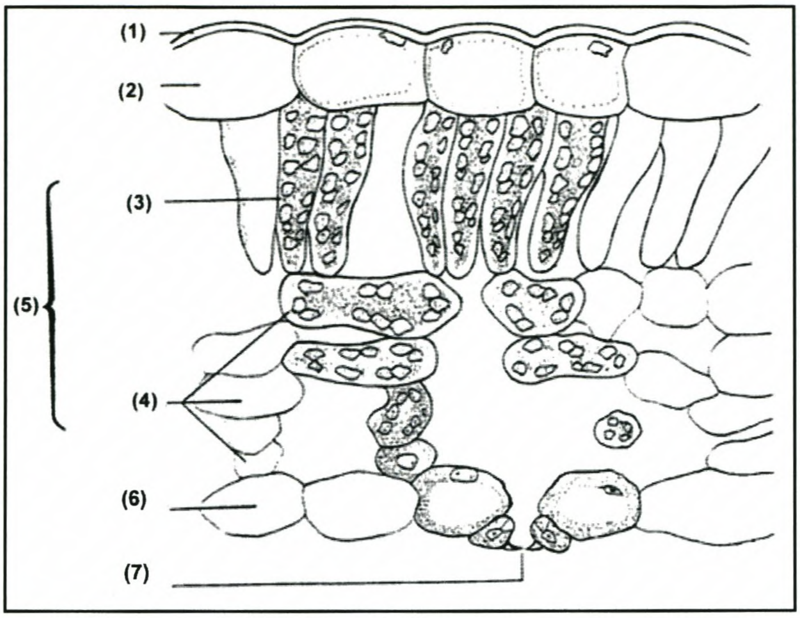

Figure 2.7 Cross-section of a mature vine leaf. (1 – cuticle; 2 – adaxial epidermis; 3 – palisade parenchyma; 4 – spongy parenchyma; 5 – mesophyll; 6 – adaxial epidermis; 7 – stomatal opening) (Archer, 1981).

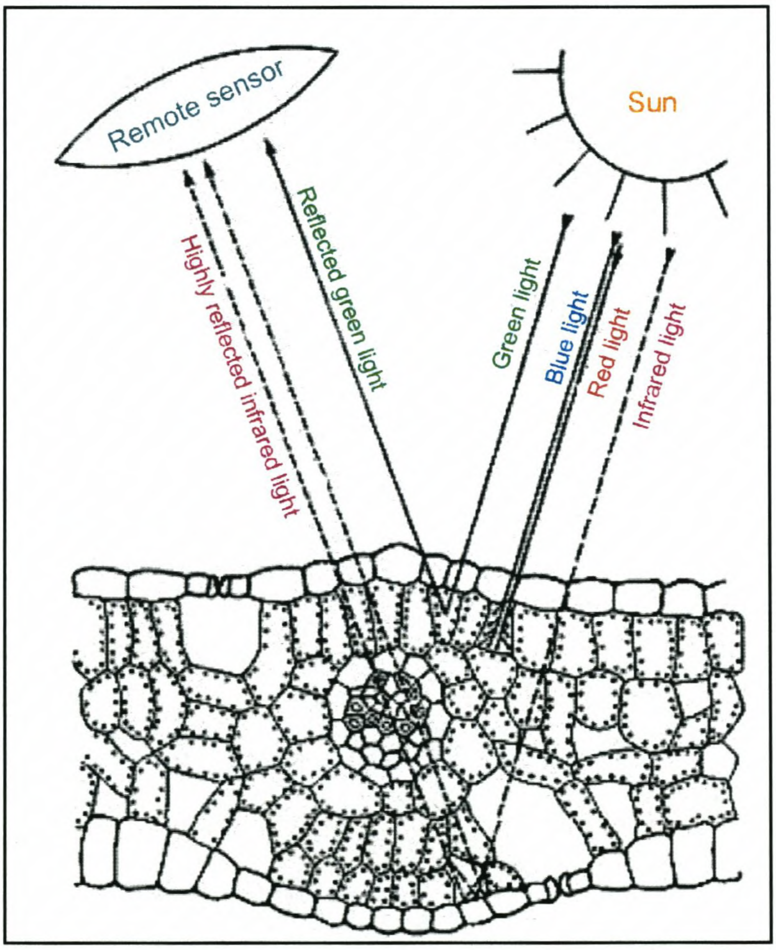

Figure 2.8 Plant leaf cell structure and interaction with radiation (NASA, 2001).

Generally, healthy leaves of the same species will reflect more near-infrared energy from the spongy mesophyll. On the other hand, damaged leaves reflect more visible energy, owing to decreased chlorophyll levels and therefore decreased absorbance of red and blue energy. Green leaves generally show a reflectance of 20% or less in the 500 to 700 nm range (green to red), with approximately 60% in the 700 to 1300 nm range (near-infrared) (NOAA(CSC), 1998). The latter explains why passive near-infrared sensors are much more sensitive to changes in plant health than visible light sensors (general light photography) (Servilla, 1998).

The typical reflectance spectra of soil and canopies are also shown in Fig. 2.9. The peak in the canopy spectra (green) around 550 nm in Fig. 2.9 explains why plants appear green (higher reflectance in this portion), while the "dip" in the crop spectra around 690 nm can be ascribed primarily due to chlorophyll absorption. The canopy reflects less in the red region compared to the soil, but much more in the NIR, which is ascribable to plant leaf structure (USWCL, 2001). Yellowing of plant leaves under senescence or severe stress is the result of increased green as well as red reflectance, which in combination creates the yellow colour (USWCL, 2001).

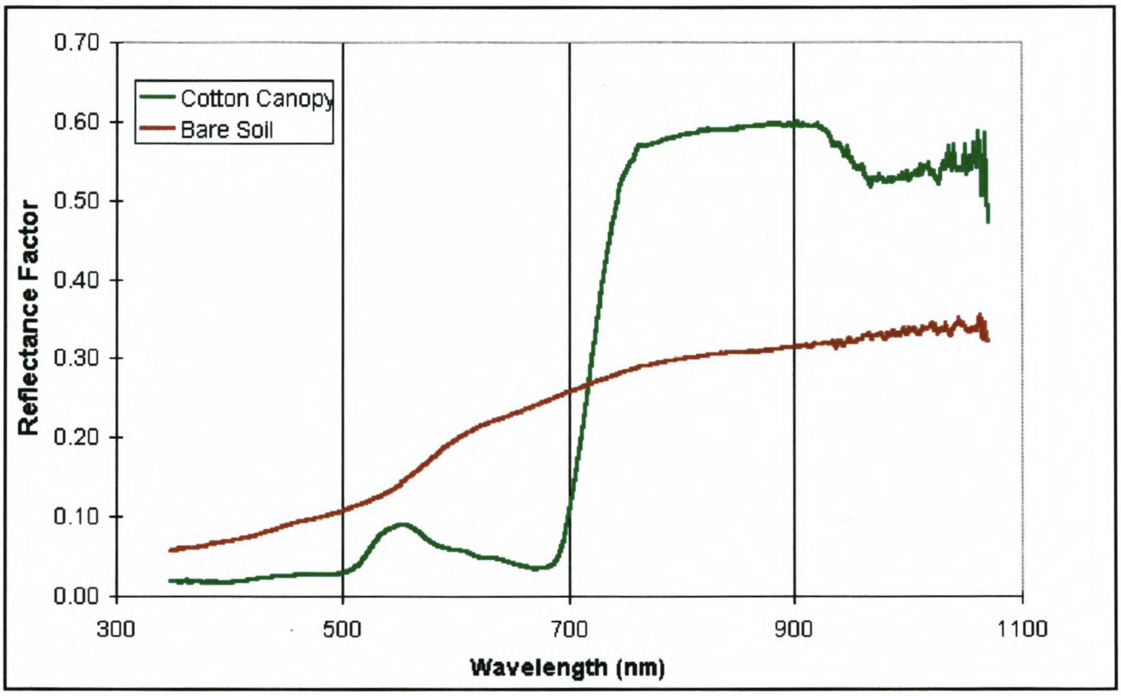

Figure 2.9 Typical reflectance spectra of soil and cotton canopy (USWCL, 2001).

In contrast with near-infrared energy, mid-infrared and thermal-infrared energy is not affected by either chlorophyll or cell structure, but rather by the water content within the leaf, owing to the absorption of energy by water in this regions (Servilla, 1998). According to the USWCL (2001), thermal-infrared radiance measurements can be used to indicate water stress by measuring leaf surface temperature as altered by transpiration levels.

2.4.3 VEGETATION INDICES

Vegetation indices derived from the near-infrared and red spectral bands have been shown to correlate highly with the green leaf area index (LAI), chlorophyll content, photosynthetically active biomass, vegetation density, photosynthetic rate, percent ground covered by vegetation and grain or forage yield (Wiegand *et al.*, 1991).

Vegetation indices are combinations of spectral measurements in different wavelengths recorded by a radiometric sensor, proving valuable in multispectral image analysis by shrinking multidimensional data into single values (Dobrowski *et al.*, 2002). Huete *et al.*, (1994), defined vegetation indices as follows: "it is dimensionless radiometric measurements of the red and near-infrared portions of the spectrum. . . (which) may be computed from digital counts of satellite radiance, apparent reflectance, land-leaving radiance or surface reflectance and require no additional ancillary information other than the measurements themselves . . . what vegetation indices specifically measure remains unclear, . . . they serve as indicators of relative growth and/or vigour of green vegetation, and are diagnostic of various biophysical vegetation parameters".

Both satellites and digital cameras can measure light as a digital number (DN), making it possible to do mathematical calculations on the resulting images. Both reflectance and radiance DN's may be used to calculate vegetation indexes, but calculations done from radiance may give inconsistent results when images of the same areas are compared on different dates (USWCL, 2001).

Vegetation indices are designed to minimise factors that lessens the strength of its correlation to plant parameters (variable irradiance, variable spectral background conditions of soil and/or groundcover, shadows, senescent vegetation presence, atmospheric conditions, sun-sensor geometry and instrument calibration) and to maximise its sensitivity towards plant biophysical parameters (Dobrowski *et al.*, 2002).

Most vegetation indices fall into one of two main categories, namely ratio indices and orthogonal indices (Dobrowski *et al.*, 2002).

2.4.3.1 Ratio vegetation indices

The first index in this class is the ratio vegetation index (RVI), defined by:

$$RVI = \frac{NIR}{R}$$ (Pearson & Miller, 1972)

Its value can range from slightly more than 1 for bare soil to more than 20 for dense vegetation. The second type is the normalised difference vegetation index (NDVI), defined by:

$$NDVI = \frac{(NIR - R)}{(NIR + R)}$$ (Rouse & Schell, 1974)

This index compensates for different amounts of incoming light, and produces numbers between zero and one (for example 0.1 for bare soils to 0.9 for dense vegetation). Large proportions of exposed soil often found in vineyards, lead to lower mean NDVI values (Johnson *et al.*, 1996). The NDVI index is also known to be more sensitive to low levels of vegetative cover (saturation at high vegetative cover). The RVI, on the other hand, is more sensitive to changes in canopy density in more dense canopies (USWCL, 2001).

Servilla (1998) showed the usefulness of an NDVI-index in the assessment of plant health in a cornfield compared to colour-infrared imagery. The NDVI imagery revealed two areas of stressed vegetation (an area of poor drainage and an area of sloped ground, resulting in poor soil moisture retention), not detectable in the colour infrared images. The NDVI-index was also shown to be well correlated with biomass, pruning mass and LAI (Tucker, 1979; Asrar *et al.*, 1984; Daughtry *et al.*, 1992; Johnson *et al.*, 2001b; Nemani *et al.*, 2001).

Johnson *et al.* (1996) showed a positive correlation between the reflectance of NIR light from the canopy and leaf area index, while reflectance of red light negatively correlated with leaf area. Johnson *et al.* (1996) also stated that in addition to its sensitivity to leaf area, NDVI tends to lessen the effect of difference in brightness associated with solar illumination or sensor viewing angle. This was confirmed by Lobitz *et al.* (1997), stating that it also compensates for the effect of differences in sunlight intensity, slope and viewing geometry, and is consistent between different sensors and different flyovers. In addition to this, Johnson *et al.* (1996) found that the absolute NDVI values might be affected by other factors such as the temporal variation in atmosphere and sensor response. This can be compensated for by creating a “relative NDVI”, where each NDVI pixel is colour coded and assigned to a predefined number of levels, ranging from low to high NDVI values.

Dobrowski *et al.* (2002) showed that the calculated values of the RVI and NDVI indices contain similar information, as shown by similar r^2-values when both are related to canopy density. This was consistent with the fact that both indices are seen to be functionally equivalent as implicated in the following relationship:

$$RVI = \frac{(1+NDVI)}{(1-NDVI)} \quad \text{(Perry \& Lautenshlager, 1984)}$$

Dobrowski *et al.* (2002) however noted that this did not necessarily indicate that these indices were equivalent in their application to remote sensing. In order to find which vegetation indices would be best suited, Dobrowski *et al.* (2002) individually analysed red and NIR spectral behaviour in relation to vine leaf area (Fig. 2.10). Reflectance in the red band decreased with an increase in canopy density due to increased red absorption by chlorophyll. The NIR response showed a weak positive linear response that is almost indiscernible due to the noise in the measurements, indicating that the red band carries the predominant vegetation signal.

Dobrowski *et al.* (2002), however, stressed that this does not mean that the NIR band carries no information. Analysis of covariance between the NIR and red bands with the effect of canopy density showed a weak positive correlation (r^2=0.30) between the two bands. High or low values of red reflectance at certain canopy density levels are generally associated with corresponding values in the NIR reflectance as shown by the numbered points in Fig. 2.10.

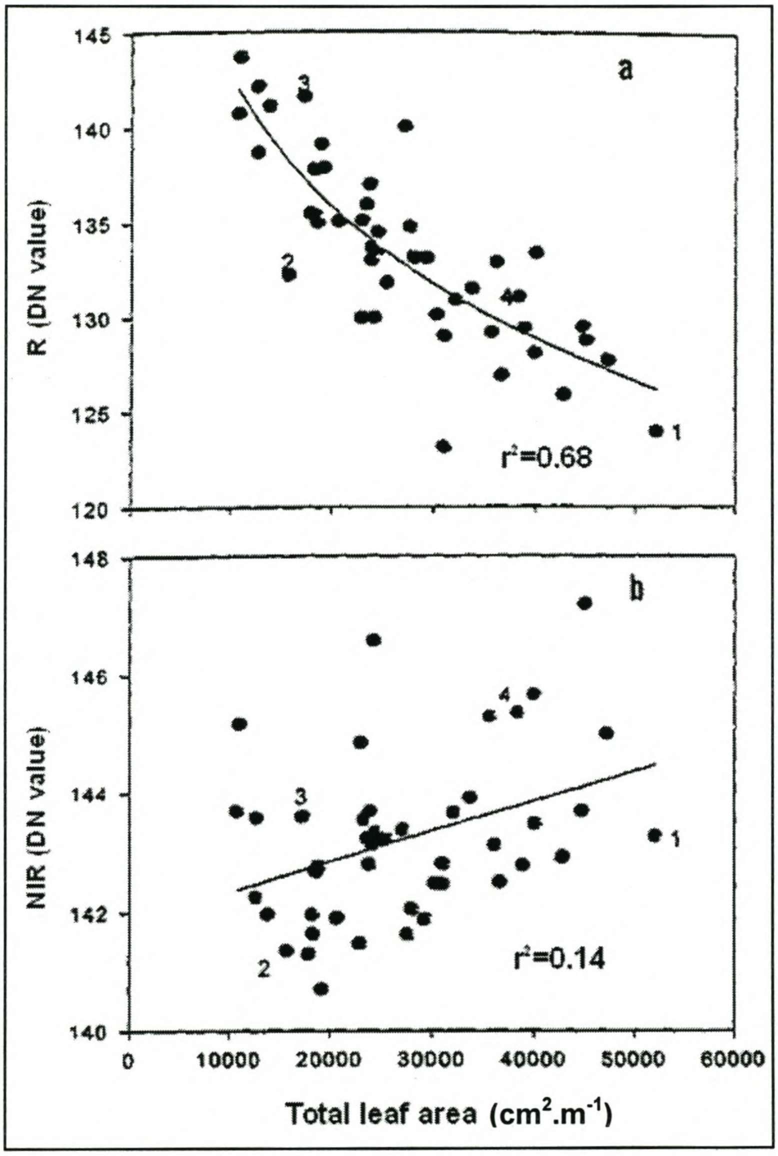

Figure 2.10 Relationship between red and near-infrared values and canopy density in a vine spacing trial. Corresponding numbered points between plots A and B represent red and NIR values obtained from the same treatment area (Dobrowski *et al.*, 2002).

This parallel behaviour between the bands was described by Chen (1996), and is caused by scene components that cause simultaneous increases or decreases in the red and NIR irradiance, such as dissimilar spectral features and shadows. When calculating the ratio of the two bands, scene-induced noise is removed (biases introduced by the noise in the two bands are often roughly in the same proportion).

An important conclusion made by Dobrowski *et al.* (2002) is that although NDVI reduces noise because of its functional equivalence to the RVI, it also normalises the difference between the red and NIR bands by their sum, leading to a non-linear relationship with vegetation parameters. RVI may therefore be a better index compared to NDVI in vertically shoot-positioned vineyards, due to its linearity and consequent sensitivity to a wide range of canopy densities (Dobrowski *et al.*, 2002).

2.4.3.2 Orthogonal vegetation indices

This category of vegetation indexes is calculated by measuring the orthogonal distance between the canopy reflectance response and that of the soil background.

The perpendicular vegetation index (PVI) measures the perpendicular distance of the vegetation spectral response from the soil background reflectance with the goal of partly reducing its effect:

$$PVI = \sqrt{\left(R_{soil} - R_{veg}\right)^2 + \left(NIR_{soil} - NIR_{veg}\right)^2}$$ (Wiegand & Richardson, 1984)

Subsequently, the following soil adjusted vegetation index (SAVI) was developed by Huete (1988):

$$SAVI = \frac{(NIR - R)}{(NIR + R)} \times (1 + L)$$

The added terms adjust for differences in brightness of the background soil, with the term "*L*" in practice varying from 0 to 1 depending on the amount of visible soil (0.5 is used as a reasonable approximation when the amount of soil in the scene is unknown) (USWCL, 2001).

In a study by the USWCL (2001) to demonstrate the usefulness of the SAVI, eight-bit digital images were collected in the red as well as the NIR spectral regions from two plant leaves lying on bare soil. The image formed by subtracting the red image from the NIR image and applying the SAVI, showed that apart from the soil and stone background, even the ribs of the green leaves disappeared, since no chlorophyll is found there. A green patch visible on a yellowed leaf, which was also put in the image, was all that appeared white in the resulting image, with the rest appearing black (USWCL, 2001).

Honey (2000) also referred to other indices that may be of potential use in viticulture, such as the Plant Cell Ratio (PCR = NIR/Green), Photosynthetic Vigour Ratio (PVR = Green/Red) and the Plant Pigment Ratio (PPR = Green/Blue).

2.5 REMOTE SENSING AND THE MEASUREMENT OF FACTORS INVOLVED IN WITHIN-VINEYARD VIGOUR VARIATION

Johnson *et al.* (2001a) used field measurements to show clear differences between low and high vigour areas in the vineyard, as determined from the zoning of multispectral images. The field measurements included leaf, shoot, canopy and vine water status measurements (Table 2.4).

It has to be noted that while most measurements discussed here will focus on the aboveground growth of the vine, the growth and physiology of the root system is also important. The size and health of a grapevine's root system is in effect reflected by the aboveground growth, which is also confirmed by the loss of vigour in phylloxera- or nematode-infected vines (Smart, 1995).

Table 2.4 Vine measurements according to vigour zones as delimited through multispectral images (Johnson *et al.*, 2001a).

Variable	Vigour [a]	Mean (std. dev.) [b]	Sample Size
Pruning mass (kg)	L	0.65 (0.40)*	20 vines
	M	0.79 (0.21)	5 vines
	H	1.13 (0.48)*	10 vines
Number of shoots	L	13.5 (2.5)**	20 vines
	M	14.4 (1.7)	5 vines
	H	14.3 (2.1)	10 vines
Canopy transmittance (%)	L	39.9 (26.7)**	20 vines
	M	11.5 (13.4)	5 vines
	H	12.1 (11.3)	10 vines
Leaf water potential (MPa)	L	1.2 (0.15)**	36 leaves
	M	1.0 (0.1)*	9 leaves
	H	0.9 (0.12)**	18 leaves
Chlorophyll concentration (no unit)	L	40.8 (2.8)	20 vines
	M	39.3 (4.1)	5 vines
	H	42.5 (3.8)	10 vines

(a) L = Low
M = Moderate
H = High.

(b) (*) = Mean significantly different at the $p \leq 0.05$ level
(**) = Mean significantly different at the $p \leq 0.01$ level (according to *a posteriori* F-test)

Bramley (2001a) found that correlations between various measured grape and vine properties were generally poor when data were treated as a set of repeated measurements, but there were similarities in the spatial distribution of the data between some of the parameters (Fig. 2.11 and 2.12). Co-variation of soil and vine or grape indices was also shown to be inconsistent.

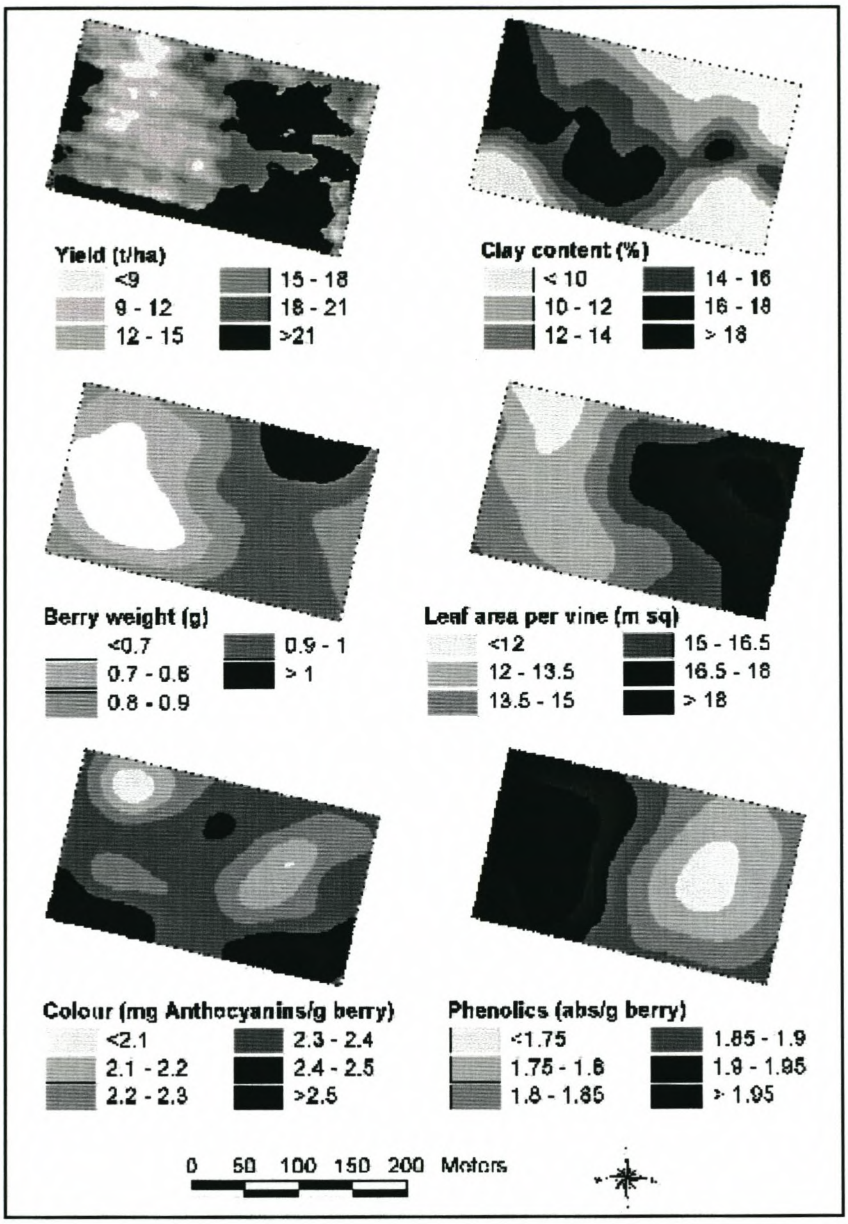

Figure 2.11 Variation in selected grape, vine and soil properties in a Sunrasya vineyard (Ruby Cabernet) (Bramley, 2001b).

2.5.1 SOIL CHARACTERISTICS

Images acquired by Johnson *et al.* (1996) were used as guidelines to place soil profile pits for soil investigation prior to replanting of a vineyard block. This was useful in identifying possible problem areas present between the areas covered by profile pits and served as a guideline for profile pit placing.

Remotely sensed soil electrical conductivity measurements have already been used as a surrogate measure for soil properties such as salinity, moisture content, topsoil depth and clay content (Sudduth *et al.,* 2000). According to Bramley (2001a), soil depth variation appeared to drive yield variation at some of his study sites. Bramley (2001a) used an instrument able to measure soil electric conductivity with electromagnetic waves, called the EM38, to create maps of inferred soil depth (Fig. 2.13). Many soil profile pits (190) were dug in the vineyard and soil depth information from this correlated very well with the estimated soil depth determined during the EM38 survey (Bramley, 2001a).

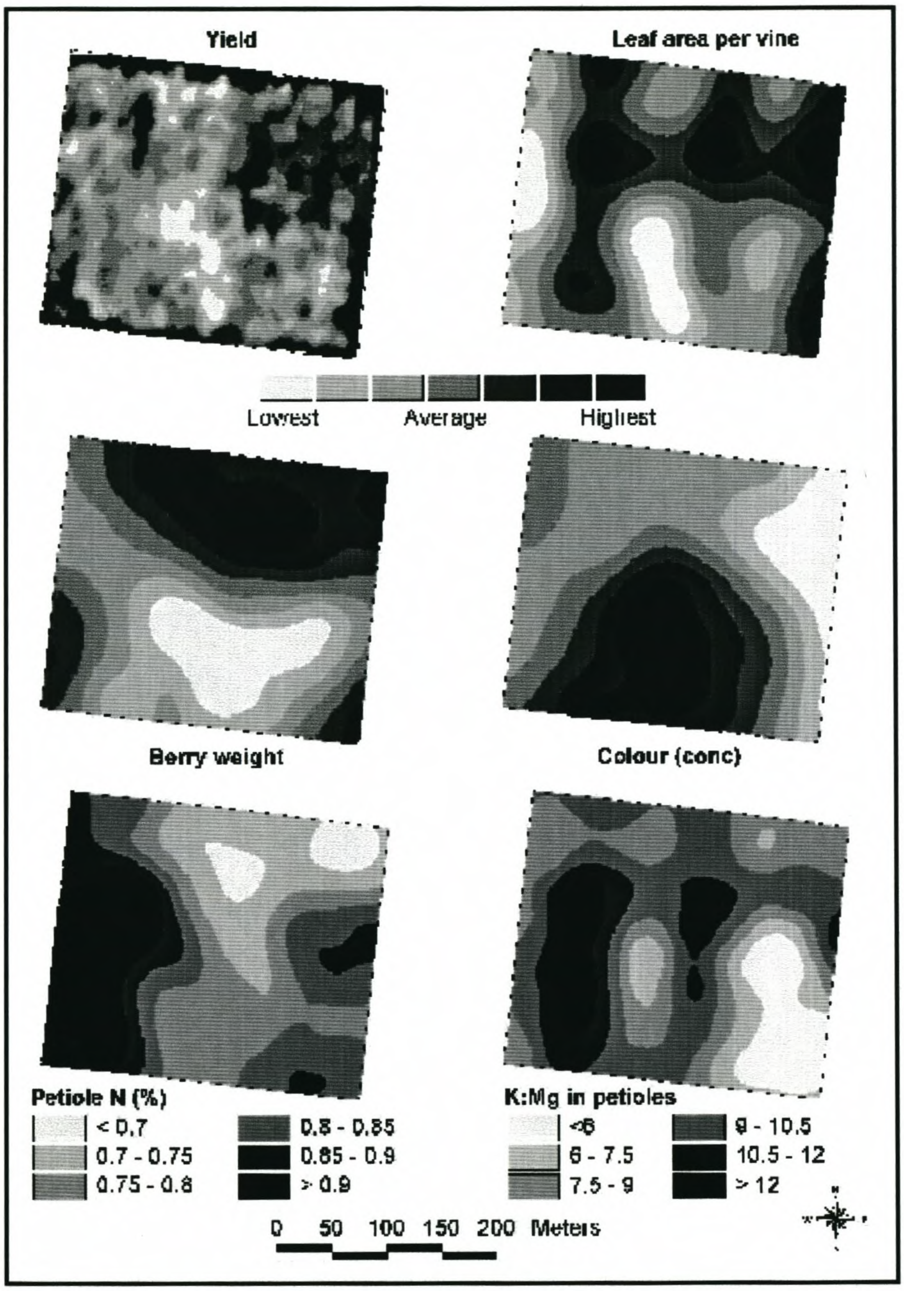

Figure 2.12 Variation in yield and selected vine and fruit indices in a Coonawarra vineyard (Cabernet Sauvignon) (Bramley, 2001b).

It therefore seems that recently introduced technologies such as EM38 surveys and remote sensing images can be valuable tools to supplement conventional soil surveys such as those done in South Africa on grids of 25 m, 50 m or 75 m, depending on the levels of variability. Even though these technologies will not necessarily replace soil surveys, recent developments in remote sensing technologies (such as ground penetrating RADAR and microwave technology) suggest that more accurate and less expensive soil surveys may be possible in future.

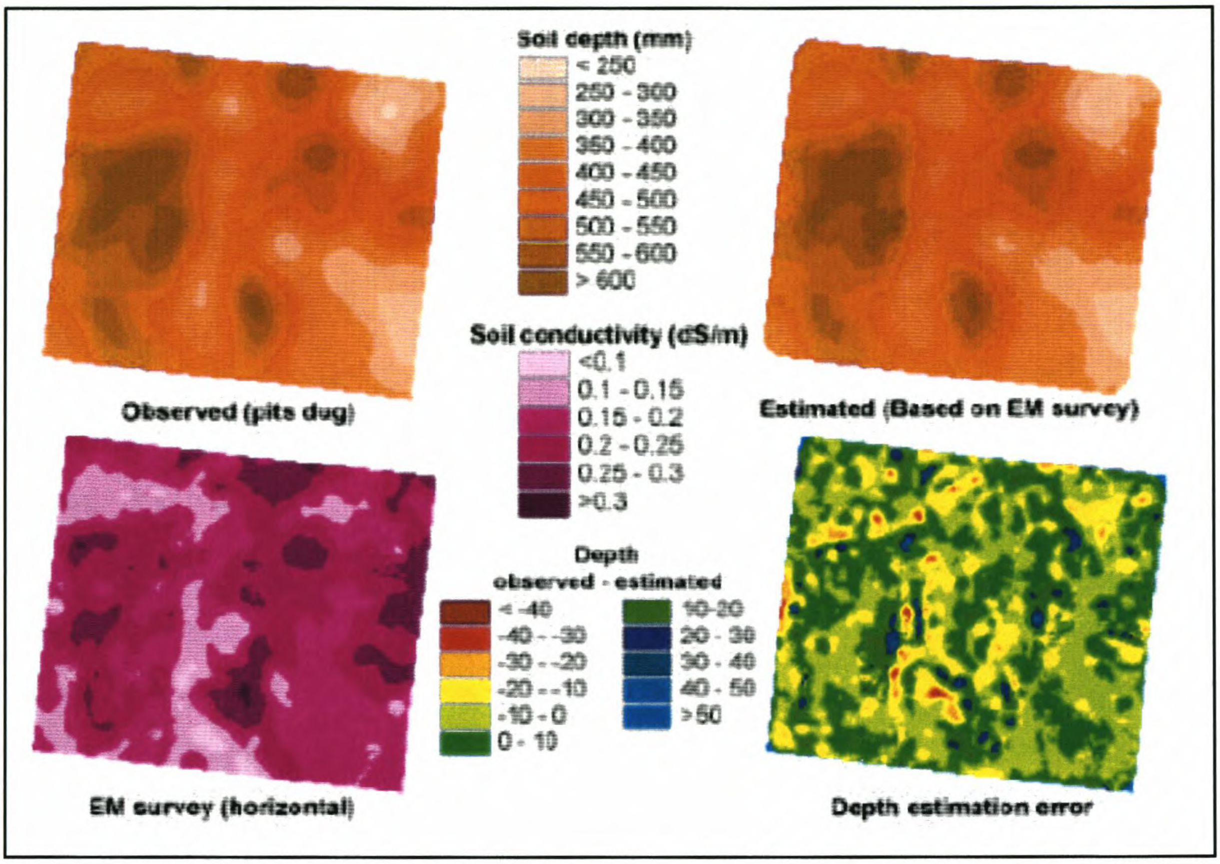

Figure 2.13 Inferred soil depth, as measured with EM38 remote sensing technology compared to observed soil depth as determined from 190 soil profile pits in a 7,5 hectare vineyard (Bramley, 2001a).

Taylor (2001) collected NDVI-images as well as subsoil apparent electrical conductivity (EC_a) using a similar instrument (Veris), with the resulting images showing a strong (r^2= 0.75) correlation between yield and NDVI (Fig. 2.14). The subsoil EC_a map also showed a similar spatial pattern than the yield map, but was negatively correlated, resolving approximately 56% of the variation in the yield map. The author noted that the EC-yield relationship might possibly stem from waterlogging, if irrigation scheduling is based on the lighter textured soil or heavier clay subsoil limiting root growth and penetration. However, no methodology or guidelines have yet been established for the correct use of EC_a data in vineyard layout (Taylor, 2001). According to R. Bramley (CSIRO, Australia, personal communication, 2003), steel posts in vineyards affect the EM38 signal significantly and makes it impossible to use the instrument successfully in these vineyards. EM38 soil surveys have been used also in a recent study by South

African researchers into the impact of dryland salinity on water quality in a river catchment (Fey *et al.*, 2002).

Ground penetrating radar might be another useful way to predict yield by plotting soil depth (Taylor, 2001), and investigations are launched into the use of gamma-radiometrics and mid-infrared remote sensing to map soil properties (R. Bramley, CSIRO, Australia, personal communication, 2003). In addition, airborne thermal scanner images have been used in Australia to detect irrigation deficiencies by linking colour patterns to vine stress (Smith, 1998).

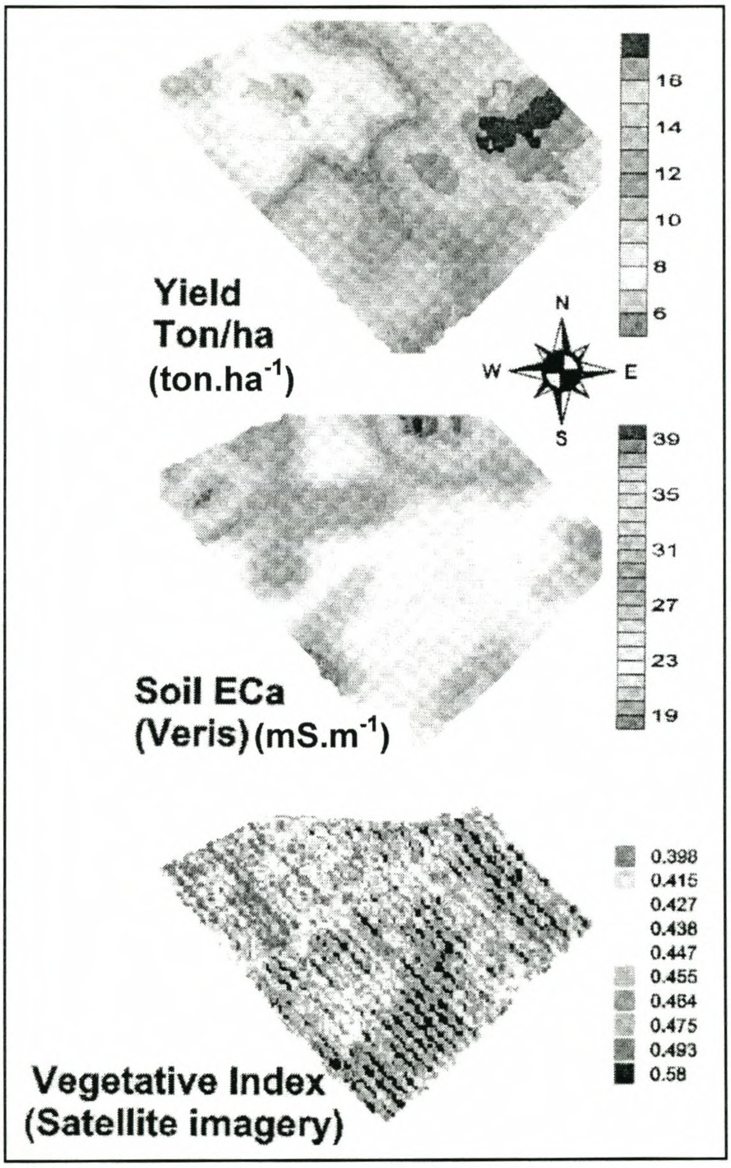

Figure 2.14 Comparison of spatial maps of yield, apparent soil EC and a satellite NDVI image (Taylor, 2001).

2.5.2 CANOPY CHARACTERISTICS

According to Lamb (2001a), more vigorous/dense vines will tend to have a higher near infrared reflectance owing to more leaves containing more water and improved cell structure and lower red reflectance due to stronger chlorophyll absorption. This will then lead to an increased infrared/red ratio, and therefore increased NDVI index values. However, it will be necessary to confirm with field studies if the higher NDVI found is due to more dense vegetation, higher chlorophyll concentration in the leaves, or simply larger canopies.

2.5.2.1 Pruning mass and shoot length

Pruning mass measurements conducted by Johnson *et al.* (2001a) confirmed the vigour level zoning established with remote sensing, with a positive correlation found between pruning mass and vigour level. This was also confirmed in another study by Johnson *et al.* (1996), where the processed relative NDVI values were significantly correlated (r^2=0.76) to field measurements of pruning mass. Baldy *et al.* (1996a) also showed a correlation of r^2=0.84 between the RVI and pruning mass. In another study by Johnson (2001a), measurement of the number of shoots per vine did not differ significantly between vigour zones, indicating that biomass differences were driven mainly by individual shoot vigour.

Pruning mass and shoot length convey useful information on vigour differences within vineyards as conventional measurement methods, and can be used to determine the optimal bud load that has to be assigned during winter pruning. Conradie *et al.* (2002) for instance showed cane mass of vines on a more humid soil to be significantly higher than that of vines on a drier soil in the same vineyard. Zeeman & Archer (1981) recommended the determination of pruning mass per vine for about 30 vines per hectare to use in calculations of the bud load that needs to be assigned during winter pruning, according to a preferred yield/pruning mass ratio. This ratio is an important determinant of the relationship between reproductive and vegetative growth in the vineyard (Zeeman & Archer, 1981; Smart *et al.*, 1990). Zeeman & Archer (1981) found ratios of between 4:1 and 10:1 to be optimal for Chenin blanc on different rootstocks and in different growing conditions, but they also noted that different ratios could be optimal depending on the scion cultivar and cultivation conditions. The use of the same bud-load per vine in a variable vineyard can therefore not be recommended and adaptation of bud-load within vineyards may be an important management tool to reduce the effects of within-vineyard vigour variability.

According to Archer (2001), the quality of a grape bunch can be directly related to the physiological quality of the shoot bearing it, with homogenous and top quality grapes coming from homogenous and even shoot strength. For each grape variety, there is an optimum amount of leaves necessary on a shoot for effective grape ripening. Archer (2001) measured shoot length in three vineyards along with grape juice measurements to determine the effect that variable shoot length can have on grape composition (Table 2.5). He noted that several of the different length shoots came from a single vine, therefore accentuating within-vine variability. Shorter shoot lengths produced grapes that could almost be classified as over-ripe, whereas long shoots produced predominantly unripe grapes, with the best quality grapes found on the medium length shoots, therefore also having the best potential for top-quality wines. For the three vineyards measured in the study by Archer (2001), the number of shoots that were either too short or too long to produce optimum quality wine was respectively 30%, 40% and 45%, which, according to the author, may lead to quality decrease in the wine of up to 50%. Factors that were to blame for this variability included bad young vine training practices and insufficient suckering of short shoots that had the potential to bear grapes. Long (1987) found that weak Cabernet Sauvignon shoots (shorter than 30 cm) produced berries with lower sugar, less colour and lower phenol concentrations. She referred to wines from "normal" shoots (1.2 m) as having "solid Cabernet fruit berry flavours" and less herbal qualities.

It has to be noted that canopy management practices such as topping of shoots may have a large effect on the pruning mass differences measured within a vineyard, and this has to be considered when interpreting shoot measurements.

Table 2.5 Grape composition of certain cultivars affected by different shoot lengths (Archer, 2001).

Cabernet Sauvignon / R99				
Shoot length (cm)	**Sugar concentration (˚B)**	**Acid concentration (g/l)**	**pH**	**Skin colour (520 nm)**
~ 60	23.4	5.2	3.8	1.203
~ 120	24.5	7.4	3.3	2.761
>200	21.9	8.9	3.2	1.078
Merlot / R99				
Shoot length (cm)	**Sugar concentration (˚B)**	**Acid concentration (g/l)**	**pH**	**Skin colour (520 nm)**
~ 60	23.6	4.2	4.1	1.341
~ 120	24.9	7.1	3.4	2.043
>200	21.3	10.3	3.9	0.981
Sauvignon blanc / R99				
Shoot length (cm)	**Sugar concentration (˚B)**	**Acid concentration (g/l)**	**pH**	**Fruit on taste**
~ 60	20.5	4.0	3.8	None
~ 120	24.3	8.6	3.3	Prominent
>200	19.1	14.0	3.7	Very little

2.5.2.2 Leaf area

According to Johnson *et al.* (2001a), an NDVI image derived per pixel may be used to emphasise differences in leaf area per unit ground area that is commonly referred to as canopy density. Johnson *et al.* (2001a) used an automated classification method based on the iterative self-organising data analysis algorithm to assign each NDVI-pixel to one of twelve groups, creating a "relative NDVI-index" image (Fig. 2.15).

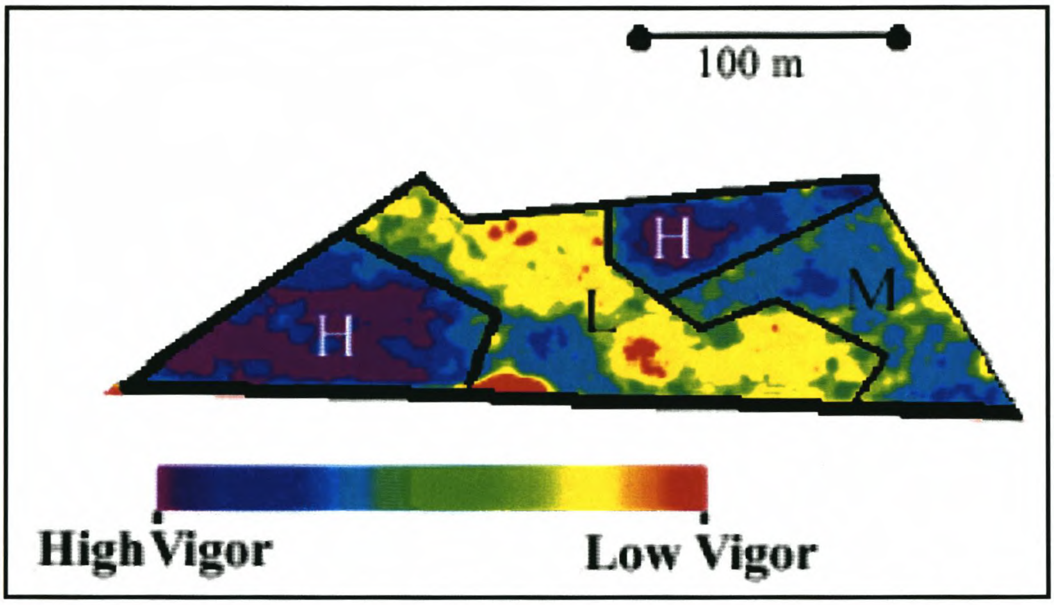

Figure 2.15 Study block with management zones defined by remote sensing and field measurements (H=high vigour; M=medium vigour and L=low vigour) (Johnson *et al.,* 2001a).

Nemani *et al.* (2001) reported a strong linear relationship between NDVI and field-estimated LAI over a variety of vine spacing levels and trellising systems. According to Myneni *et al.* (1997), theory suggests that this relationship becomes asymptotic at high LAI's. It is also possible that sensor calibration, soil colour, soil moisture, sun angle and viewing geometry will affect the NDVI-LAI relationship. This can especially lead to problems if images are captured at different dates. In Baldy *et al.* (1996a) the RVI and leaf area (LA) also correlated very well ($r^2 = 0.82$).

As a conventional measurement technique, mostly reserved for research studies linked to vegetation cover, LA per unit soil area can be seen as a major determinant of evaporation and productivity of ecosystems (Ollat *et al.*, 1998). In a vineyard environment, LA and leaf area density (LAD or "leaf area per unit volume") can be measured on a single vine, unit length, or unit area basis and can be used as indicators of vine vigour as well as inputs into models of evapotranspiration, whole-vine photosynthesis, or sunlight penetration (Wolpert, 1999). Smart (1995) also showed canopy microclimate and LA measurements to be very well correlated.

Areas of higher vigour in vineyards will normally be associated with an increase in LA, which may lead to internal canopy shading if the trellis is unable to accommodate the canopy vigour (Smart *et al,* 1985a). According to Smart *et al.* (1985a), this shading can result in higher potassium concentration in leaves and petioles, stems and rachises with the ultimate effect of higher must potassium levels and higher wine pH. The ratio of leaf area (LA)/canopy surface area (SA) is according to Smart (1985) a good measurement of shading within the canopy. For a canopy with no internal leaves, this ratio will theoretically amount to one, with higher values indicating an increase of internal leaves and potentially internal canopy shading.

2.5.2.3 Canopy sunlight penetration

Canopy density and therefore sunlight penetration is mainly dependent on shoot density, shoot orientation and shoot vigour (Smart, 1995). Canopy sunlight transmittance (%) measurements done in vineyards confirmed the vigour level zoning established with remote sensing (Johnson *et al.*, 2001a). These measurements yielded the highest values in the low-vigour zones with the moderate and high-vigour areas being much lower and statistically inseparable. No results could be found where spatial maps of canopy transmittance were used to evaluate vigour images.

Light measurements (photosynthetically active radiation from 400 to 700 nm), assessment of the sunfleck pattern on the soil shade and canopy evaluation (scoring) are all measurements related to the amount of sunlight intercepted by the leaves and bunches in the canopy. These measurements may therefore be seen as important indicators of the effects that a certain vigour level in the vineyard can potentially have on the microclimate and eventually wine quality. They are, however, difficult to conduct on farm level and are normally only conducted in a limited sample area in the vineyard. Wolpert (1999) also noted that the high levels of spatial and temporal variation in canopies complicate measurements related to canopy structure and light transmittance.

In an investigation by Smart (1982), sensory evaluation of Shiraz wines led to judges distinguishing two wine groups, which they considered to be either from over-cropped vines in hot, irrigated areas or low yielding vineyards in cooler climates. The wines were actually from shaded and open canopies from the same vineyard, being inherently high yielding and situated in a hot area. This emphasised the importance of canopy structure with respect to wine quality, and implicated that within-vineyard variability in canopy structure and subsequent variability in sunlight penetration may have a large effect on wine quality.

2.5.3 FRUIT MEASUREMENTS

2.5.3.1 Grape composition

Johnson *et al.* (2001a) measured sugar, titratable acidity, pH and malic acid for low and high vigour parts of the same vineyard. Especially malic acid varied tremendously, with the high vigour parts producing the highest (5.51 $g.L^{-1}$) and the low vigour parts the lowest

(3.94 g.L^{-1}) levels. The author ascribed this to excess canopy density and internal canopy shade in the high-vigour parts. According to Johnson *et al.* (2001a), elevated malic acid could result in immature grapes, yielding a flat tasting and lower quality wine. Profitt & Hamilton (2001) also studied the spatial variation in grape quality parameters by collecting a number of vine and berry characteristics from geo-referenced vines, finding the spatial variation pattern of these parameters to be, as for yield, relatively consistent between vintage years. This means that it would be possible to identify distinct zones of consistently poorer or better quality in order to better target management practices.

An example of the correlations found with grape parameters is shown in Fig. 2.16 where spatial maps of grape phenolic ground measurements (approximately 200) and a corresponding vine-vigour image acquired at véraison were created (Lamb 2001a). Notable in these images are both the variability in phenolic compounds within the vineyard, as well as the correlation with the vigour image. This suggests that the use of phenolic measurements in order to determine optimum ripeness in vineyards has to be done with consideration of possible high levels of variability in these components within the vineyard.

Studies utilising conventional measurement techniques already showed how grape composition could vary within vineyards. Conradie *et al.* (2002) found grape ripening to be affected by soil type, with the harvesting date being sixteen days later on a wet Westleigh soil as opposed to a drier Tukulu soil in the same vineyard block (the soil form names are based on the South-African Binomial Soil Classification System as described in MacVicar *et al.*, 1977). This was brought about by higher vine vigour on the Westleigh soils, actively growing shoot tips during ripening, and therefore slower sugar accumulation in the berries. The latter was confirmed by the lower sugar concentration of the grapes from the Westleigh soil despite a delayed harvesting date.

Changes in vigour levels that result in different levels of bunch exposure may play an important role in determining grape composition. Berry composition may be affected by both direct (light quantity and quality) and indirect (temperature mediated) effects of sunlight exposure (Berqvist *et al.*, 2001).

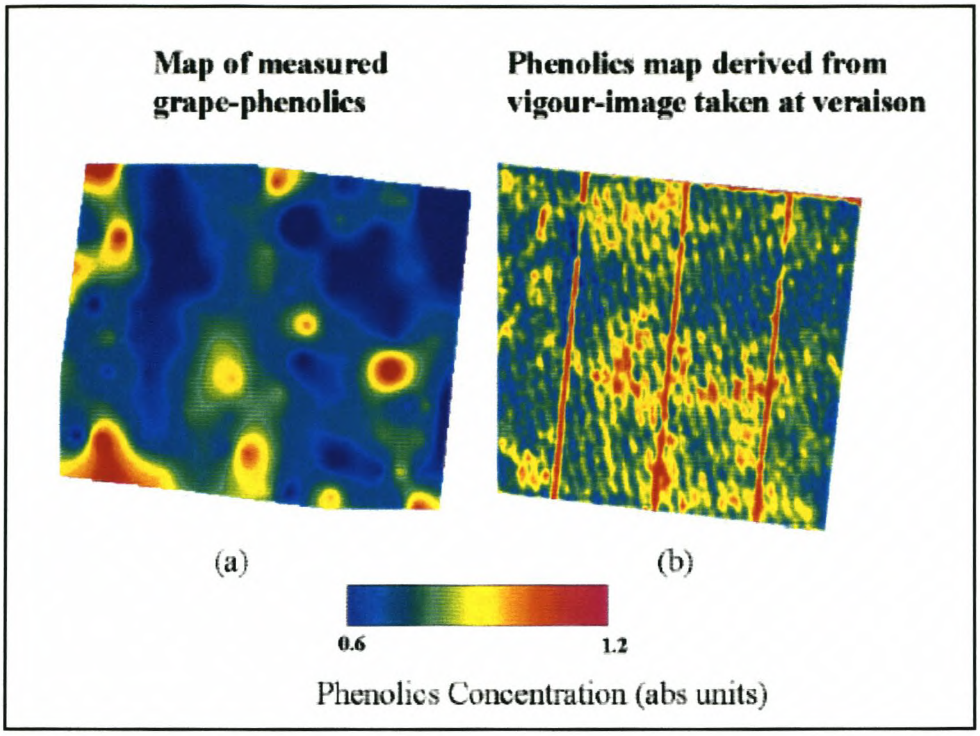

Figure 2.16 Maps of grape-phenolics generated from (a) approximately 200 measurements made on individual grape samples, and (b) a vine-vigour image acquired at véraison 2001 (Lamb, 2001a).

Juice from shaded berries is often associated with high titratable acidity, high malate concentration, elevated pH levels, high potassium, low proline, high arginine, low total phenols, low total soluble solids, low anthocyanin concentration in red cultivars and high chlorophyll versus flavanoid pigments in white cultivars (Smart, 1985; Zoecklein *et al.,* 1995). Some of the results reported by Zoecklein *et al.* (1995) are shown in Table 2.6.

Table 2.6 Effect of shade on the fruit composition of Cabernet Sauvignon (Zoecklein *et al.*, 1995).

Parameter measured	Control*	Shade	Significance level
Harvest date	17 Sept.	19 Oct.	
°Brix	23.3	21.1	+
T.A. ($g.L^{-1}$)	5.5	6.4	+
pH	3.4	3.7	++
K^+ ($mg.L^{-1}$)	2325	2510	+++
Malate ($g.L^{-1}$)	1.65	2.84	++
Tartrate ($g.L^{-1}$)	0.86	0.83	NS
Anthocyanins (g.g $fruit^{-1}$)	0.98	0.56	+++

* Control treatment was a bilateral cordon 3-wire "T" trellis; shaded treatment consisted of bunching the foliage around the fruit using bird netting

It can be reasoned that variability in certain grape components may enhance wine complexity, but most studies showed proof to the contrary. Long (1997), for instance, illustrated the effect of berry uniformity on wine flavour by taking 400 berry samples from two blocks of Cabernet Sauvignon in California, one block being Rosé quality and the other Cabernet Reserve quality. Although the average °Brix of both samples was approximately 23.5°B, the plotted °Brix distribution of each sample varied dramatically. The Rosé berries ranged from 17°B to 30°B, whereas the Reserve berries ranged from 21°B to 26°B, suggesting that average °Brix alone lacks in utility for measuring ripeness and uniformity in both blocks. Long (1997) also referred to other experiments where wines were made from grapes of different maturity levels on the same vine, showing dramatic wine differences if fruit uniformity is lacking. Long's conclusion was that uniformity forms the foundation of flavour quality and that it is only attainable with good vineyard quality control. In a similar study by Archer (2001), bunch quality was linked to shoot uniformity.

Of the different berry quality measurements, Smart (1982) showed pH to be the most readily affected by microclimate, while Carbonneau *et al.* (1978) showed that shade could cause reduced anthocyanin levels in Cabernet Sauvignon. Increases in potassium concentration, pH and titratable acidity were found by Archer & Strauss (1989) with an increase in shading levels, whereas Cabernet Sauvignon skin colour and overall wine quality showed a decrease. The titratable acidity increase was ascribed to higher levels of malic acid (which is more sensitive to temperature degradation) in the shade, with a decrease in tartaric acid. Morrison & Noble (1990) found that shading of bunches had no effect on sugar, potassium and acid concentrations, but that it reduced phenol and anthocyanin concentrations. Leaf shading, however, was found to cause a delay in berry growth and sugar accumulation with an increase of potassium and malic acid contents as well as an increase in pH of the juice. According to Jackson & Lombard (1993), musts with high amounts of potassium tend to have high pH values and high malate contents, the latter of which may drop during vinification. This would not be the case with the pH, which could increase even further during winemaking.

2.5.3.2 Yield measurements

While the conventional methods of yield measurement could shed some light on the productivity of single vines on average or a vineyard as a whole, yield monitoring technology is nowadays available that can also determine the spatial variability in yield within a vineyard block.

Cook & Bramley (2001) indicated that a significant problem in the application of precision agriculture technologies in broad-acre industries is the inconsistent variation of yield and other factors from one season to the next. Proffitt & Hamilton (2001), however, suggested that the perennial nature of grapevines might contribute to some constancy in the patterns of within-vineyard variation. It was also shown experimentally by these authors that the spatial pattern of yield variation in vineyards could be relatively stable over time.

Spatial yield differences of 2.5 fold was found by Baldy *et al.* (1996a), but he stated that shoot thinning was performed on higher vigour vines, probably resulting in reduced yields of these vines due to the cluster thinning effect, therefore causing smaller differences in yield between lower and higher vigour vines. Profitt & Hamilton (2001) found a much larger variability in yield within the vineyards, typically in the order of eight to ten-fold, while Taylor (2001) reported a three-fold variation in yield (ranging from 6-17 ton/ha) in a three-hectare vineyard block. Fig. 2.17 shows a yield map derived from harvester yield measurements as well as from a vigour image acquired at véraison. Shearer (2001) created normalised yield maps to compare vine yield data between seasons, where the data was expressed with a mean value of zero and a degree of standard deviations from the mean (95% of the values were situated within approximately 2 standard deviations from the mean for a normally distributed data set). Fig. 2.18 shows that yield attained across the majority of a vineyard block over two seasons could be classed as normally distributed. When the two seasons were compared by subtracting the 2000 normalised yield map from 2001 normalised yield map, areas of yield increment and decrement from the 2000 to the 2001 season could be seen (Fig. 2.19). The results also indicated that the performance across the majority of the block was relatively consistent from 2000 to 2001.

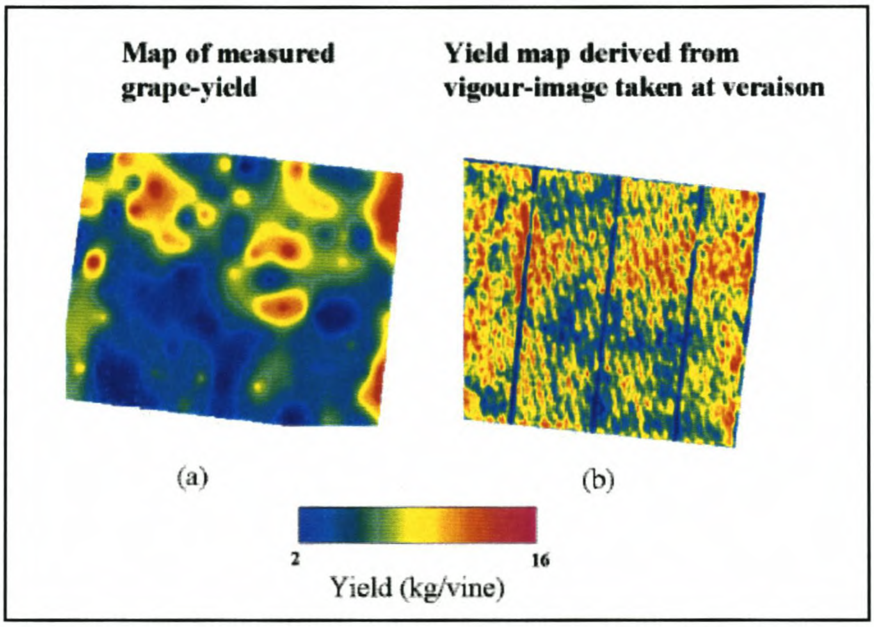

Figure 2.17 Yield maps generated from (a) approximately 200 measurements of vine yield, and (b) a vine vigour image acquired at véraison (2001). (From a 7-hectare Cabernet Sauvignon block in Coonawarra) (Lamb 2001a).

In Fig. 2.19, it is shown how this data can be used to identify areas within the block that are of consistently good or poor performance from 2000 to 2001.

In Baldy *et al.* (1996a) it was shown that phylloxera was the principal stress factor affecting yield ($r^2=0.92$). In the same study, ratio vegetation index values (NIR/R) and chlorophyll measurements were found to correlate highly with the yield datasets from both seasons, confirmed by significant regressions between chlorophyll measurements and mean plot yield ($p \leq 0.05$) as well as NIR/R and mean plot yield ($p \leq 0.001$).

Conventional measurement of yield on a single-vine basis as conducted during research has already shown differences in yield within vineyards in areas of differing vigour. Conradie *et al.* (2002), for instance, found yield to be significantly lower for a wetter soil in contrast to a drier soil in the same vineyard. He ascribed this to bud infertility, induced by too vigorous growth and within-canopy shade at flowering. According to Smart (1991), vigorous grapevines can become increasingly vegetative and produce less fruit, with shade depressing bud break, fruitfulness, berry set and berry size.

In a study by Zeeman (1981), it was shown that an increase in the effective LA per vine on the same soil and for the same scion and rootstock cultivars, induced by using different trellis sizes, could significantly increase yield. It can therefore be concluded that factors increasing vine vigour and LA within a vineyard block may lead to significant yield variability. If, however, the canopy size gets too large for the trellis system, internal leaf shading will again come into play. This may lead to yield reduction either due to lower leaf photosynthetic activity or due to bud shading and subsequent decrease in fertility.

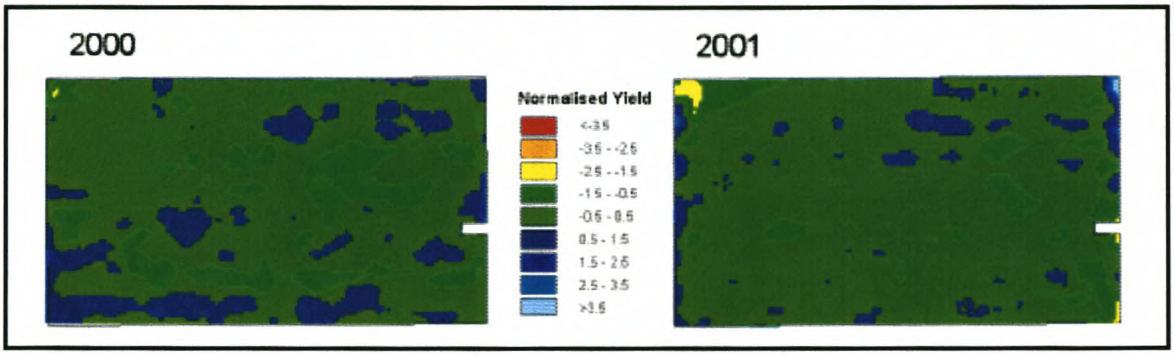

Figure 2.18 Comparison in yield between 2000 and 2001 where the yield data has been normalised to a mean of zero and a standard deviation of one (Shearer, 2001).

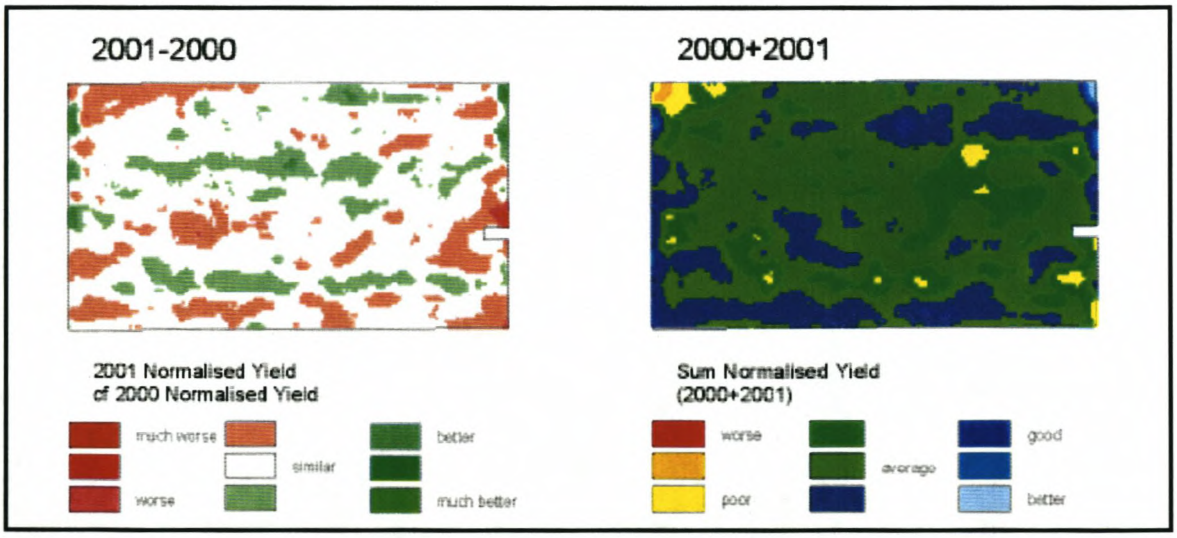

Figure 2.19 Difference between the normalised yields of two seasons indicates areas of improved or declining yield (2001-2000). The sum of normalised yields identifies areas of relative performance in the block (2000+2001) (Shearer, 2001).

2.5.4 PLANT PHYSIOLOGICAL PROPERTIES

2.5.4.1 Leaf water potential

No results could be found of spatial relationships between leaf water potential measurements and vigour images. Johnson *et al.* (2001a), however, reported an inverse relationship between measured leaf water potential and vine vigour classes, with vines from the lower vigour areas having a more negative leaf water potential, probably related to increased levels of water stress in these areas.

According to McCarthy *et al.* (1999), drought stress symptoms, as assessed from changes in vine growth, may only appear after irrigation should have taken place. It was however shown by E. Archer (University of Stellenbosch, personal communication, 2002) that the second tendril at the shoot growth tips can start to droop as early as at -800 kPa, forming an angle with the shoot of approximately 90° (Fig. 2.20 and 2.21). Shoot tip growth arrest can also be a useful indicator of the amount of stress experienced by the vine (Fig. 2.22). Leaf water potential measurements may therefore be used in conjunction with observations of vine growth changes to determine differences in stress levels in a vineyard and to make informed decisions on irrigation scheduling. The measurement of leaf water potential in lower vigour areas in the vineyard, presumed more stressed, might provide useful information on the water balance situation of the vines, and therefore indicate if the reduced vigour is related to water stress in these vines.

In highly variable vineyards, where the causes of variability are in many cases related to differences in soil water holding capacity (due to soil type differences), it is important to consider the effects that moisture stress can have on the vegetative and reproductive performance of the vine. As the assessment of shoot tip growth arrest or water potential everywhere in the vineyard is an impossible task, correlations between these parameters and remote sensing data would prove particularly useful.

Figure 2.20 Symptoms of water stress as seen on Sauvignon blanc growth tips. Leaf water potential measured on the left was -800 kPa, while -425 kPa was measured on the right. Note the angle of the second tendril. (Used with permission from E. Archer, University of Stellenbosch, unpublished data, 2002).

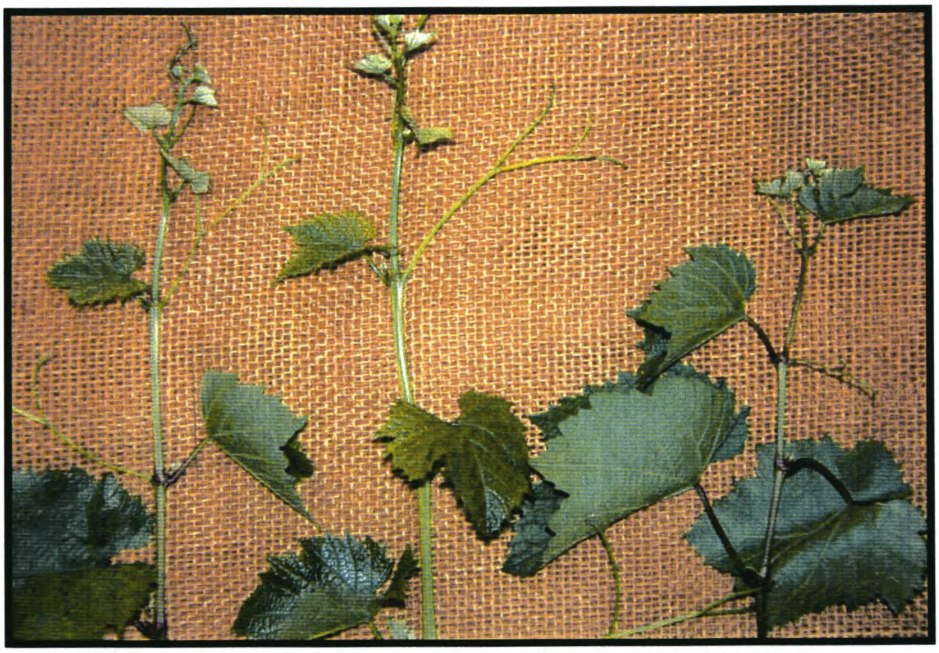

Figure 2.21 Symptoms of water stress as seen on Chardonnay growth tips. The leaf water potential measured on the left was -400 kPa, -600 kPa in the middle and -1 220 kPa on the right. Note the angle of the second tendril as well as the petiole colour (Used with permission from E. Archer, University of Stellenbosch, unpublished data, 2002).

Figure 2.22 Arrest of shoot tip elongation at -880 kPa. Note the first unfolded leaves bypassing the shoot tip, which is characteristic of growth arrest. Note also the wilting of the tendrils (Used with permission from E. Archer, University of Stellenbosch, unpublished data, 2002).

2.5.4.2 Leaf chlorophyll

In Johnson *et al.* (2001a), no significant differences were found in leaf chlorophyll concentration between vigour levels, indicating that the remotely sensed NDVI responded primarily to differences in foliar biomass rather than leaf spectral properties. However, as remote sensing instruments become more sensitive to the spectral properties of chlorophyll, this attribute may become an important ground-truth parameter in future studies.

Chlorophyll meters are used for the *in vivo* measurement of the ratio of light transmittance through the leaf at two wavelengths, namely 650 nm (red) and 940 nm (near infrared). According to Stutte & Stutte (1992), chlorophyll shares the attributes ascribed to nitrogen as a "physiological indicator of cumulative stress", as it responds to long-term stress and is easily measurable. Chlorophyll measurements may therefore be used (in conjunction to other measurements such as leaf water potential) to indicate the levels of stress experienced by vines in lower vigour areas of a variable vineyard. Baldy *et al.* (1996a) considered field chlorophyll measurements and the recording of the ratio vegetation index (NIR/R) with airborne sensors to be the most practical way to quantify vine stress differences within vineyards. He especially noted its affordability, independence of readings to the meter operator (readings are comparable to those taken a year later, something not easily attainable with subjective vine scoring) and its non-invasive nature as positive attributes. Field instrument readings (Minolta SPAD-502) were also shown to be strongly related (r^2=0.91) to the laboratory measurement of chlorophyll concentration in grape leaves (Baldy *et al.*, 1996a; Johnson *et al.*, 2001a).

2.5.5 ROOT DISTRIBUTION

Although no remote sensing technique known to date can measure root distribution non-destructively, the knowledge we have on the reaction of roots to different soil types and conditions may make it possible to infer root distribution from a range of other measurable parameters. Several local studies have already confirmed the effect that differences in soil type can have on vine root distribution (E. Archer, University of Stellenbosch, personal communication, 2002). Conradie *et al.* (2002) for instance found that vine root distribution was largely affected by factors such as soil moisture, compact soil layers and percentage stone and not necessarily by geological parent material differences in vineyards. It is anticipated that these factors will have a large effect on root distribution in vineyards where soil types differ significantly within vineyards, as is often found in South Africa (Burger, 1977; Saayman, 1977). Root studies in vineyards therefore supply very useful information on the soil-borne causes for different vine vigour. It may be contested whether this is really a practical way of measuring variability, considering the amount of time and effort needed for these studies, and therefore it may prove more useful to develop new technologies that can minimise the need for these studies. This can be done through the inference of soil depth, structure and water holding capacity, all factors known to affect root distribution. The inferred parameters can then be considered together with data from soil studies on the expected reaction of the specific rootstock/scion combination under the relevant environmental conditions.

2.6 THE IMPORTANCE OF TIMING IN VITICULTURAL REMOTE SENSING

Lamb (2001a) indicated that the correlation between remotely sensed vigour images and ground measurements starts very low at bud-burst, increases to a maximum at véraison and, according to the author, depending on the type of irrigation strategy employed, drops off at harvest or remains strong. There is also a notable decrease in the correlation when vines start to stress again a while after irrigation took place.

According to Lamb (2001a) preliminary research indicated little value in the imaging of vines too early in development (before flowering), but he also warned against leaving imaging too late if vines are stressed after véraison.

2.7 POSSIBLE OUTCOMES/APPLICATIONS OF VITICULTURAL REMOTE SENSING

Vineyard management after the assessment of variability may involve minimising, maximising or simply accounting for spatial variations in specific variables, according to desired production outcomes (Lamb, 2001b). Taylor (2001) also indicated that different approaches could be followed when managing variability. One approach involves the accounting for variability by designing vineyard blocks based on knowledge of variability, whereas the other approach involves treating the effects of variability in the established vineyard using differential management practices. Maybe the site-specific management of vineyards will ultimately encompass both facets, leading to an overall improvement in the understanding and management of vineyards (Taylor, 2001).

2.7.1 VINEYARD PLANNING AND ESTABLISHMENT

As already mentioned, Johnson *et al.* (1996) used remote sensing image guidelines for soil profile pit placement prior to replanting and this lead to improved block boundaries. Images such as these can also be useful to compare the replanted vineyard's performance to the previous vineyard in order to determine the success of the replanting operation. Nemani *et al.* (2001) also stated that over the long term, information on spatial heterogeneity can be utilised to plan the vineyard (variety, spacing and trellising type), as well as for seasonal vineyard management after block establishment. New emerging technologies that can map soil properties prior to vineyard establishment may also prove useful in future plantings. It has to be remembered, however, that the most important part of vineyard establishment is following the correct practices in ground-level management, and advanced measurement methods must not even be considered before this is not optimal.

2.7.2 SEASONAL VINEYARD MANAGEMENT

Blocks may be divided into uniform zones that can be managed differently for fertiliser application and irrigation (Nemani *et al.*, 2001). The managing of zones with respect to fertiliser and sprays can also aid to show that environmentally friendly practices have been used, apart from the possibility to improve cost effectiveness (Profitt & Hamilton, 2001).

Johnson *et al.* (1996) also indicated the value of remotely sensed images to assess year-to-year changes in canopy vigour. He did this by superimposing a 1994 relative NDVI image upon a 1993 relative NDVI, subtracting the images pixel by pixel, which resulted in an image showing a canopy density decline in severely infested phylloxera plots. This can also be used to monitor the effects of canopy management in specific areas of the vineyard.

2.7.3 HARVEST MANAGEMENT

The additional expenditure of labour and resources required for remote sensing and block subdivision might be rewarded by increased uniformity of grape lots from zones in the vineyard (Johnson *et al.,* 2001a). Johnson *et al.* (1996) found maturity measures (°Brix, TA, pH and flavour intensity) to differ between the different vigour areas shown in imagery, and he subsequently executed a limited test in which the imagery were used to subdivide fields for harvest based on vigour. Resulting wine quality was found to be dramatically different between the higher and lower vigour areas. In Johnson *et al.* (2001a), vigour zoning and harvesting that took place accordingly, allowed the production of reserve quality wines for the first time ever in the vineyard block's history.

Johnson *et al.* (2001a) also noted that the separation of grape batches might also provide the winemaker with increased flexibility in the blending process. Profitt & Hamilton (2001) indicated that yield-monitoring technology might also be used as an aid to tailor harvesting to winery storage capacity.

2.7.4 MANAGEMENT OF VINEYARD SAMPLING STRATEGIES

A significant problem in the management of wine quality in the vineyard is to decide on the positions and quantity of sample sites in vineyards for, amongst other purposes, grape maturity assessment. Monitoring of vine vigour through the vineyard and correlation of image data with grape quality parameters may be an important step towards harvesting vineyards at optimum ripeness levels.

Relative NDVI-imagery was used by Johnson *et al.* (1996) for strategic placement of sampling sites to monitor sugar (°B). The author also stated that the imagery could potentially be useful for establishing sample sites for node levels and cluster numbers for improved yield prediction. Profitt & Hamilton (2001) also acknowledged the potential benefit of spatial information to aid in maturity assessment through targeted sampling. This was confirmed by Bramley (2001b), showing a high level of variation present in vineyards and the role of this variation in sampling strategies.

2.8 CONCLUDING REMARKS

The importance of the contributions from several factors causing vigour variation within vineyards is still a subject of controversy. This may be largely ascribed to the significant amount of variability in vineyards that researchers have to deal with during viticultural studies. Within-vineyard variability not only needs to be managed better in production systems, but research should also incorporate measures to account for it. Methods to ground-truth the data obtained from images also need to be optimised in order to exploit the full potential of these images as management and research tools.

It was clear from the literature studied that even though the factors leading to variability within vineyards and its effects are very complex, new high-precision technologies may offer better ways of monitoring, researching and managing these factors. In addition to the possible benefits of aerial or satellite remote sensing, new methods of mapping soil spatial variability as well as advances in GPS technologies puts precision tools in the hands of both researchers and producers. It is however of cardinal importance that research stays in the front ranks of the war against "recipe vineyard management", while still keeping close contact with the situation on the ground.

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Chapter 3

EXPERIMENTAL PLOT LAYOUT AND VALIDATION

Characterisation of a highly variable vineyard

EXPERIMENTAL PLOT LAYOUT AND VALIDATION

3.1 INTRODUCTION

One of the goals of this study was to identify the sources of vigour variation in a highly variable vineyard and to investigate the spatial nature of this variability using different plot layouts.

The area chosen for the study was the Perdeberg area, where other studies are also running on the effect of dryland salinity in the Berg River catchment area (Fey *et al.*, 2002). The main parent substrates found in this area include shales, phyllites and schists of the Malmesbury Group in different stages of weathering (Schloms *et al.*, 1983).

A commercial dryland Chenin blanc vineyard block was located in this area, which was known for its unequal vigour as well as fruit ripening. In contrast with this, the vineyard still produced excellent grape quality resulting in award-winning wine quality. The vineyard was situated on a crest position in an undulating shale landscape, with duplex Swartland and residual Glenrosa being the dominant soil forms throughout the vineyard.

The main cause of variability in this vineyard was presumably an extremely high salt content in the soil, as well as very high pH levels in some areas. Initial observations of strips of weaker growth running along the row direction, corresponding with the main soil preparation direction in the vineyard as well as on the aerial image, suggested that soil preparation practices might also have been involved in the high levels of variability found.

Saline soils can still have reasonably favourable physical soil conditions due to the excess salts preventing the deflocculation of soil-colloids. However, these soils may still affect plants by retaining water through high osmotic pressures (Saayman 1981b).

A colour aerial image of the block was analysed to identify and discern areas of vigour variability for subsequent plot layouts. In order to ensure that soil-related parameters, namely salinity and soil preparation practices, were the cause of the vigour variability and were well differentiated in the plot layouts, soil and root analyses were performed and correlated with the vigour variability indicated by the image and by aboveground growth observed in the field. The latter mentioned aboveground vigour variability will be discussed fully in Chapter 4, while in this chapter only the aerial image is used as a reference to the state of aboveground growth vigour.

3.2 MATERIALS AND METHODS

3.2.1 AERIAL IMAGE ANALYSIS

An aerial photograph was obtained from an aerial survey of vineyards from the Perdeberg Cooperative Winery (Fig. 3.1). The photograph was of the standard colour (RGB) type, and image analyses were kept as simple as possible, mostly being conducted with standard image editing software and conventional measurement techniques. Some image contrast enhancement and conventional image manipulation techniques described by Porter (2001) were also used in this study.

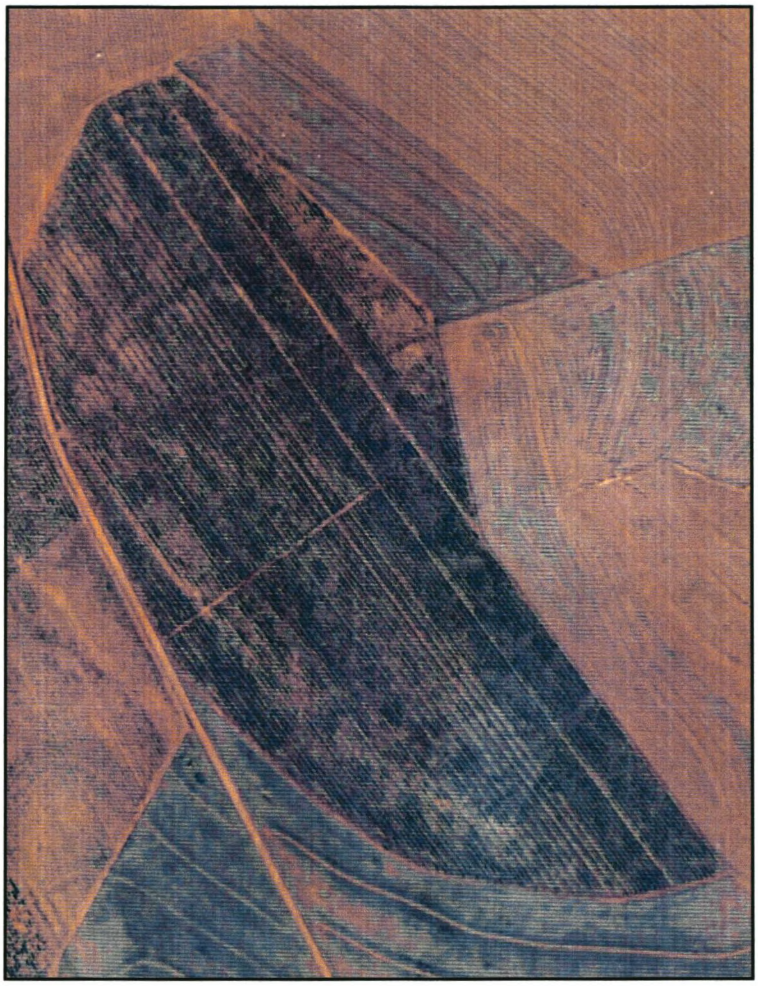

Figure 3.1 Aerial image of a Chenin blanc/R99 vineyard block (14.6 ha) with high vigour variability in the Perdeberg area.

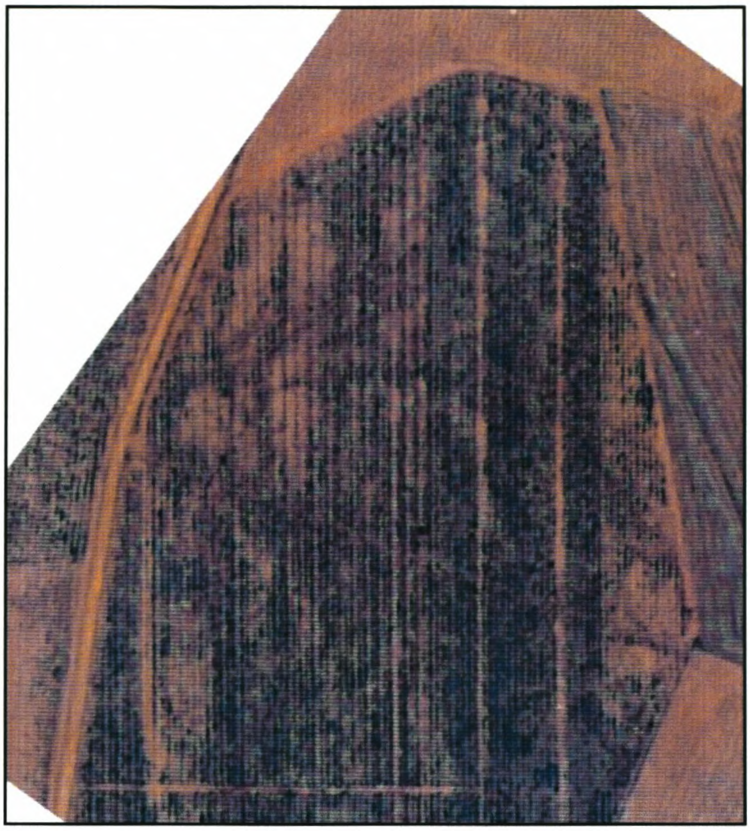

Figure 3.2 Section (almost half) of the Chenin blanc/R99 vineyard block shown in Fig. 3.2 used in a study of vigour variability (Perdeberg area).

3.2.1.1 General image manipulation

A feature characteristic of the very low vigour areas was the visible patches of bare soil. In an effort to enhance these bare-soil patches on the aerial photograph, the image software's colour picker and colour replacement tools were used to pick up a colour from a pixel in a known bare soil area (road next to the vineyard) and all instances of this colour were replaced by a selected colour (in this case red).

The aerial image of the vineyard, and specifically the part of the block used in the study (Fig. 3.2), was also examined to determine the extent of vigour variability in the vineyard. Image data was examined together with the ground-truth data collected during visits to the block. Corel Photo-paint (Ver. 9.337) was used to optimise the contrast and intensity of the image of the study block section (Fig.3.2). The resulting image was not used for image analysis purposes, but mainly to confirm the vigour variability contained in each plot layout.

After plots were chosen with different levels of vigour, the method used to determine the positions of the plots on the aerial image was to measure the row length of two rows at different positions on the photograph and compare this to the number of vines counted in the row during a field visit, therefore yielding the distance represented in the field. This then made it possible to determine the image scale relatively accurately without the use of

GPS technology. The plot positions on the image could then be derived by noting the number of vines from the edge of the row until the start of the plot.

3.2.1.2 Numerical image analysis

Although within-vineyard vigour appeared to vary considerably based on observations of the aerial image (qualitative analysis), it was necessary to link numerical values to this variability in order to quantify vigour differences. This was also important for statistical analysis purposes.

A digital version of the aerial image was available and was converted to a greyscale image to characterise the relative intensity of pixels. The image mode was changed to greyscale (8-bit), and then split into each of its three colour channels (red, green or blue). These four resulting images (Fig. 3.3) were then visually evaluated to determine which best corresponded to vigour variability in the field.

The software was then used to create standard masks, which were sized to correspond to the canopy sizes in the experimental plots and therefore included the minimum of soil background. The masks created were subsequently overlaid on the chosen plot sections for both plot layouts B and C to obtain an "image histogram" for each area represented by the mask. The high vigour variability in the vineyard facilitated this task, for clear transitions in vigour levels were visible in the field as well as on the photograph. The value obtained from each mask placing, was the average intensity of the pixels contained in the mask, for which the software also showed an image histogram. These values had a possible range of zero (black) to 255 (white). Pixels in highly vegetated areas showed darker in the red channel image, and therefore had values closer to zero. Average pixel values were calculated from four placements of the mask per plot.

Reference pixel values were also calculated for use in a normalisation technique to increase the sensitivity of the pixel values to the vineyard environment, by displaying values relative to the highest and lowest vigour values observed in the image. This was done by firstly placing the pixel mask over a road next to the vineyard (very low vegetative cover) and secondly in one of the very high vigour areas in the vineyard (confirmed in the vineyard as well as on image). This was done before using the average pixel values in correlations, to narrow the wide range of 0 to 255 for pixel intensity. The real observed maximum and minimum now formed the boundaries of the scale. Equation 3.1 was used to achieve this result.

$$\text{Referenced image pixel value} = \frac{A\text{-}B}{255\text{-}C} \qquad \text{(Equation 3.1)}$$

Where:
A = Average pixel value of mask
B = Average pixel value of highest vigour reference plot (in vineyard)
255 = Maximum pixel value (white)
C = Average pixel value of lowest vigour reference plot (bare soil)

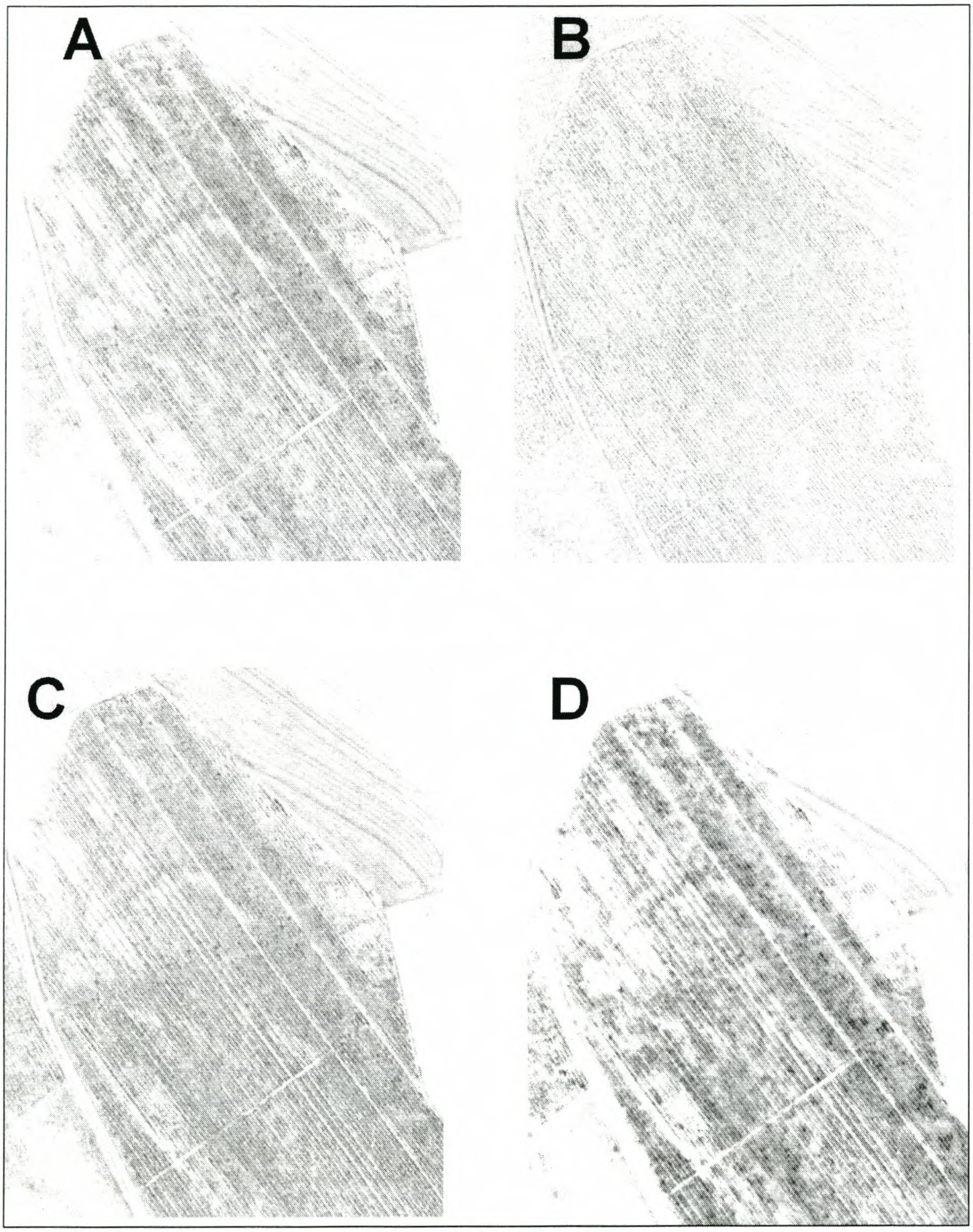

Figure 3.3 Greyscale image (A) and single channel greyscale images from the blue (B), green (C) and red (D) channels of an aerial photograph showing a vineyard block (Chenin blanc/R99, Perdeberg area).

3.2.2 PLOT LAYOUT AND SOIL ANALYSES

It was hypothesised that the variability visible on the aerial image was caused by soil conditions, and the analyses of soil properties and its effect on root distribution was conducted to provide an important basis for further investigations into the high level of within-vineyard variability found in this block.

3.2.2.1 General soil sampling (plot layout A)

In order to diagnose the degree of soil chemical variability in the vineyard soil samples were collected from low and high vigour sites to analyse soil chemical variability. The plot layout used here therefore had a predominant diagnostic goal of investigating the general nature of the soil conditions leading to the high level of variability by analysing soils in different positions, chosen according to extremes of low and high vigour.

A soil auger was used to collect soil samples from three depth levels (0-30 cm, 30-60 cm and 60-90 cm) at four locations (two high vigour, two low vigour) in the vineyard as shown in Fig. 3.4. The sampling position was located more or less in the centre of an area representing an extreme of a specific vigour level, with samples collected between rows at a 50 cm distance from a vine trunk. The corresponding depth levels of the two samples from a vigour level were thoroughly mixed to obtain a composite sample of each vigour level. These samples were then taken to an independent laboratory (Bemlab Pty Ltd) for a standard soil chemical analysis.

3.2.2.2 Soil sampling in areas with differing vigour (plot layout B)

In an effort to correlate some of the soil properties assessed during the general soil analyses with values extracted from the aerial image, plots were chosen throughout a large part of the vineyard representing larger patches of lower or higher vigour. The plot choice was governed mainly by studying the aerial image, but was also verified through field visits. The plot layout is shown in Fig. 3.5, superimposed on the same image used for pixel analysis (paragraph 3.2.1.2).

Soil samples were again collected with a soil auger over three depth increments (0-30 cm, 30-60 cm and 60-90 cm) at each of the row sections of the plots indicated on Fig. 3.5. The samples were collected at a distance of 50 cm from the trunk of either one of the vines in the middle of a row section. The samples were analysed for pH (KCl) as well as for the resistance of a saturated soil paste (R_s) at the Department of Soil Science, University of Stellenbosch.

3.2.2.3 Main experimental plot layout – investigating vigour differences in close vicinity (plot layout C)

Governed by the large variability between soil samples observed for plot layouts A and B, it was decided to test vigour variability over much shorter distances. A plot layout was therefore designed to incorporate both higher and lower vigour levels within a single plot (Fig. 3.6), with the sections differing in vigour situated inside each plot, in close vicinity.

Accurate plot positioning was only possible through a combination of studying the aerial image as well as field visits to confirm the observed variability. Most of the measurements in this study, which included vegetative measurements, soil profile pit and root studies, harvest measurements, hyperspectral data analysis as well as experimental winemaking, were from the plots based on plot layout C (Fig. 3.6).

3.2.2.4 Soil profile pit study (plot layout D)

Plot layout D represented a selection of plots from plot layout C that was chosen specifically for soil profile and root studies conducted early in June. The plots were selected to represent different areas within the experimental vineyard block and therefore differing levels of vine vigour (Fig. 3.7).

Soil profile pits were dug at the six positions indicated in Fig. 3.7. The pits were dug next to a vine that best represented the average vigour level of the relevant row section, always keeping to the same side of the row within a specific plot.

The soil profile wall was prepared according to the method of Böhm (1979), where a trench of at least 1.3 m deep was dug parallel to the vine row, 50 cm from the vine trunks. After roots were carefully exposed, a 200 x 200 mm grid system, 1.2 m high and 1.6 m wide was placed against the profile wall to map the root system. A digital camera (Epson 3100z) was used to photograph the different sections of the profile walls. The photographs of the profile pit walls (up to six individual photos in some profile holes) were merged to form a single image with the aid of image processing software (Coreldraw ver. 9.0). The high resolution of the photographs made it possible to zoom into each individual 20 x 20 cm area on the grid, identify the roots and to “paint” the roots precisely according to its diameter. The conventional method of spray-painting the roots prior to taking photographs was applied, but photographs in some cases did not clearly show roots owing to the high level of variability in the soil background colour. The total amount of roots observed was also counted for each depth level and the aboveground parts of the vine were photographed.

Soil samples were collected with a soil axe from the walls of the profile pits over each 20 cm depth level. These samples were analysed for pH (KCl) and the resistance of a saturated soil paste (R_s).

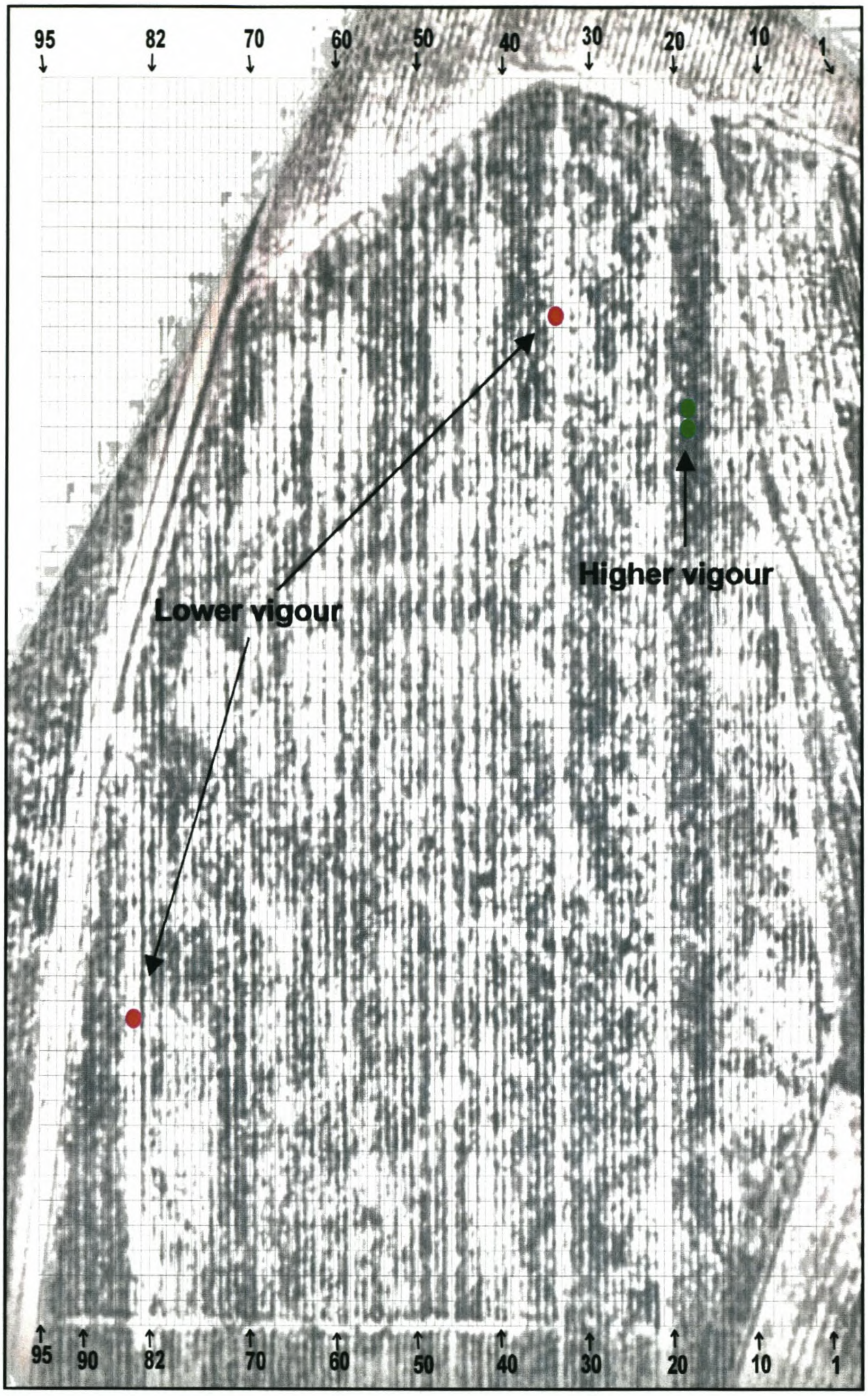

Figure 3.4 Locations used for diagnostic soil sampling with a soil auger in a Chenin blanc/R99 vineyard block, Perdeberg area (plot layout A).

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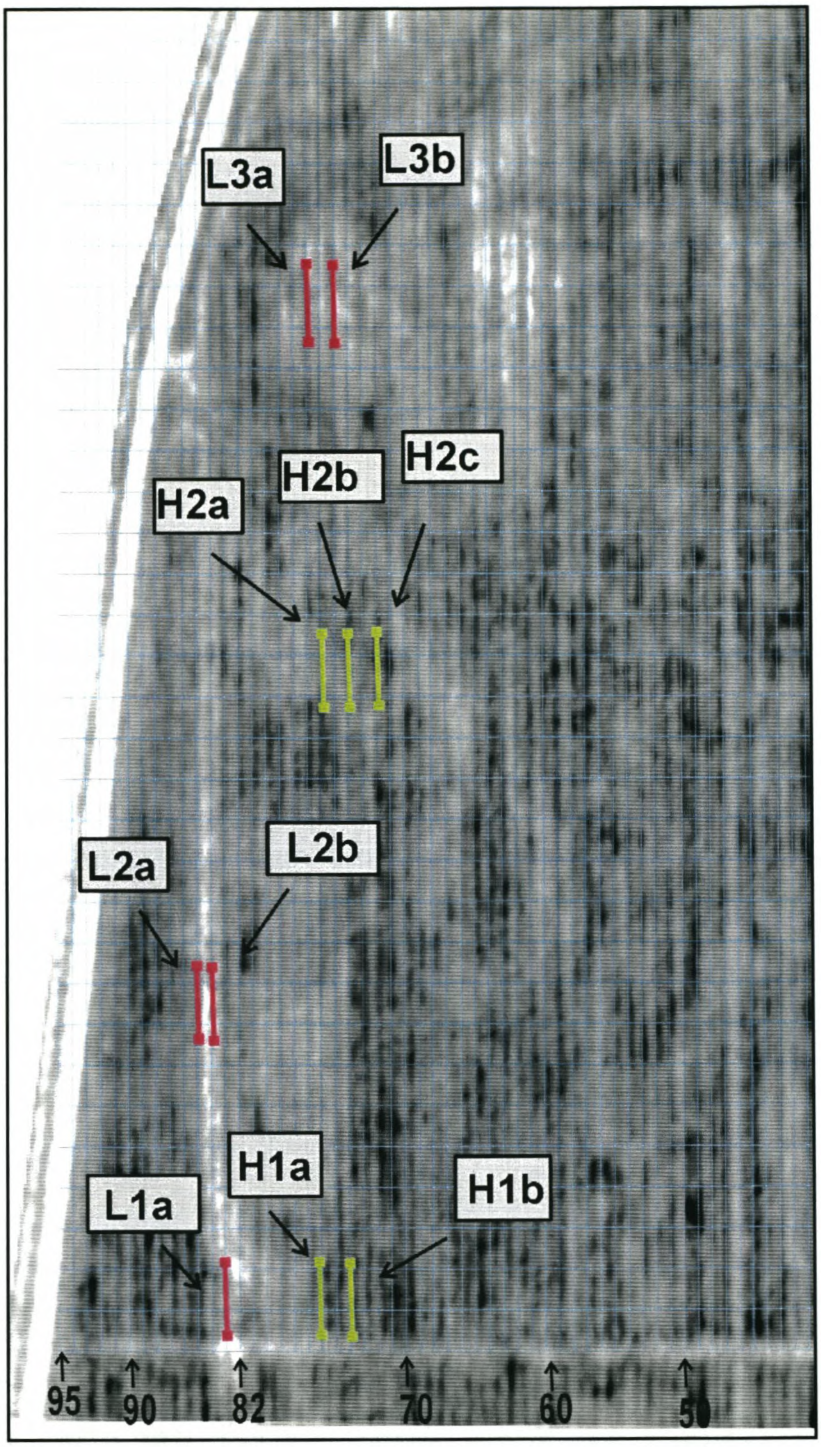


Figure 3.5 Plots of differing vigour with row sections indicated (plot layout B) superimposed on the same image channel (red) used in image pixel analysis (Chenin blanc/R99 vineyard in the Perdeberg area). Red lines represent lower vigour sections of 14 vines, while green lines represent the higher vigour sections. The first letter in the annotation represents the vigour level (H - higher vigour; L - lower vigour), the second number indicates the plot number inside the specific vigour level and the last letter indicates the row number inside the plot.

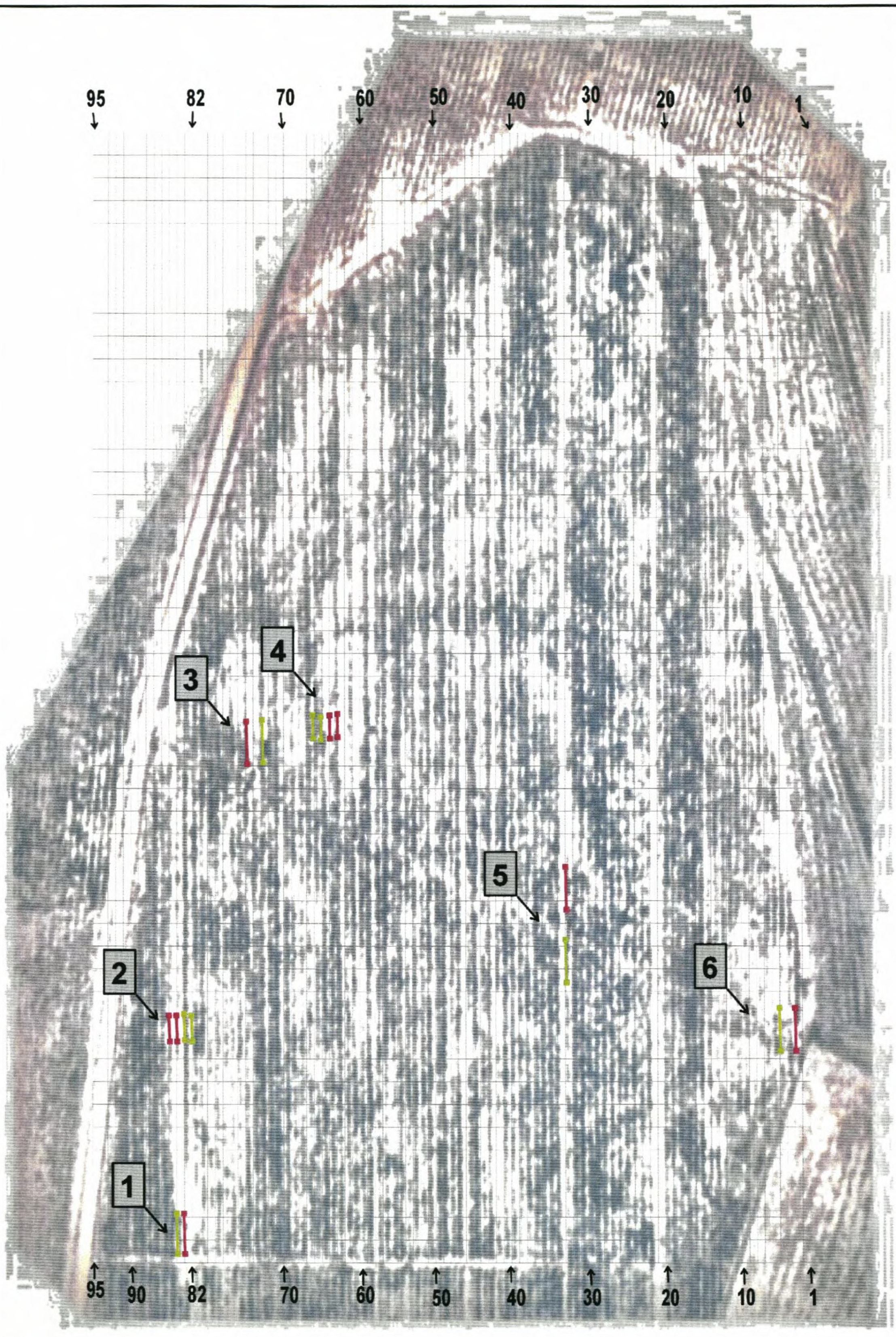


Figure 3.6 Positioning of main experimental plots in a Chenin blanc/R99 vineyard in the Perdeberg area (plot layout C). Red lines represent lower vigour sections while green lines represent higher vigour sections. The plots consisted of 28 vines (14 higher vigour and 14 lower vigour vines).

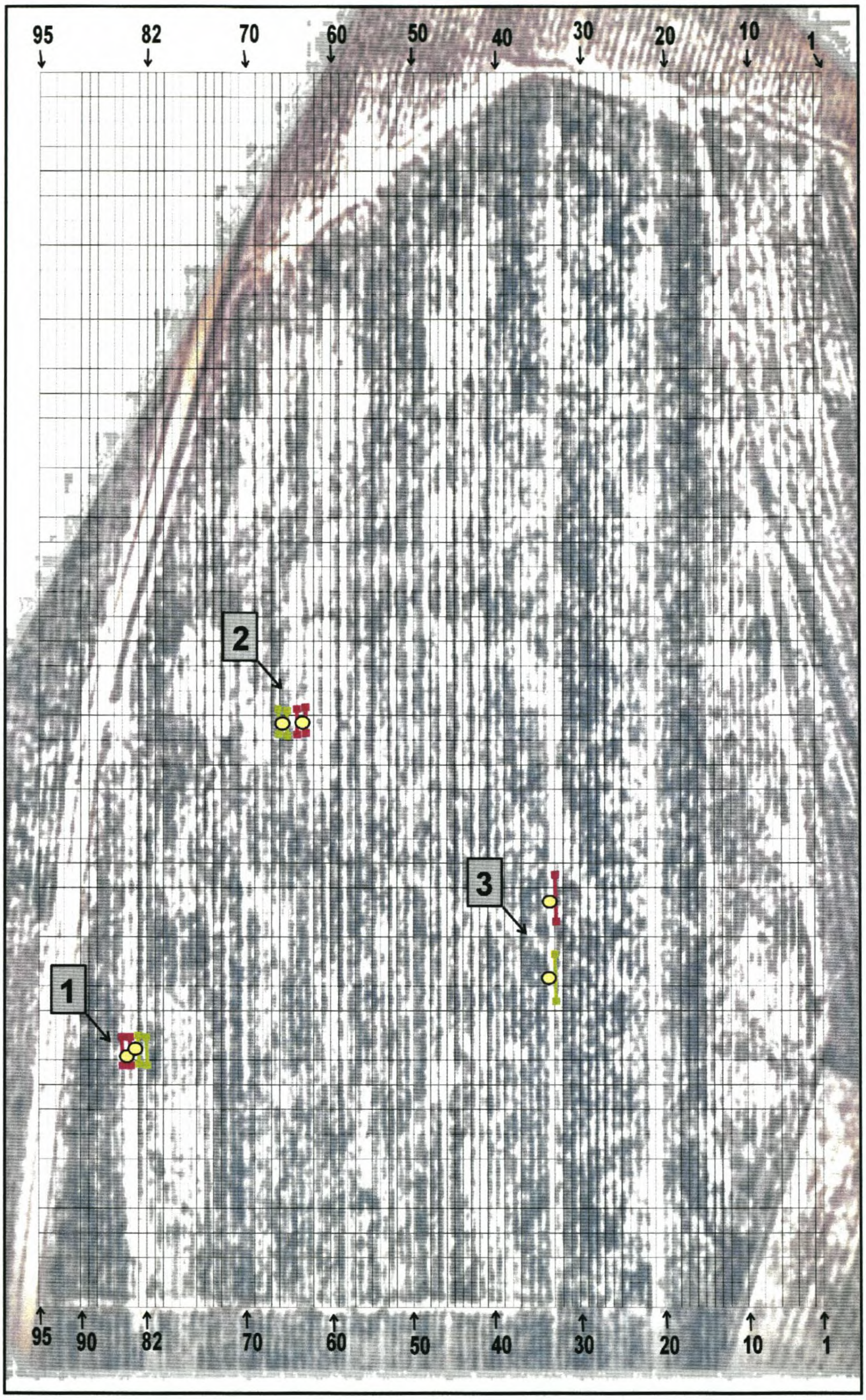


Figure 3.7 Positions chosen for soil profile pit studies in a Chenin blanc/R99 vineyard, Perdeberg area (plot layout D). (Red lines represent lower vigour sections, while green lines represent higher vigour sections. Yellow dots represent the soil profile pit positions).

3.3. RESULTS AND DISCUSSION

3.3.1 IMAGE ANALYSIS FOR VIGOUR CLASSIFICATION

General image analysis: Low vigour patches observed in the image resulting from selective colour replacement (Fig. 3.8) corresponded well with field observations, except for the area outlined in blue in Fig. 3.8, where, for some reason the bare soil patch areas were highly exaggerated. It is interesting to note the two red lines running from the top to the bottom on the right hand side of the image, which correspond to a wider row spacing (inter-row spaces used as roads in the vineyard). A possible explanation for the difference in the area on the right hand side may be the differences in surface soil colour that were observed in the vineyard, being much redder in these parts with more rocky topsoil. The colour of the soil background coming through in the image pixels from these parts may have been coloured more similar to the picked colour than that of bare patches in the rest of the vineyard.

The blue channel image did not correspond to the vigour variation at all, probably because blue light is more subject to scattering by the atmosphere. When examined closely by zooming into areas of interest, the red channel image showed changes in plant vigour better than the greyscale or green images. The improved correspondence of the red band with canopy density was also noted by Dobrowski *et al.* (2002), when evaluating the ratio vegetation index (RVI) (see Chapter 2). It was therefore decided to use this image in further analyses.

Image analysis according to experimental plots: The results from the image analysis of plot layout B (Fig. 3.5) are presented in Figs. 3.9 and 3.10.

A large difference in image pixel values between the two graphs was evident, with high image pixel values corresponding to lower vigour areas and lower image pixel values corresponding to higher vigour areas. The referenced pixel values were used in further calculations, of which the results therefore represented the area in between the two red reference lines. The results from image analysis of the lower and higher vigour plots according to plot layout C are presented in Fig. 3.11.

Figure 3.8 Selective image colour replacement used to indicate bare soil patches in a Chenin blanc/R99 vineyard, Perdeberg area.

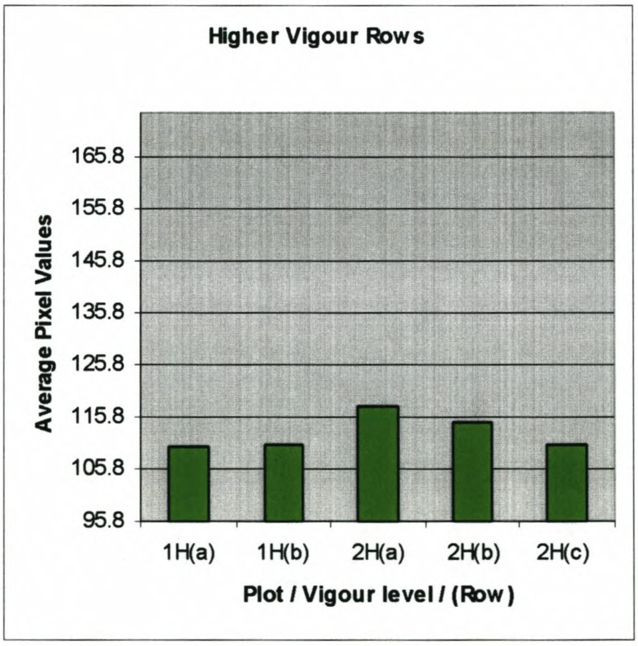


Figure 3.9 Average image pixel values obtained for the higher vigour plots according to plot layout B. Minimum and maximum scale values represent the value determined for the bare soil area and the higher vigour area in a Chenin blanc/R99 vineyard (Perdeberg area), respectively. See Fig. 3.5 for a description of codes used for plots (H = higher vigour; L = lower vigour).

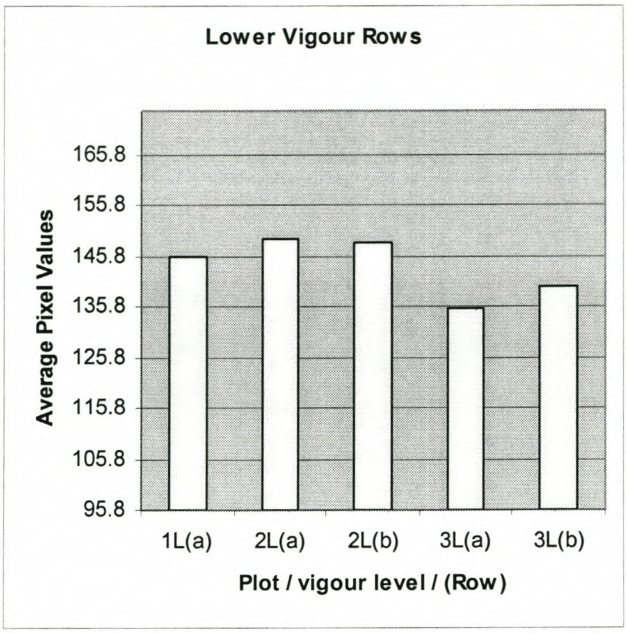


Figure 3.10 Average image pixel values obtained for the lower vigour plots according to plot layout B. Minimum and maximum scale values represent the value determined for the bare soil area and the higher vigour area in a Chenin blanc/R99 vineyard (Perdeberg area), respectively. See Fig. 3.5 for a description of codes used for plots (H = higher vigour; L = lower vigour).

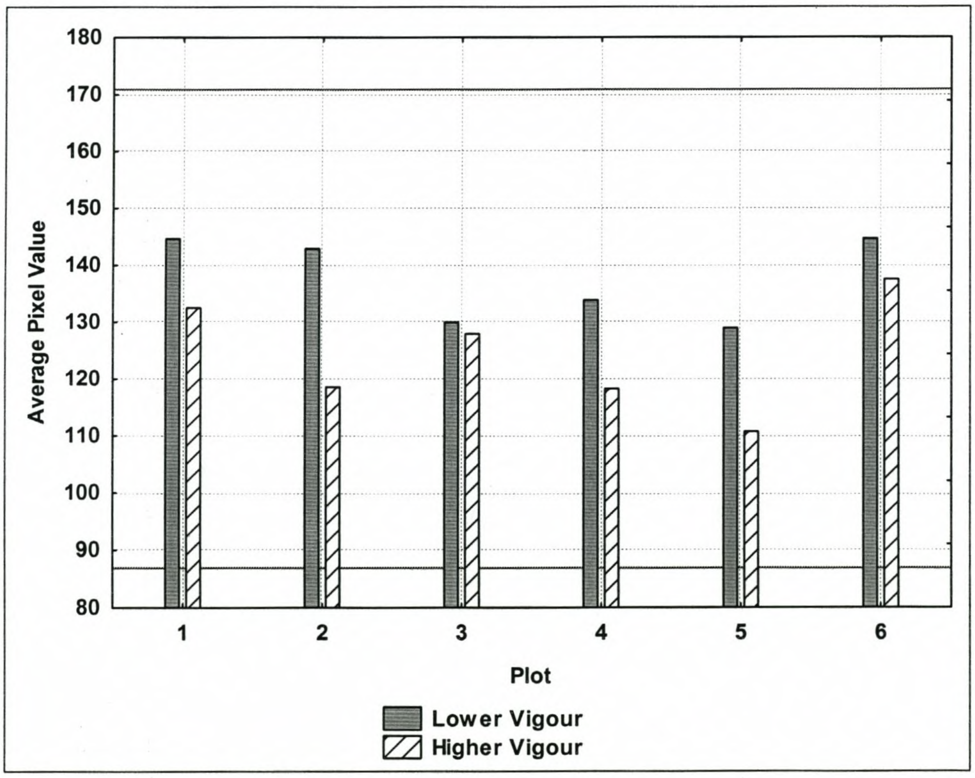


Figure 3.11 Average image pixel values obtained for the plots according to plot layout C. The bottom horizontal line represents the value determined for the bare soil area and the top horizontal line the value determined for the highest vigour area in a Chenin blanc/R99 vineyard (Perdeberg area).

3.3.2 SOIL ANALYSES ACCORDING TO DIFFERENT PLOT LAYOUTS

3.3.2.1 Plot layout A

A summary of the results from a general soil analysis is shown in Table 3.1. Soils of the lower vigour regions can either be classified as non-saline alkali or saline-alkali soils according to the classifications found in the USDA Salinity Handbook 60 (Richards, 1954) and Saayman (1981b). According to Prof. M. Sumner (USA, personal communication, 2003) recent studies have been undertaken to review these classifications, with preliminary results suggesting that crops may already be affected by exchangeable sodium percentages of as low as 4%.

Table 3.1 Analysis of results from soil sampling in higher (H) and lower (L) vigour areas in a Chenin blanc/R99 vineyard on Swartland/Glenrosa soils, Perdeberg.

Vigour Level	**Depth (cm)**	**pH (KCl)**	**Resistance (ohm)**	**T-Value (cmol (+).kg^{-1})**	**P* (mg.kg^{-1})**	**Exchangeable cations (cmol (+).kg^{-1})**			
						K	**Ca**	**Mg**	**Na**
H	0-30	5.00	2210	3.7	13	0.35	2.05	0.66	0.11
H	30-60	5.50	1510	4.52	8	0.16	2.24	1.04	0.19
H	60-90	7.00	530	5		0.09	2.36	1.91	0.64
L	**0-30**	**7.50**	**170**	**26.62**		**0.35**	**18.11**	**5.96**	**2.21**
L	**30-60**	**7.90**	**140**	**27.36**		**0.56**	**17.97**	**5.98**	**2.86**
L	**60-90**	**8.00**	**190**	**23.21**		**0.26**	**15.41**	**5.36**	**2.18**

Vigour Level	**Depth (cm)**	**Cation / T-Value %**			
		K	**Ca**	**Mg**	**Na**
H	0-30	9.48	55.49	17.93	3.04
H	30-60	3.56	49.51	23.04	4.19
H	60-90	1.77	47.24	38.21	12.77
L	**0-30**	**1.32**	**68.02**	**22.38**	**8.29**
L	**30-60**	**2.04**	**65.65**	**21.85**	**10.46**
L	**60-90**	**1.12**	**66.4**	**23.11**	**9.37**

* If pH (KCl) > 7.0, the Olsen method was used for the determination of P

The soils from the lower vigour areas (L) consistently showed a much higher pH (KCl) and sodium/T-value percentages, and much lower soil resistance levels than soils from the higher vigour areas (H). The high calcium and magnesium concentration in the lower vigour soils suggest the presence of alkaline-earth carbonates (lime) in all depth levels, leading to an increase in the calcium and magnesium contents, therefore also leading to a high T-value and high pH. The pH (KCl) levels of higher than 7.5 in the lower vigour areas may also affect the availability of nutrient cations to the grapevine (Northcote, 2000), while such high pH levels also implicates excess sodium and probably potassium, which may potentially increase wine pH through neutralisation of tartaric acid (Saayman, 1981a). The increased calcium in the soil of the lower vigour areas may have a positive effect on soil structure, leading to a less negative effect of the extremely high pH and soil resistance. Analysis of microelements showed no apparent deficiencies or toxicities (data not shown).

3.3.2.2 Plot layout B

The pH (KCl) and soil resistance (R_S) sampled over the whole soil profile (0-90 cm), showed significant differences between the two vigour levels, with a high mean pH (KCl) and low mean R_s for the lower vigour areas (Table 3.3). Although it is useful to note the mean differences in soil conditions at different locations, it is also important to take into account the depth distribution of these conditions. When the separate depth levels are compared it is evident that the largest differences in both pH (KCl) and R_s are found in the topsoil (0-30 cm), which may have significant implications for water infiltration through these levels in the lower vigour areas (Fig. 3.12 and Fig. 3.13). This is especially relevant considering the dependence of the vines on rainfall for its moisture requirements under these dryland conditions.

Table 3.3 Difference (Welch t-test) in mean pH (0-90 cm) and resistance between higher (H) and lower (L) vigour areas in a Chenin blanc/R99 vineyard on Swartland/Glenrosa soils, Perdeberg (Plot layout B). Shaded values are significantly different at the $p \leq 0.05$ level.

	Mean	Mean				Separate variance estimates		
	H	L	t-value	df	P	t-value	df	p (2-sided)
pH (KCl)	7.57	8.20	-3.26	28	0.0029	-3.26	16.01	0.0049
R_S (ohm)	1338.99	292.23	5.42	28	0.000009	5.42	14.99	0.000071

	Valid N H	Valid N L	Std.Dev. H	Std.Dev. L	F-ratio Variances	p Variances
pH (KCl)	15	15	0.72	0.19	13.88	0.000015
R_S (ohm)	15	15	735.19	138.13	28.33	0.000000

Table 3.4 Significance of differences (Welch t-test) in mean pH and resistance for different soil depths between higher (H) and lower (L) vigour areas in a Chenin blanc/R99 vineyard on Swartland/Glenrosa soils, Perdeberg (Plot layout B). Shaded values are significantly different at the $p \leq 0.05$ level.

Analysis	Depth Level	p-value	p-value (2-sided)
pH (KCl)	0-30	0.001	0.0018
	30-60	0.226	0.2514
	60-90	0.312	0.3311
Resistance (ohm)	0-30	0.001	0.0058
	30-60	0.0001	0.0001
	60-90	0.0006	0.0013

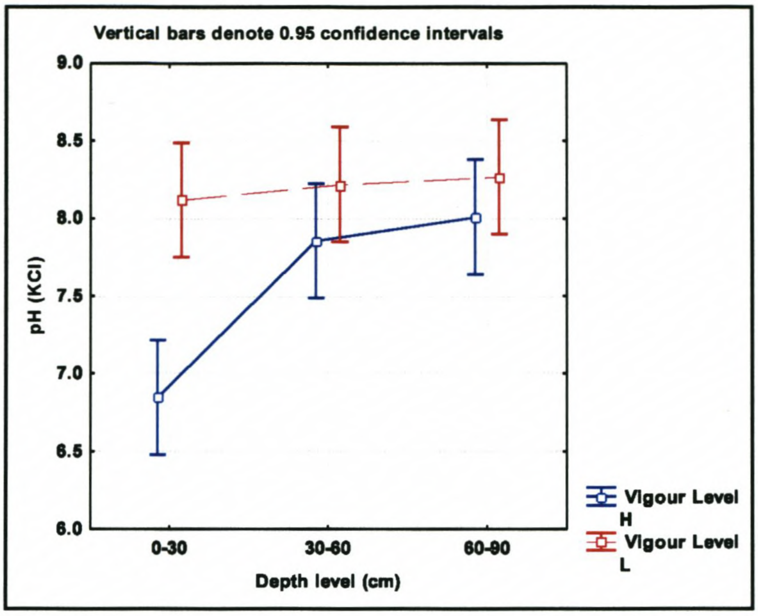


Figure 3.12 Difference in mean pH between higher (H) and lower (L) vigour areas in a Chenin blanc/R99 vineyard on Swartland/Glenrosa soils, Perdeberg (Plot layout B).

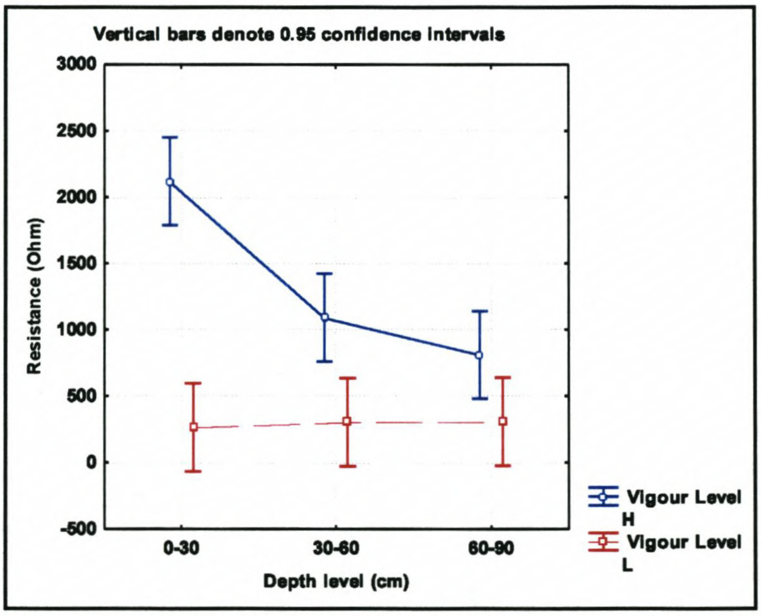


Figure 3.13 Difference in mean resistance between higher (H) and lower (L) vigour areas in a Chenin blanc/R99 vineyard on Swartland/Glenrosa soils, Perdeberg (Plot layout B).

Although a strong correlation existed between soil resistance and the referenced image pixel values, the data was not homogenously distributed along the regression line (Fig. 3.14). This emphasised the importance of incorporating intermediate vigour levels in these types of studies. Fortunately, supplemental resistance values as well as image pixel values were available from the soil sampling according to plot layout D (profile pits). Even though the plots still represented only high and low vigour levels, presumably the proximity of the plots resulted in less extreme R_s values. The resulting correlation, combining the soil resistance values from the sampling from plot layouts B and D, was highly significant (r^2=0.76) (Fig. 3.15). This suggested a strong relationship between the resistance values and image pixel values, even though the values were measured on different plot levels.

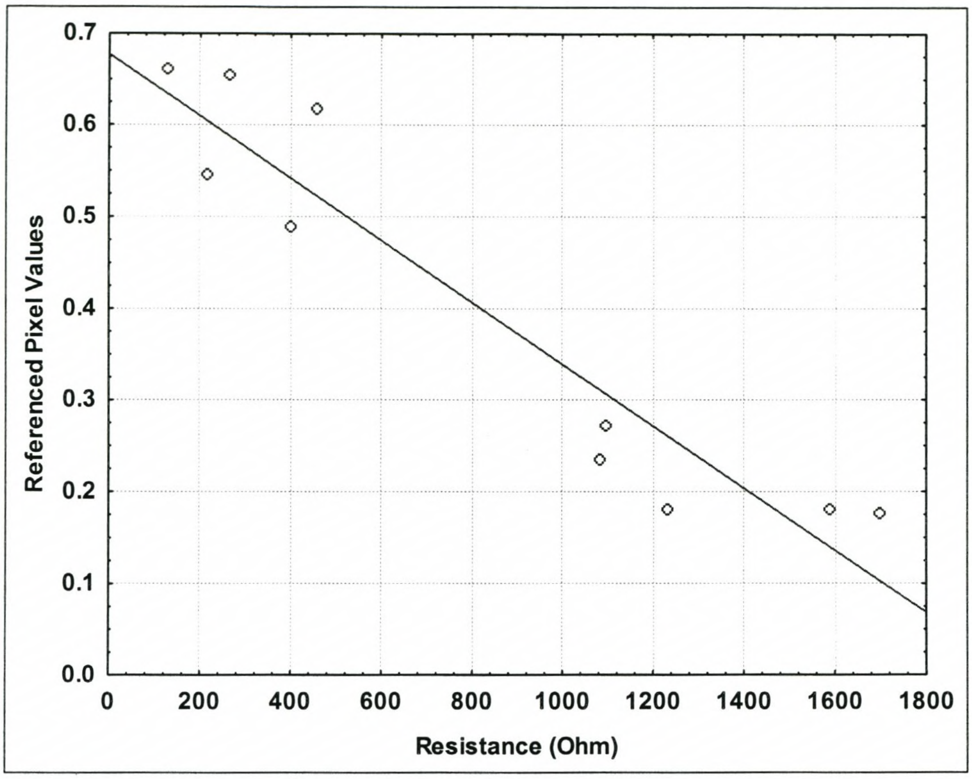


Figure 3.14 Relationship between the resistance of a saturated soil paste (ohm) and the referenced average image pixel values in a Chenin blanc/R99 vineyard on Swartland/Glenrosa soils, Perdeberg (plot layout B) (r^2 = 0.90; r = -0.95, p = 0.00003).

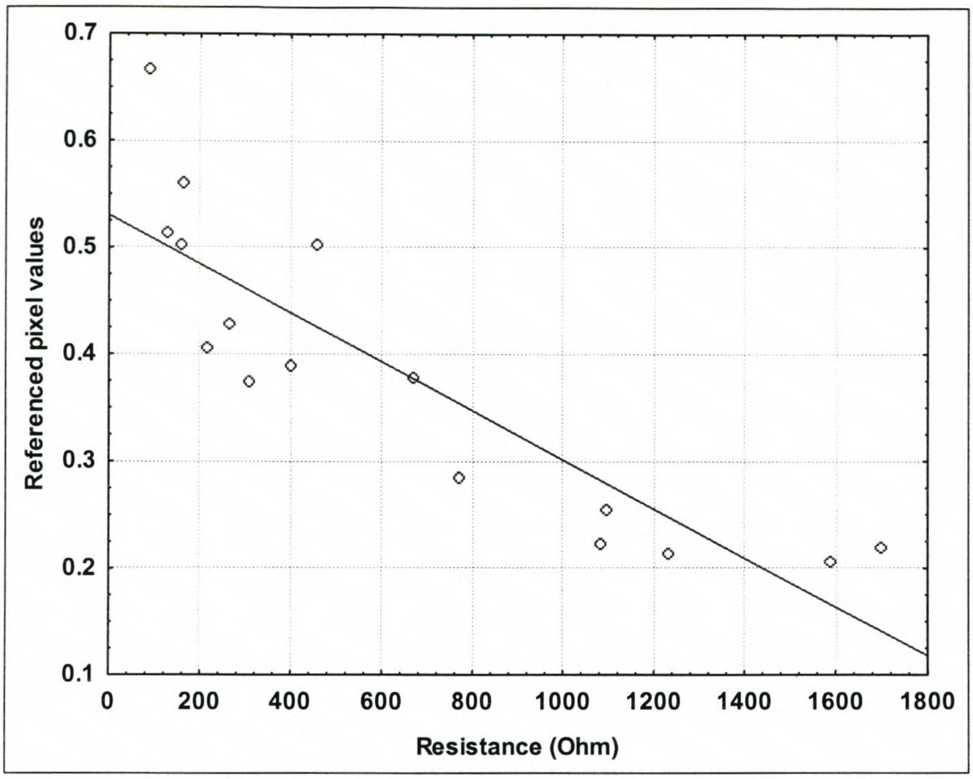


Figure 3.15 Relationship between the resistance of a saturated soil paste (ohm) and the referenced average image pixel values for all values measured in a Chenin blanc/R99 vineyard on Swartland/Glenrosa soils, Perdeberg (plot layout B combined with plot layout D) ($r^2 = 0.76$; $r = -0.87$; $p = 0.00001$).

3.3.2.3 Plot layout D

Soil variability is not sufficiently typified when using a soil auger for sampling purposes, due to the localised nature of the measurement. According to Conradie (1994), soil profile pits are preferred, enabling the researcher to study soil characteristics, root distribution and to facilitate the collection of representative soil samples.

The results from the soil samples obtained from the profile pits, where the means over all depth levels were considered, showed significant differences in the resistance of a saturated soil paste between vigour levels (Table 3.5). It is also notable that the mean resistance levels of the lower vigour levels corresponded to the classification proposed by Saayman (1981b) of “severe salt damage, poorly ripened shoots”.

If the differences between depth levels are considered separately (Table 3.6), a notable decrease in resistance can be observed over depth at the soils of the higher vigour areas. The differences in resistance values between the depth levels of the plots was only statistically significant for certain depth levels, with the non-significant results for the other depth levels, as well as for most of the pH (KCl) values, appearing to be more the result of high levels of soil chemical variability within the treatments.

Table 3.5 Differences (Welch t-test) in soil resistance and pH over 0-120 cm soil depth between higher (H) and lower (L) vigour areas in a Chenin blanc/R99 vineyard on Swartland/Glenrosa soils, Perdeberg (plot layout D). Shaded values are significantly different at the $p \leq 0.05$ level.

	Mean	Mean				Separate variance estimates		
	H	L	t-value	Df	P	t-value	df	p (2-sided)
pH (KCl)	7.46	7.61	-1.12	34	0.2702	-1.12	27.73	0.2720
R_s (ohm)	582.3	137.5	7.38	34	0.0000	7.38	20.18	0.0000

	Valid N H	Valid N L	Std.Dev. H	Std.Dev. L	F-ratio Variances	p Variances
pH (KCl)	18	18	0.488	0.291	2.81	0.040
R_s (ohm)	18	18	244.30	75.08	10.59	0.00001

A relationship suggested by Saayman (1981b) was modified to include values in between classes and used in interpretations of vine response relating to soil resistance (Table 3.7). It was assumed here that the effects on vines reported at different R_s levels in this table may be used as an indication of the vine performance that could be expected in different areas of the study area.

Values were chosen as boundaries for pH, with values for pH (KCl) ≥ 7.5 indicated in bold and pH (KCl) values ≤ 7.5 indicated in normal text. This was done according to Saayman (1981a), attributing pH values higher than 7.5 (KCl) to wine quality decrease.

Table 3.6 Differences (Welch t-test) in soil resistance and pH for each 20 cm depth level between higher (H) and lower (L) vigour areas in a Chenin blanc/R99 vineyard on Swartland/Glenrosa soils, Perdeberg (plot layout D). Shaded values are significantly different at the $p \leq 0.05$ level.

		Mean	Mean				p
		H	L	t-value	df	p	(2 sided)
R_s (ohm)	0-20	742.00	132.00	3.185	4	0.033	0.053
	20-40	632.33	155.00	2.533	4	0.064	0.112
	40-60	633.33	153.33	2.989	4	0.040	0.086
	60-80	552.67	149.33	2.804	4	0.049	0.098
	80-100	517.00	118.00	3.190	4	0.033	0.700
	100-120	416.67	117.33	2.206	4	0.092	0.126
pH (KCl)	0-20	7.07	7.30	-0.41	4	0.700	0.711
	20-40	7.10	7.63	-1.68	4	0.169	0.179
	40-60	7.53	7.83	-2.01	4	0.114	0.121
	60-80	7.53	7.80	-2.53	4	0.065	0.105
	80-100	7.83	7.70	0.66	4	0.547	0.556
	100-120	7.70	7.40	1.26	4	0.276	0.294

		Valid N	Valid N	Std.Dev.	Std.Dev.	F-ratio	p
		H	L	H	L	Variances	Variances
R_s (ohm)	0-20	3	3	298.712	144.357	4.282	0.379
	20-40	3	3	315.730	82.529	14.636	0.128
	40-60	3	3	271.397	61.011	19.788	0.096
	60-80	3	3	243.857	51.003	22.860	0.084
	80-100	3	3	207.805	61.294	11.494	0.160
	100-120	3	3	217.523	88.929	5.983	0.286
pH (KCl)	0-20	3	3	0.907	0.361	6.333	0.273
	20-40	3	3	0.458	0.306	2.250	0.615
	40-60	3	3	0.153	0.208	1.857	0.700
	60-80	3	3	0.058	0.173	9.000	0.200
	80-100	3	3	0.306	0.173	3.111	0.486
	100-120	3	3	0.361	0.200	3.250	0.471

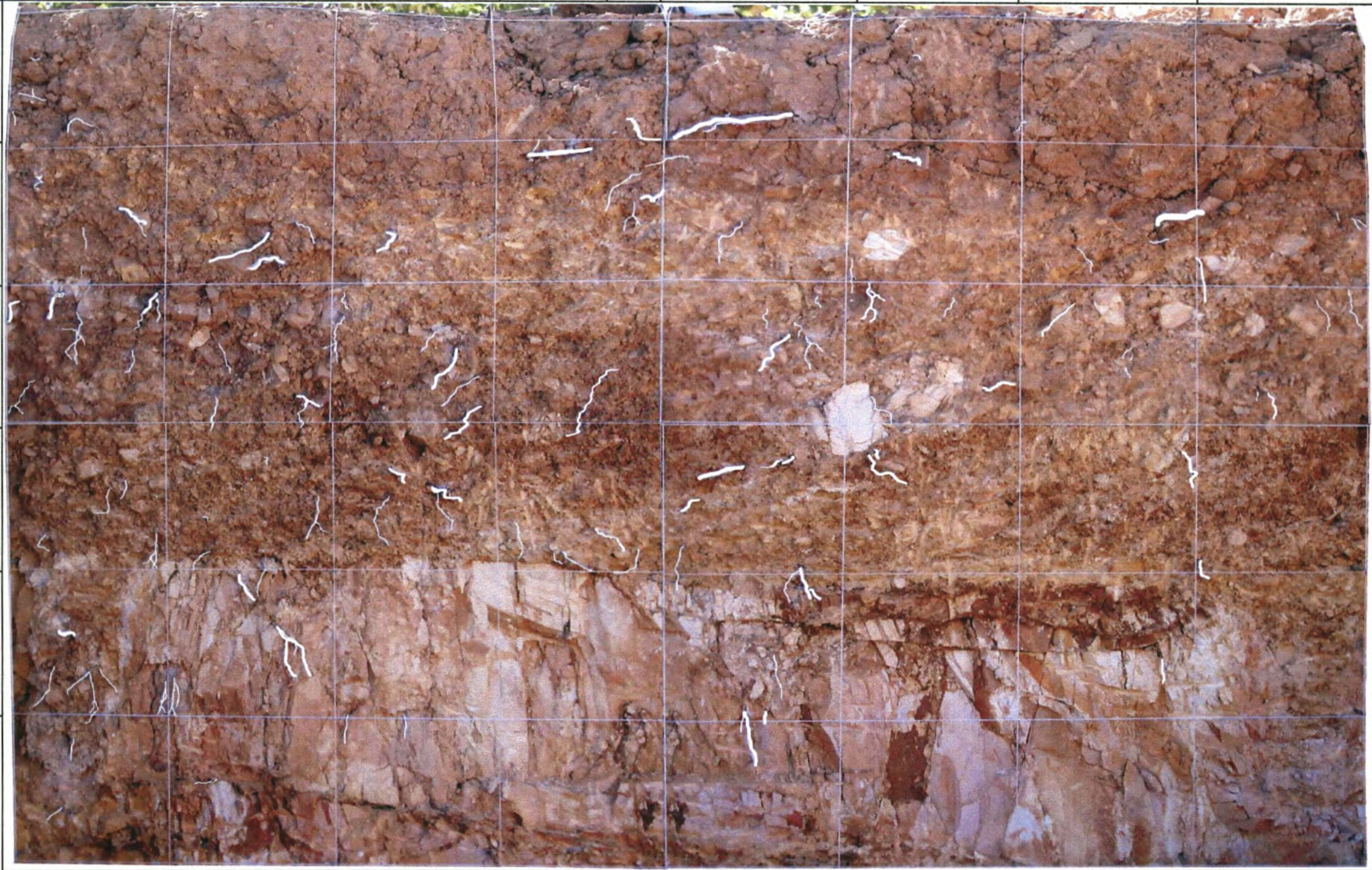
Table 3.7 Relationship between the electrical resistance of a saturated soil paste (R_s), salt content and conductivity (EC_e) of a saturation extract and the related salt effect on the vine (adapted from Saayman, 1981b). The colour coding was also used in the figures showing the soil profile pit walls (Fig. 3.16 – 3.21).

R_s (ohm)	Salt content of soil extract (%)	EC_e ($mS.m^{-1}$)	Effect on the vine
350-1100	0.032-0.128	50-200	Salt effect insignificant
200-350	0.128-0.26	200-400	Symptoms of salt damage
113-200	0.26-0.51	400-800	Severe salt damage, weakly ripened shoots
64-113	0.51-1.02	800-1600	Viticulture not viable over long term
< 64	> 1.02	> 1 600	Totally unsuitable

Each soil profile was also classified into its soil form, including soil family codes according to the Binomial System for Soil classification of MacVicar *et al.* (1977), which is also indicated on Figs 3.16 to 3.21.

The soils of the vineyard studied were delve-ploughed to a depth of approximately 70-80 cm, which was not the correct decision for the soil types found here (ripping would have had a much more desired effect). If the aerial photograph is studied closely, it can be seen that the vigour variability in many cases seem to be directional, namely in the same direction as the vineyard rows. This was also confirmed by R. Bramley (CSIRO, Australia, personal communication, 2003) during a vineyard visit. The latter directional trend in vigour variation can most probably be ascribed to soil preparation practices causing differences in vigour. This will again be discussed when referring to the profile pits.

In general, the amounts of roots counted with diameters larger than 3 mm, differed significantly between the vigour levels. In the sections to follow, each soil profile will be discussed separately.



R (ohm)	pH (KCl)		Roots (> 3 mm)
755	7.2	0-20	9
771	7.2	20-40	26
879	**7.7**	40-60	44
657	**7.6**	60-80	30
588	**8.1**	80-100	25
363	**8.0**	100-120	3

Figure 3.16 Root distribution of Chenin blanc/R99 on Glenrosa 2112/Swartland 21/212 (MacVicar, 1977) soil. **Location:** plot 1, higher vigour (plot layout D). Figures above and on the left of plate indicate distance from the vine and depth, respectively.

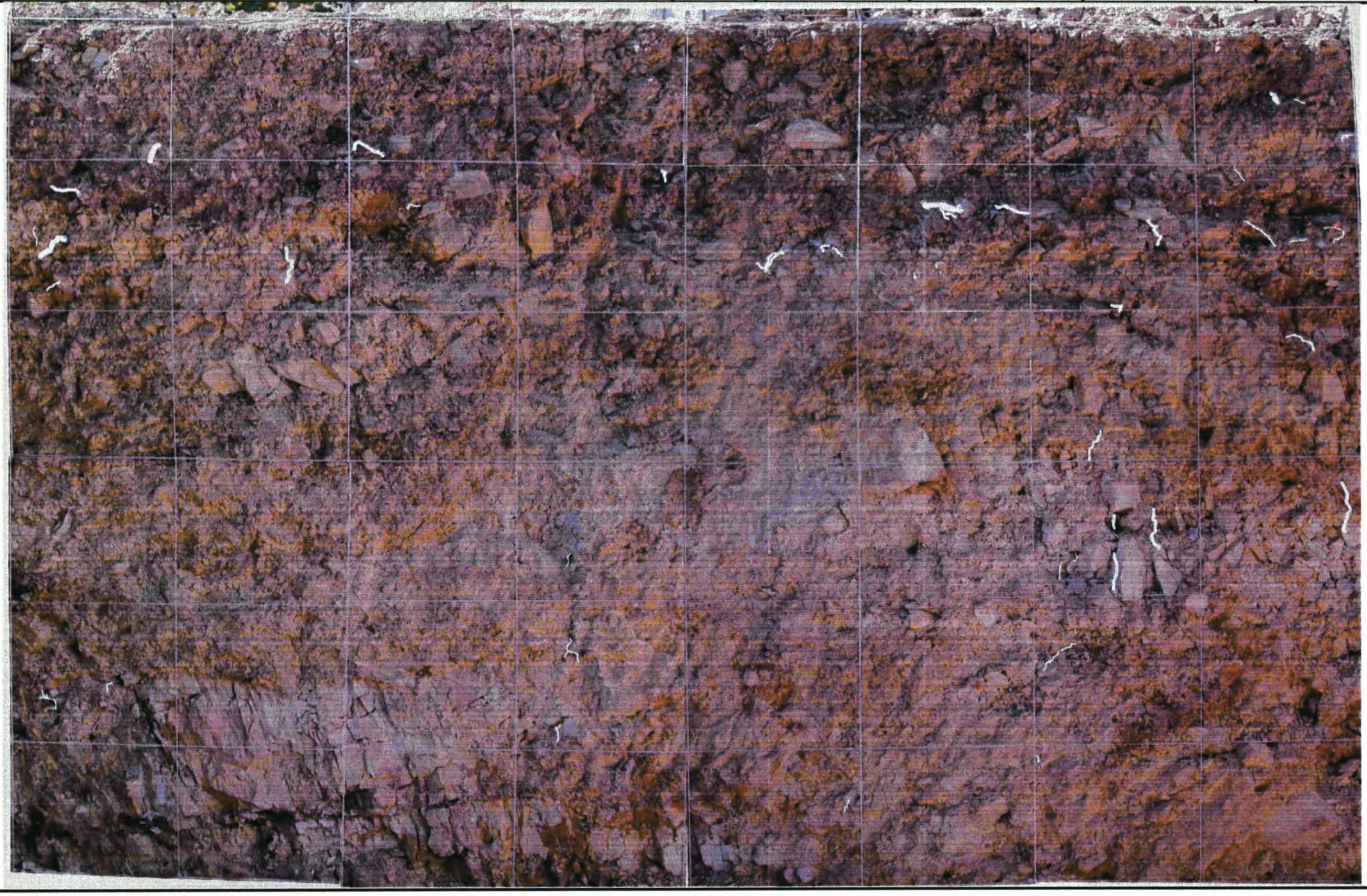
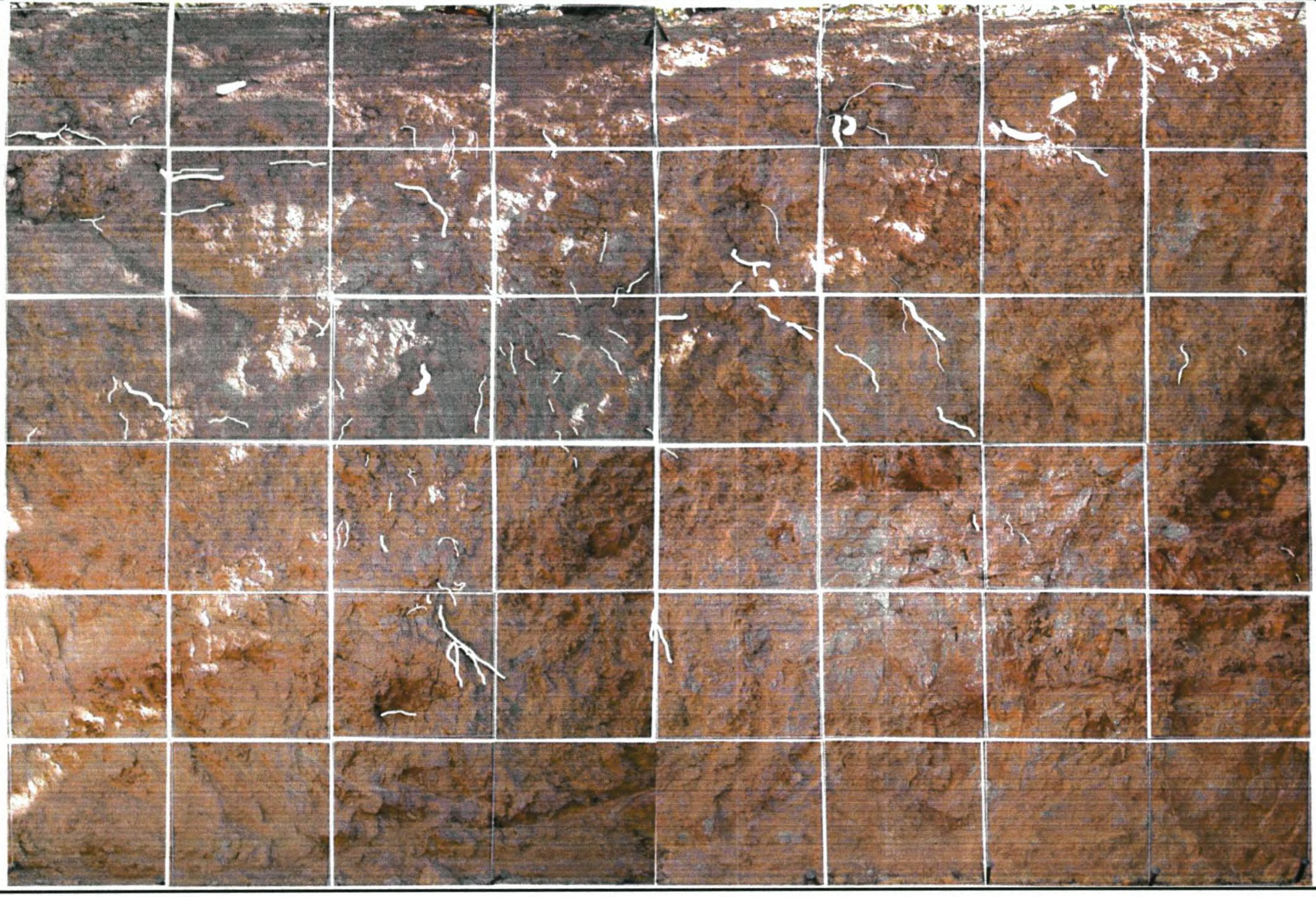
R (ohm)	pH (KCl)		60-80	40-60	20-40	0-20	Vine	0-20	20-40	40-60	60-80	Roots (> 3 mm)
70	7.6	0-20										5
81	7.9	20-40										21
93	8.0	40-60										2
98	7.9	60-80										7
101	7.9	80-100										7
79	7.4	100-120										3

Figure 3.17 Root distribution of Chenin blanc/R99 on Glenrosa 2112/Swartland 21/212 (MacVicar, 1977) soil. **Location:** plot 1, lower vigour (plot layout D). Figures above and on the left of plate indicate distance from the vine and depth, respectively.



R (ohm)	pH (KCl)		60-80	40-60	20-40	0-20	Vine	0-20	20-40	40-60	60-80	Roots (> 3 mm)
437	**7.9**	0-20										20
271	**7.5**	20-40										19
342	**7.5**	40-60										36
274	**7.5**	60-80										17
283	**7.9**	80-100										9
231	**7.8**	100-120										2

Figure 3.18 Root distribution of Chenin blanc/R99 on Glenrosa 2112 (MacVicar, 1977) soil. **Location:** plot 2, higher vigour (plot layout D). Figures above and on the left of plate indicate distance from the vine and depth, respectively.

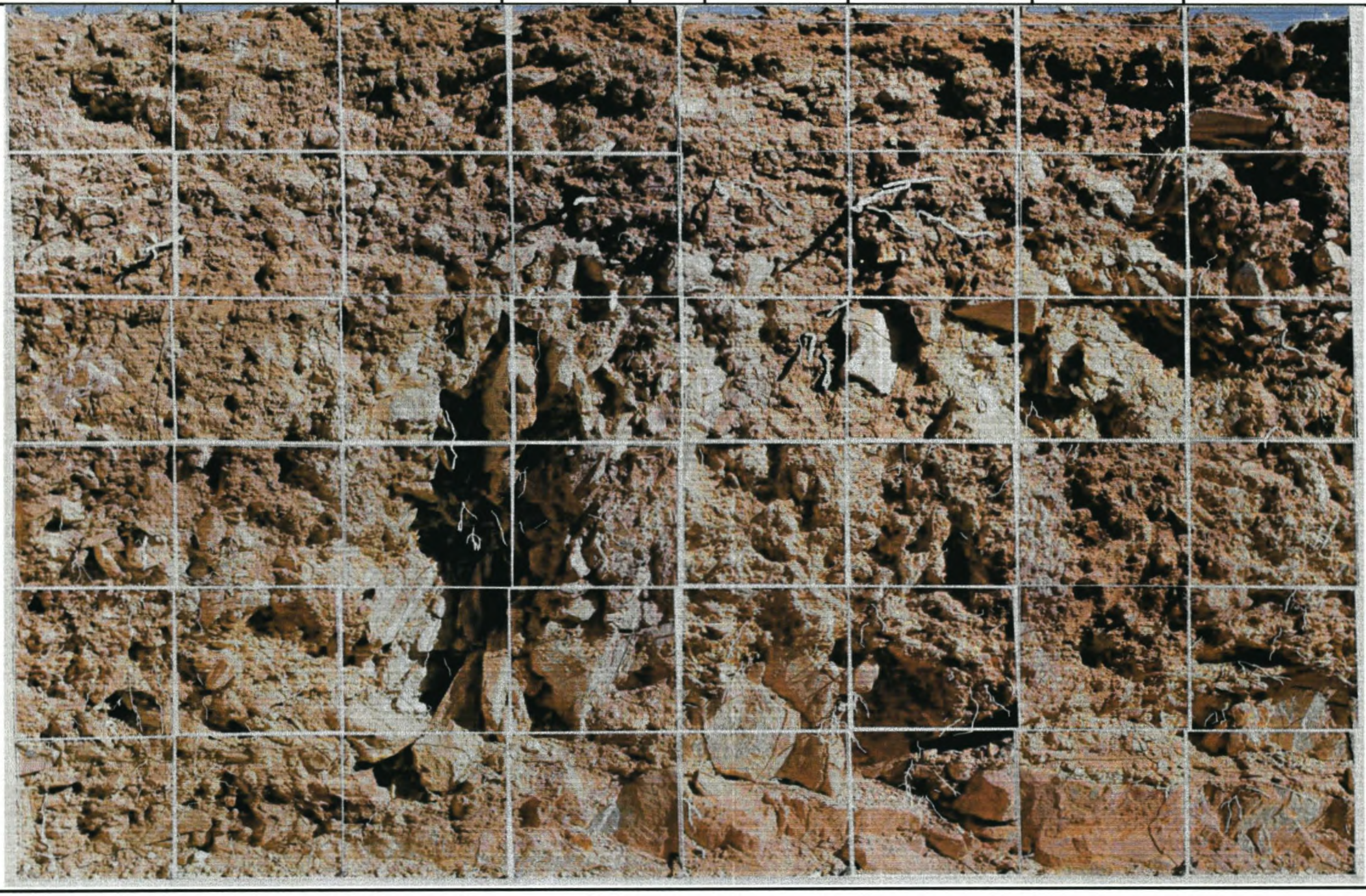
R (ohm)	pH (KCl)		60-80	40-60	20-40	0-20	Vine	0-20	20-40	40-60	60-80	Roots (> 3 mm)
29	6.9	0-20										0
140	7.3	20-40										12
215	**7.9**	40-60										6
200	**7.9**	60-80										6
186	**7.6**	80-100										14
219	**7.6**	100-120										5

Figure 3.19 Root distribution of Chenin blanc/R99 on Glenrosa 2112 (MacVicar, 1977) soil. **Location:** plot 2, lower vigour (plot layout D). Figures above and on the left of plate indicate distance from the vine and depth, respectively.

<table>
<tr><th>R (ohm)</th><th>pH (Kcl)</th><th></th><th>60-80</th><th>40-60</th><th>20-40</th><th>0-20</th><th>Vine</th><th>0-20</th><th>20-40</th><th>40-60</th><th>60-80</th><th>Roots (> 3 mm)</th></tr>
<tr><td>297</td><td>7.4</td><td>0-20</td><td rowspan="6" colspan="9"></td><td>13</td></tr>
<tr><td>244</td><td>7.7</td><td>20-40</td><td>16</td></tr>
<tr><td>152</td><td>7.6</td><td>40-60</td><td>13</td></tr>
<tr><td>150</td><td>7.6</td><td>60-80</td><td>11</td></tr>
<tr><td>67</td><td>7.6</td><td>80-100</td><td>38</td></tr>
<tr><td>54</td><td>7.2</td><td>100-120</td><td>1</td></tr>
</table>

Figure 3.20 Root distribution of Chenin blanc/R99 on Swartland 2112/Glenrosa 2112 (MacVicar, 1977) soil. **Location:** plot 3, lower vigour (plot layout D). Figures above and on the left of plate indicate distance from the vine and depth, respectively.

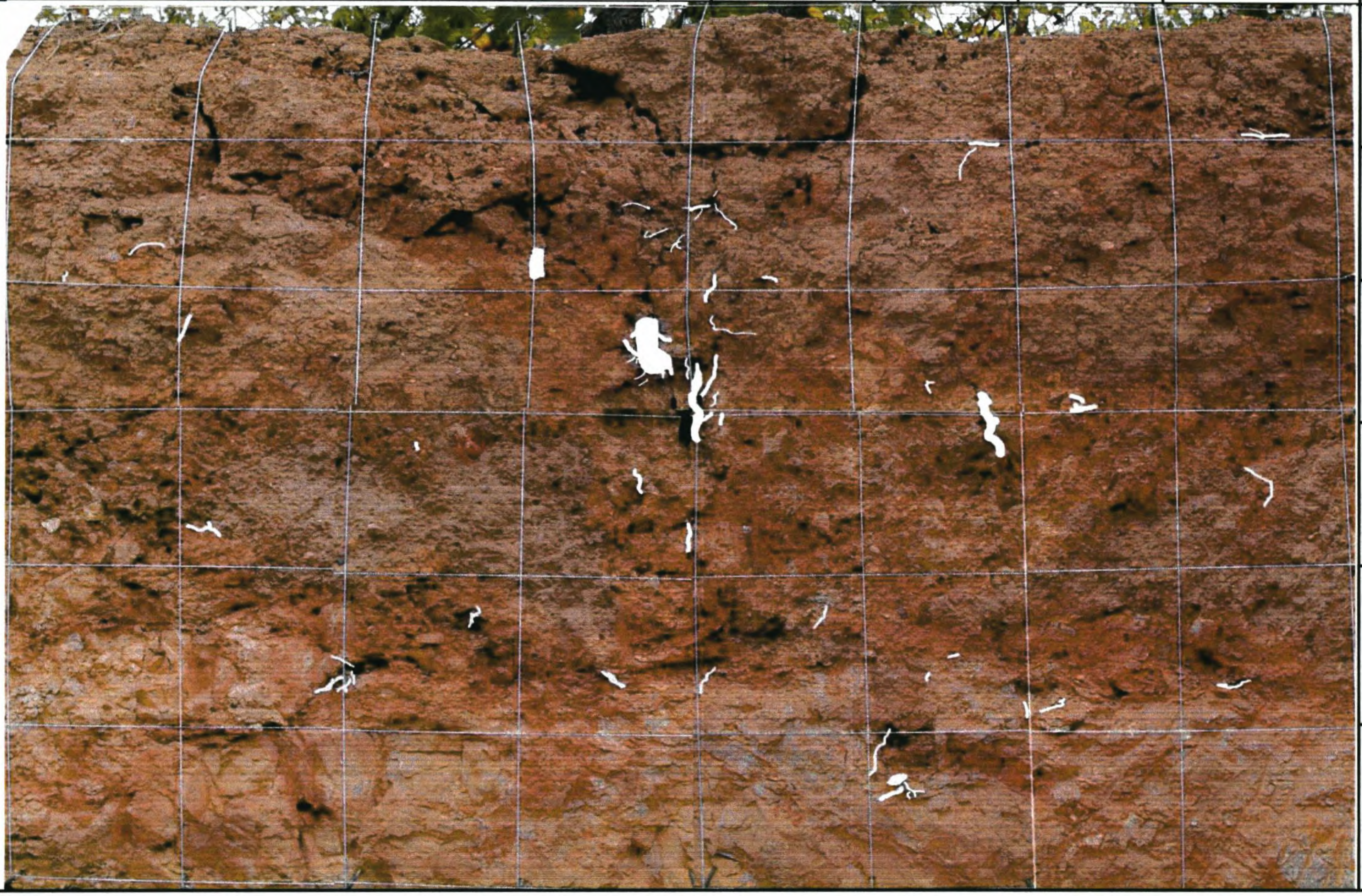
R (ohm)	pH (Kcl)		60-80	40-60	20-40	0-20	Vine	0-20	20-40	40-60	60-80	Roots (> 3 mm)
1034	6.1	0-20										2
855	6.6	20-40										16
679	7.4	40-60										13
727	7.5	60-80										7
680	7.5	80-100										17
656	7.3	100-120										6

Figure 3.21 Root distribution of Chenin blanc/R99 on Swartland 2212 (MacVicar, 1977) soil. **Location:** plot 3, higher vigour (plot layout D). Figures above and on the left of plate indicate distance from the vine and depth, respectively.

Figure 3.22 Differences in above-ground growth of the vines of plot 1, higher vigour (plot layout D) in a Chenin blanc/R99 vineyard on Swartland/Glenrosa soils, Perdeberg.

Figure 3.23 Differences in above-ground growth of the vines of plot 1, lower vigour (plot layout D) in a Chenin blanc/R99 vineyard on Swartland/Glenrosa soils, Perdeberg.

Figure 3.24 Differences in above-ground growth of the vines of plot 2, higher vigour (plot layout D) in a Chenin blanc/R99 vineyard on Swartland/Glenrosa soils, Perdeberg.

Figure 3.25 Differences in above-ground growth of the vines of plot 2, lower vigour (plot layout D) in a Chenin blanc/R99 vineyard on Swartland/Glenrosa soils, Perdeberg.

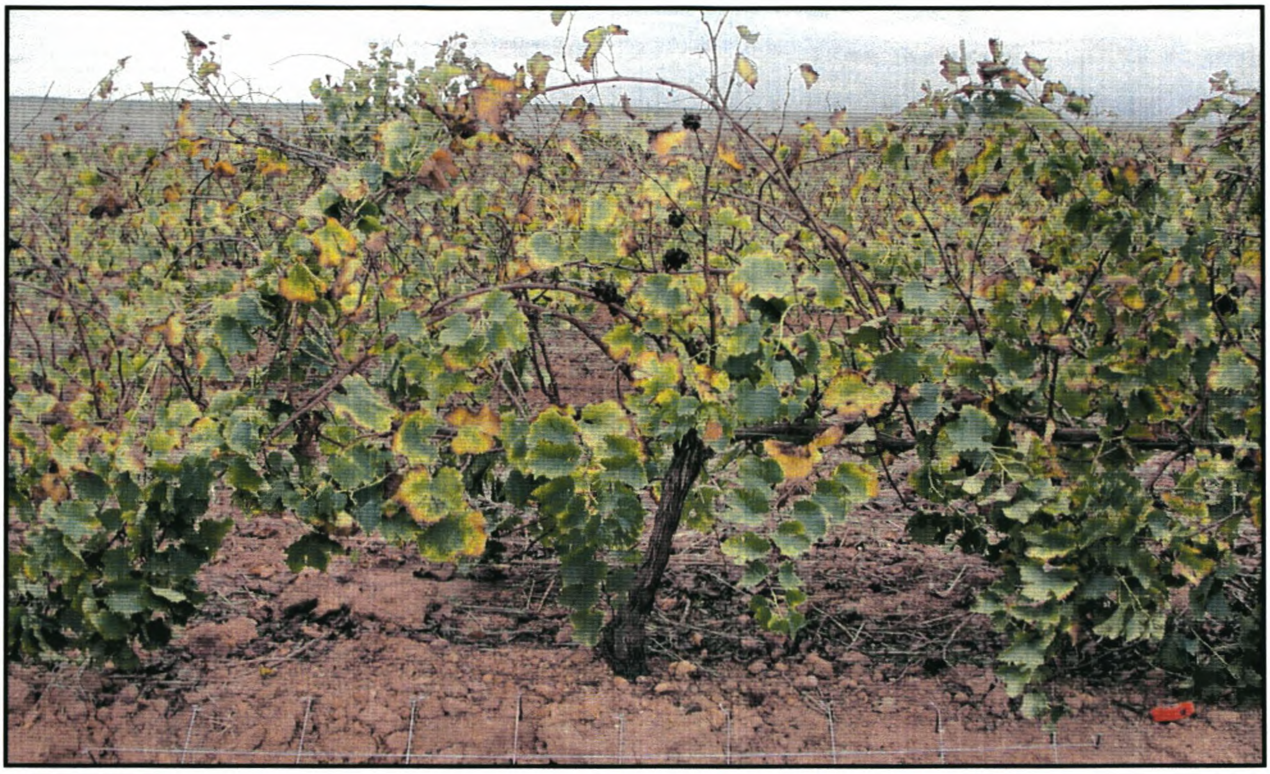


Figure 3.26 Differences in above-ground growth of the vines of plot 3, higher vigour (plot layout D) in a Chenin blanc/R99 vineyard on Swartland/Glenrosa soils, Perdeberg.

Figure 3.27 Differences in above-ground growth of the vines of plot 3, lower vigour (plot layout D) in a Chenin blanc/R99 vineyard on Swartland/Glenrosa soils, Perdeberg.

Plot 1, higher vigour (Figs. 3.16 and 3.22): It was apparent in this profile that most of the roots were found in the layers from 0-80 cm. Root distribution was fairly homogenous through the profile, except for the shale layer, where only fine roots could be found where they grow through cracks between the shale plates.

Plot 1, lower vigour (Figs. 3.17 and 3.23): The colour hue differences between the soil profiles of the higher and lower vigour areas in plot 1 were not visible in the field and are due to the digital camera settings. It is evident here that roots are predominantly found in the 0-40 cm depth levels. Another important observation was the position of the shale layer, of which a part was found intact in the left-hand bottom corner of the profile, while it was mixed into the B-horizon on the right hand side. This could have been caused by the delve-ploughing action, which was not the desired soil preparation method in this case, stressing the importance of judicious soil preparation techniques, as discussed by Van Huyssteen (1988).

Plot 2, higher vigour (Figs. 3.18 and 3.24): In this profile hard and dense zones were found that did not allow for easy root penetration, probably caused by the soil preparation method. In this case it also seemed that sampling of the lighter coloured area on the bottom right of the image (60-100 cm) would have been a better option than only taking a pooled sample of the whole depth layer, as it was evident that root growth was inhibited strongly in this area.

Plot 2, lower vigour (Figs. 3.19 and 3.25): With this profile the high root count should be seen in perspective with the preparation of the profile. A lot less fine roots were broken off or damaged during preparation of this profile wall owing to the much weaker structured soil found here, especially in the regions where a lot of shale particles were found. An important observation in this profile was the extremely low resistance levels found in the 0-20 cm soil layer, where no roots could be found. The extremely high salt content in the topsoil may cause lower permeability to moisture (Richards, 1954; Northcote, 2000), which may be an important factor in a dryland cultivated vineyard. This was supported by the observation that water remained on the soil surface after rainfall in many of the lower vigour areas, unable to penetrate sufficiently into the deeper soil layers.

Plot 3, lower vigour (Figs. 3.20 and 3.26): An interesting observation made in plot 3 was the differences between the soil colours of the two profile pits. This was even more clearly visible when looking at the heaps of soil that came from the pits (Fig. 3.28). The redder soil colour observed at the soil profile in the higher vigour area at plot 3 may be a sign of a better soil structure and also higher soil fertility in comparison with this soil profile.

In both the profiles of plot 3, the effect of the ploughing-in of the topsoil could be clearly seen. These ploughed-in sections were hard and dense, not allowing for easy root penetration. The main reason for the weaker growth at this profile may be explained by the position of most of the roots (in this case also the thickest roots). Most roots were localised in the 0-40 cm soil layers owing to the relatively more favourable chemical conditions (higher resistance). The top soil layers dry out much quicker than the deeper soil layers and roots are left in a relatively un-buffered situation. The high number of roots observed in the 80-100 cm layer actually originates from the bottom of the 60-80 cm layer, where it grows through the boundary formed as the B-horizon changes into the shale layer.

Soil heap from soil profile 5 **Soil heap from soil profile 6**

Figure 3.28 Differences in soil colour observed at plot 3 between the soil profile holes of differing vigour levels in a Chenin blanc/R99 vineyard on Swartland/Glenrosa soils, Perdeberg (Plot layout D).

Plot 3, higher vigour (Figs. 3.21 and 3.27): In this profile most roots were situated in the deeper soil layers, where moisture will be available much longer than in the case of the lower vigour area at this plot, where the roots were mostly found in the upper soil layers. The soil zones where most of the roots were found were also redder in colour and presumably more favourably structured, as already mentioned before.

Chemical soil analysis, root distribution observations, as well as the observations relating to soil preparation practices therefore suggests that, in combination, these factors cause an extremely high level of variability in aboveground growth over the short distances included in the plot layout.

3.4 CONCLUSIONS

It was possible to identify a suitable vineyard for a study on within-vineyard variability. The vineyard had highly heterogeneous aboveground growth, and an aerial image could be used to investigate the sources of the high levels of variability. Selective image colour replacement successfully showed areas that were worst affected by the soil conditions.

The different plot layouts used to study soil variability proved to be effective, with plot layout A showing large differences between soils of the extremes in vigour, plot layout B confirming that these differences are also large for larger areas representing a specific vigour level and with the main experimental plot layout (plot layout C) expressing the highest level of variability over the shortest distances. Apart from the significant differences found between several soil-related parameters measured for the higher and lower vigour levels, a strong correlation was found between soil resistance levels and the calculated image pixel values. The simple method of image pixel analysis therefore proved effective, with the values extracted for the plots of plot layouts B, C and D confirming the levels of variability found in soil resistance. Heterogeneous growth between the vines was shown to be the result of high salt content in the soil, worsened by the delve-ploughing action performed during soil preparation. A combination of soil pH and resistance analyses and soil profile pit studies suggested that a combination of soil chemical as well as soil physical conditions played a role in the high levels of within-vineyard vigour variability. It was also shown that the resistance of the topsoil played an important role in the observed growth reaction of the vines. The results obtained suggest that higher vigour areas exist where soil physicochemical conditions are less limiting to water infiltration to deeper soil layers, an important factor in dryland conditions. Although the observations related to aboveground vigour differences between the soil profile pits of the different vigour levels was not always consistent, it is evident that the extreme differences could only have been caused by a combination of factors, of which all were not measured in this study.

The soil-borne sources of variability in this vineyard have therefore been investigated and have also been associated with pixel values extracted from an aerial image. Further ground truthing would be needed to confirm the effect these sources of variability can have on aboveground growth and eventually wine quality. The latter is addressed in the next chapter.

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Chapter 4

RESEARCH RESULTS

Characterisation of above-ground vigour variability at Perdeberg with conventional and hyperspectral analyses

RESEARCH RESULTS

4.1 INTRODUCTION

It was shown in the research design chapter how soil conditions in a highly variable vineyard can be related to values extracted from an aerial image that convey information about the aboveground growth of the vine. However, it is necessary to characterise the aboveground vigour variability with field measurements in order to determine if the spatial distribution of this variability conforms to the values from the aerial image. In addition to this, these measurements must also be compared with values describing soil conditions, in order to quantify the strength of the link between the causes and effects of the variability. The most important link, however, is the one with grape and wine quality and character, in order to move a step closer to explaining the high wine quality levels obtained from such a variable vineyard.

Improved techniques for determining canopy and leaf spectral response to stress conditions have recently become available in the form of hyperspectral reflectance measurements. While multispectral technologies only measure reflectance from a target in four or five relatively wide wavebands, hyperspectral instruments measure reflectance in numerous narrow wavebands yielding a spectral graph which describes the target. Lang *et al.* (2000) used this technology to show distinct changes at specific wavelengths for vine leaves that were exposed to ultraviolet radiation or water-deficit stress. This technique will also be evaluated here as a tool to measure the spectral properties of stress in vine leaves and canopies, while also showing how these measurements correspond to information extracted from the aerial image.

4.2 MATERIALS AND METHODS

4.2.1 PLOT LAYOUT

Plot layout C was used as a basis for all the measurements made in this chapter (refer to Section 3.2.2.3 and Fig. 3.6). Producer and viticulturist inputs regarding large differences in fruit analyses from different areas in the vineyard, suggested that the high level of variability in the vineyard would be expressed explicitly if a “vigour differences in different vineyard areas” approach (more or less a “plot layout B” approach – see Fig. 3.5) is followed. It was therefore rather decided to test the levels of variability in canopy, fruit and wine characteristics over much shorter distances, as is expressed in plot layout C. The results from data collected therefore have to be considered while taking into account the limited area in which spatial variability could be expressed.

4.2.2 VEGETATIVE MEASUREMENTS

4.2.2.1 Trunk circumference

The trunk circumference of each vine of plot layout C was measured with a flexible tape measure at a position 10 cm above the graft union.

4.2.2.2 Canopy measurements

Destructive leaf area measurements were conducted shortly after harvest on two shoots from each harvested vine of plot layout C. One shoot was removed from each cordon at a spur position close to the centre of the vine. All leaves from the respective shoots were separated into bags, keeping lateral shoot leaves apart. A leaf area meter (Li-Cor 3000) was used to determine the total leaf area for both the main and lateral shoots. From this the average leaf size could be determined as well as the total leaf area per shoot.

Light measurements of the photosynthetically active radiation (400-700 nm) were also conducted on a hot, cloudless day (32°C) with a sunfleck ceptometer (Decagon Devices, Inc., Pullmann, Wash.) in the canopies of the vines in plot 2 (plot layout C).

The lengths of the shoots that were destructively harvested for leaf area measurements were determined with a tape measure. The unripe shoot tips were measured separately and lateral shoots were counted as well as the nodes of the main shoot. The number of shoots was also counted on each vine, only including shoots on spur positions that had the potential of bearing grapes.

4.2.2.3 Leaf water potential

Pre-dawn as well as midday leaf water potential were measured with a pressure chamber (PMS Instrument Co., Corvallis, Orc.) early in January (post-véraison). The plots where these measurements were conducted are shown in Fig. 4.1.

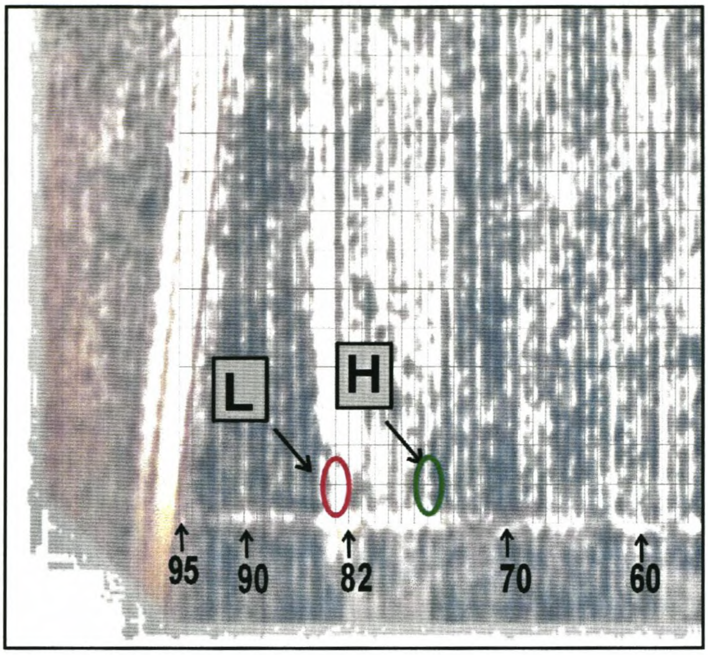

Figure 4.1 Row numbers and positions in Chenin blanc/R99 vineyard, Perdeberg, where leaf water potential measurements were conducted in January 2002. Lower vigour (L) and higher vigour (H) plots are indicated.

The leaves chosen for the measurements were young, but fully expanded leaves near the main shoot tip (approximately 6 nodes from the shoot tip). Leaf water potential was measured according to the method of Scholander *et al.* (1965). The midday measurements were done in December (pre-véraison) at approximately 12:00 on a hot day (30°C), using the same plots and method as in the pre-dawn measurements.

4.2.3. HARVEST MEASUREMENTS

4.2.3.1 Yield measurements

Based on plot layout C, grapes were harvested from randomly selected vines of each vigour level. This took place at the same time as harvest for the whole block. Yield per vine was recorded and approximately 50 kg of grapes were sampled for small-scale winemaking.

4.2.3.2 Bunch mass

A sample of 20 bunches were selected at random from the grape batches that were harvested from the plots of each vigour level. These bunches were all weighed on a laboratory scale, from which the average bunch mass was calculated.

4.2.3.3 Berry mass

Ten bunches were selected at random from those used in the bunch mass determination for each vigour level and the sample was split into five sub-samples of two bunches each. All berries were removed from these bunches and the berries from each two-bunch sample were pooled and 100 berries were randomly picked and weighed. This yielded five values for average mass per 100 berries (g) for each vigour level.

4.2.3.4 Juice chemical analysis

After destemming and lightly pressing the grapes in a miniature bag press, grape juice samples were collected from each of the vigour levels for analysis of total soluble solids (electronic refractometer), pH and titratable acid (automatic Swiss Lab 702 SM Titrino titration device).

4.2.4. EXPERIMENTAL WINEMAKING

4.2.4.1 Winemaking procedures

Experimental wines were made according to the standard winemaking procedures of the University of Stellenbosch Oenology Department. The wines were dry-fermented with the neutral yeast strain VIN 13. The grape condition was very good, but SO_2-levels were nevertheless monitored through the winemaking process and kept at acceptable levels.

4.2.4.2 Wine chemical analysis

An automatic titration machine (Swiss Lab 702 SM Titrino) was used for pH, titratable acid and SO_2 determination in the wines before and after bottling. The wines were also analysed for volatile aroma compounds with a gas chromatograph (HP 6890 series).

4.2.4.3 Wine sensory analysis

A wine sensory analysis was conducted with four panel members with high levels of experience in wine tasting. Three of the judges were highly reputable winemakers and the fourth was a British Master of Wine. The wines from each vigour level were tasted separately in a blind tasting and members of the panel were asked to write descriptive comments on the aroma and taste characteristics of both wines.

4.2.5. HYPERSPECTRAL MEASUREMENTS

4.2.5.1 Measurements in the field

Hyperspectral field measurements were conducted on 23 February. It was a hot day (over 30°C), and vines from the lower vigour areas showed visual stress symptoms (tendrils started to droop on many vines). The non-destructive measurement of leaf and canopy reflectance took place at plot 2 as indicated on Fig. 3.6 (plot layout C). The plot was chosen because of the high measured variability in trunk circumference between the vines of the different sections, as well as visual differences in growth and stress levels.

Measurements were conducted with a Fieldspec Pro FR Field Spectroradiometer (Analytical Spectral Devices, Inc., Boulder, Colorado, USA) that sampled each target's reflectance from 350 nm to 2500 nm. The instrument was initially standardised from memory and again after each subsequent measurement cycle by using a standard white reference panel set up in the vineyard. Reflectance from both the adaxial and abaxial sides from 10 leaves of each of the vigour levels was measured. The full sun-exposed leaves were chosen at random from different vines in the plots moving down the rows (Fig. 4.2). Vine canopy reflectance was also measured by performing four canopy transect measurements along the canopies of the vines of the respective plots, with the instrument probe held in a position perpendicular with the soil surface and at approximately 25 cm distance from the vine canopy.

The instrument took five subsequent readings of the whole spectrum from 350 to 2500 nm at intervals of one second for each measured target. Each target type's reflectance was computed from the mean of these five readings, as well as the mean of all the repetitions for the specific target. For instance, all 10 of the higher vigour plot's adaxial leaf reflectance readings were averaged to produce the relevant graph, with the same procedure followed for the lower vigour area.

4.2.5.2 Data processing for image pixel correlations

In order to test the relationship between the referenced image pixel values and the hyperspectral field measurements, it was decided to use a narrow band normalised difference vegetation index (NDVI) as proposed by Thenkabail *et al.* (2001). The wavelength used for the red band was the chlorophyll absorption maxima (reflectance minima) at 682 nm, and the maxima of the near-infrared shoulder at 920 nm (Table 4.1 and Equation 4.1).

$$\text{Narrow - waveband NDVI} = \frac{(R_{IR} - R_{R})}{(R_{IR} + R_{R})} \qquad \text{(Equation 4.1)}$$

Where: R_{IR} = Reflectance at 920 nm (infrared shoulder peak)
R_{R} = Reflectance at 682 nm (red chlorophyll absorption peak)

The next step was to extract image pixel values from plot 2 (plot layout C) on the aerial image, that was comparable to the calculated narrow band NDVI. For this it was necessary to zoom in further on the image and to change the mask size so that it represented only a few pixels corresponding to the width of the canopies (Fig. 4.2). To account for the possibility of slight errors in measurement (as geo-referencing up to a single-vine level was not possible in this study), a slightly longer part of the row was analysed than the actual plot size used in the hyperspectral field study. The pixel mask was moved in small increments on the image in the same direction in which the hyperspectral data acquisition took place, recording values for every subsequent placement along the row. It was kept in mind that some of the values at the ends of the plots would not necessarily correspond to the hyperspectral data when the values from the two analyses were compared.

The image pixel values were also not normalised in accordance with reference plots as was the case in the other plot layouts, but rather adapted for comparison to the hyperspectral narrow-band NDVI values. Firstly, the average pixel values were converted to values between zero and one in order to correspond with the values for NDVI normally found in vegetation targets. As already mentioned, the lower average pixel values represented higher vigour levels and the higher pixel values represented the lower vigour levels. This was not the case for the NDVI values, which represented values from zero to one, with higher values representing the higher vigour areas. Equation 4.2 had to be used to make the necessary adjustments.

$$P_B = 1 - \left(\frac{P_A}{255}\right) \qquad \text{(Equation 4.2)}$$

Where: P_A = Average pixel value from image analysis (not referenced)
P_B = Average processed pixel value for narrow-band NDVI comparison.

The second step involved normalising the values of P_B to the narrow-band NDVI in order to compare relative differences between the vigour levels. Equation 4.3 was used for this.

$$\text{Normalised } P_B = P_B \frac{\text{NDVI}_{\text{NB}}(\text{Max})}{P_B(\text{Max})} \qquad \text{(Equation 4.3)}$$

Where: NDVI_{NB} (Max) = Maximum value recorded for the narrow-band NDVI
P_B (Max) = Maximum value recorded for P_B (Equation 4.2)

4.2.5.3 Data processing for spectral feature analysis

Large amounts of reflectance noise occurred in the spectral regions near 1370 nm, 1827 nm and 1870 to 1920 nm. This was due to reflectance of atmospheric gases such as carbon dioxide as well as water vapour (ASD, 1999). To enable a comparison of reflectance data for high and low vigour, it was necessary to remove reflectance values in these regions from the data in order to obtain meaningful data ranges for graphical presentation in the other spectral regions. Another problem that had to be overcome was the slight changes in reflectance between different readings of one feature, as are normally caused by variables such as actual reflectance difference, the time interval between readings or distance from the measured object (ASD, 1999). As this experiment was aimed to determine wavelengths that differ in reflectance owing to changes in certain components in stressed plants, some manipulations had to be made to the data. The data was therefore normalised and converted to a ratio of lower vigour/higher vigour, according to a method proposed by Greg Okin (University of Santa Barbara, CA, USA, personal communication, 2002). His proposed method was rewritten as in Equation 4.4.

$$\text{RF Ratio} = \frac{\text{RF}_\text{L} \div \text{RF}_\text{Max}}{\text{RF}_\text{H} \div \text{RF}_\text{Max}}$$

(Equation 4.4, Greg Okin, University of Santa Barbara, CA, USA, personal communication, 2002)

Where: RF Ratio = Reflectance ratio between lower and higher vigour measurements

RF_L = Reflectance measured from the target in the lower vigour area

RF_H = Reflectance measured from the target in the higher vigour area

RF_{Max} = Reflectance value at brightest wavelength (usually between 1000 and 1150 nm, in this case approximately 1086 nm)

This formula was applied to all of the wavelengths sampled from 350 to 2500 nm for all the targets and the resulting graphs plotted. The resulting value for each wavelength normally yields a number near unity where the amount of reflected light from components specific to that wavelength does not differ between the vigour levels. Where the reflectance ratio value for a wavelength rises above unity, it means that more light is reflected from the components specific to that wavelength or wavelength region in the lower vigour area than in the higher vigour area. For a component such as chlorophyll, that utilises light in specific wavelengths to function, a higher reflectance ratio at the functional wavelength regions and therefore decreased light absorption, could point to either decreased functioning by the light harvesting apparatus, or to decreased amounts of the component.

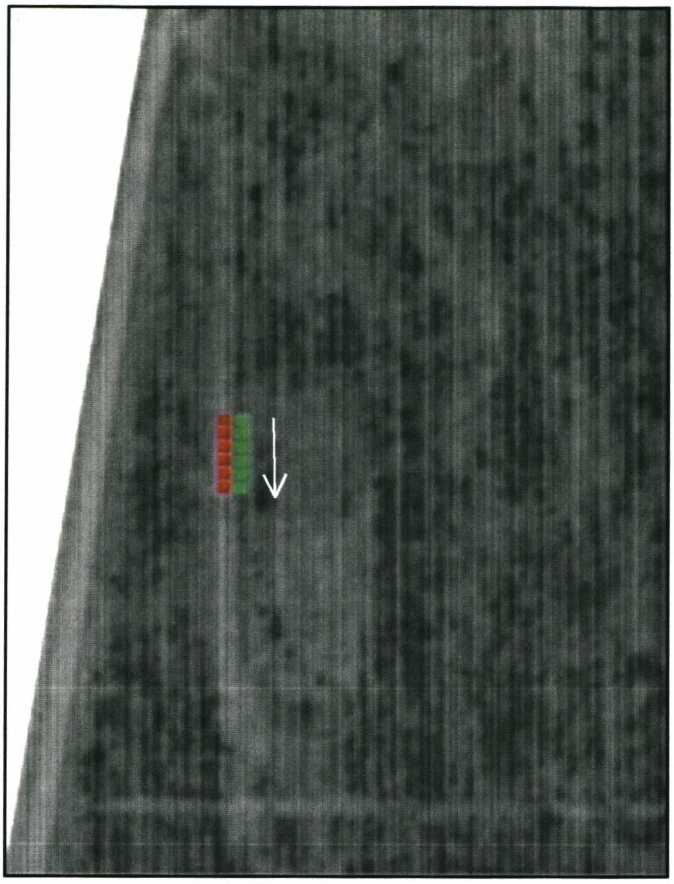

Figure 4.2 Locations for hyperspectral field measurements as well as pixel analysis (plot 2, plot layout C) in a Chenin blanc/R99 vineyard in the Perdeberg area. The arrow indicates the direction in which the leaf samples were collected (The image shown is of the red band, and the green dots represent higher vigour segments, while the red dots represent lower vigour segments of the rows).

Table 4.1 Recommended optimal visible and near-infrared hyperspectral narrow-wavebands for agricultural crop and vegetation studies (Thenkabail *et al.*, 2001)

Wavelength portion name	Waveband number	Waveband Center (nm)	Waveband width (nm)	Waveband description.
1. Blue	1	495	30	Latter portion of blue band.
2. Green	2	525	20	Positive change in reflectance per unit change in wavelength of the visible spectrum is at its maximum around this green wavelength.
	3	550	20	Green band peak or maxima. This is the best of the 4 green wavebands.
	4	568	10	Negative change in reflectance per / unit change in wavelength of the visible spectrum is maximum around this green wavelength.
3. Red	5	668	4	Chlorophyll absorption pre-maxima (or reflectance minima) 1.
	6	682	4	Chlorophyll absorption maxima (or reflectance minima) 2. This is the best of the three red wavebands.
	7	696	4	Chlorophyll absorption post-maxima (or reflectance minima) 3.
4. Red-edge	8	720	10	Positive change in reflectance per unit change in wavelength of the NIR spectrum is at a maximum around this wavelength, in most cases.
5. NIR	9	845	70	Center of NIR shoulder
6. NIR peak	10	920	20	Peak or maxima of NIR shoulder
7. NIR (Moisture sensitive)	11	975	30	Center of the moisture sensitive "trough" portion of NIR
8. NIR late	12	1025	10	Portion of sudden rise after the moisture sensitive waveband

4.3 RESULTS AND DISCUSSION

4.3.1 VEGETATIVE MEASUREMENTS

4.3.1.1 Trunk circumference measurements

During field visits, it became apparent that the trunk circumference of vines seemed highly reduced in the lower vigour areas, with a high level of variation found between vines. The measurement of trunk circumference was therefore aimed at confirming if these observed differences were consistent with variation in soil conditions, as well as other vegetative properties of the vine. Significant differences ($p \leq 0.05$) in trunk circumference occurred between low and high vigour vines (Table 4.2).

Table 4.2 Differences (Welch t-test) in trunk circumference between lower (L) and higher (H) vigour vines in a Chenin blanc/R99 vineyard, Perdeberg.

	Mean	Mean				Separate variance estimates		
	L	H	t-value	df	P	t-value	df	p (2-sided)
Mean trunk circumference (mm)	93.39	125.25	-13.48	154	0	-13.50	152.69	0.0000

	Valid N	Valid N	Std.Dev.	Std.Dev.	F-ratio	p
	L	H	L	H	Variances	Variances
Mean trunk circumference (mm)	77	79	13.85	15.60	1.27	0.2995

The relative differences between the mean trunk circumferences of each vigour level in a plot are also shown for the separate plots in Fig. 4.3. From this it was apparent that Plot 3 showed the least difference, while the largest difference was observed at Plot 2. When this is compared to the differences measured in the average image pixel values (Fig. 3.11), it is notable that plot 2 again shows the largest difference in pixel value, with plot 3 showing the least. The large difference in trunk circumferences at plot 2 was also taken into account before choosing this plot for the hyperspectral data analysis.

When considering the relationship between soil conditions and trunk circumference, a logarithmic relationship is expected rather than a linear one. It is anticipated that a vine would in practice reach a maximum value for trunk circumference, due to environmental and genetic limitations. In addition to this, soil resistance levels would theoretically never reach zero. The asymptotic nature of these aspects would therefore suggest a possible logarithmic relationship as shown in Fig. 4.4.

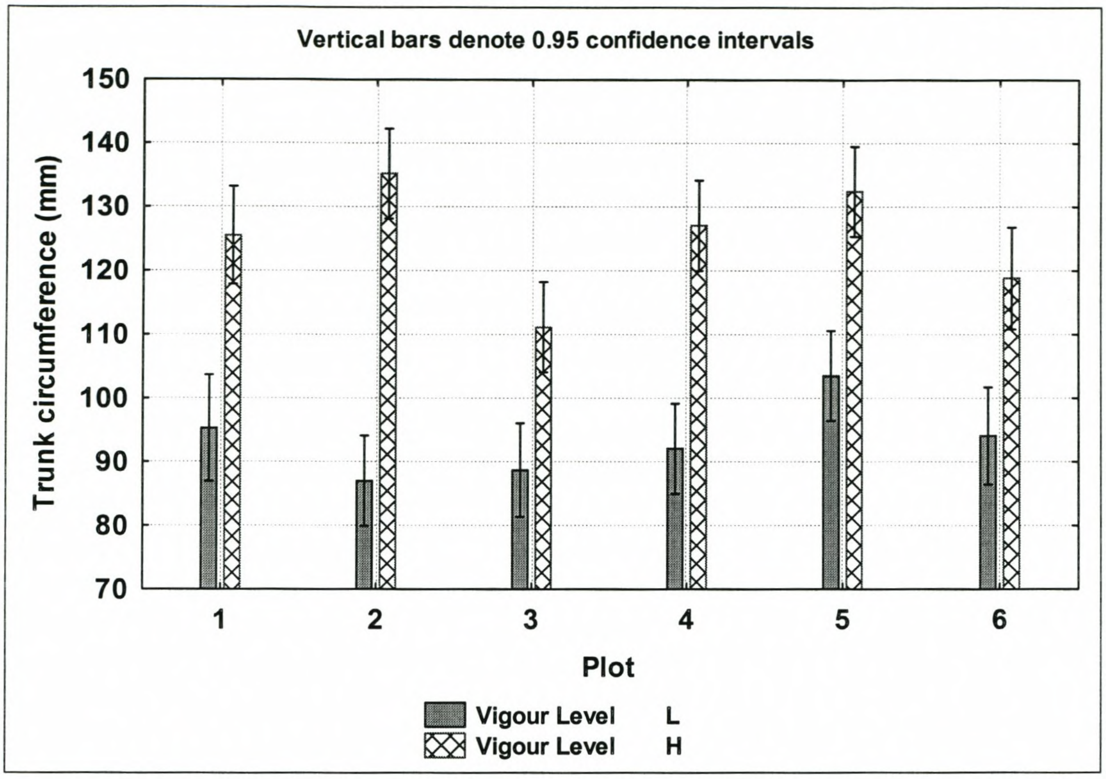

Figure 4.3 Mean trunk circumference for the vines in plots of each vigour level (higher and lower) in a Chenin blanc/R99 vineyard, Perdeberg (plot layout C).

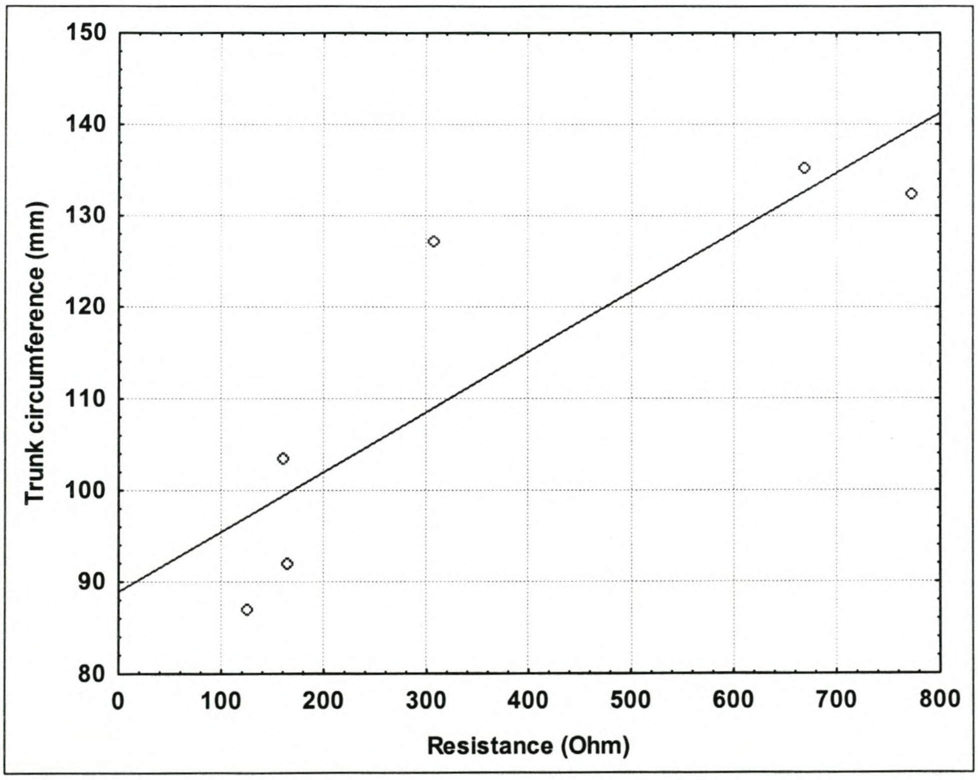

Figure 4.4 Relationship between the mean trunk circumference per plot and the mean resistance of a saturated soil paste in a Chenin blanc/R99 vineyard on Swartland/Glenrosa soils, Perdeberg (plot layout C) ($r^2 = 0.75$; $r = 0.87$; $p = 0.025$).

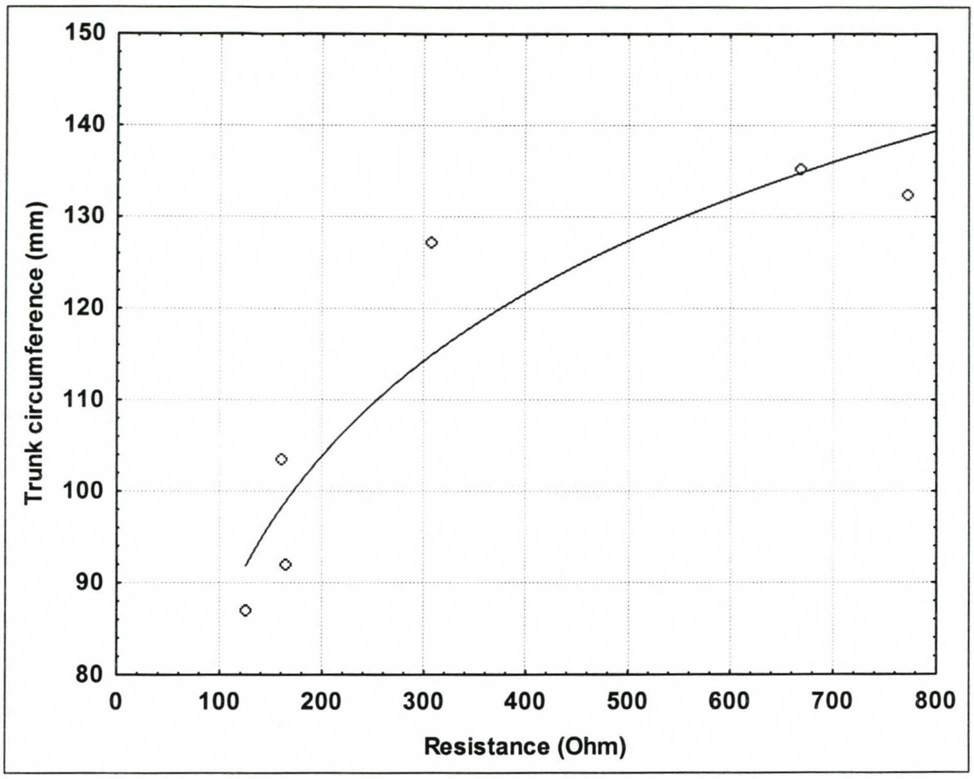

Figure 4.5 Possibility of a logarithmic relationship between the mean trunk circumference per plot and the mean resistance of a saturated soil paste in a Chenin blanc/R99 vineyard on Swartland/Glenrosa soils, Perdeberg (plot layout C) (r = 0.87; p = 0.025).

Trunk circumference did not correlate significantly with soil pH (KCl) levels (data not shown). When the trunk circumference measurements were plotted against the referenced image pixel values, however, interesting results were obtained (Fig. 4.6). The coefficient of determination suggested that up to 56% of the variation in trunk circumference could be explained by the variation in image pixel values, therefore confirming that a reduced trunk circumference is associated with an increase in image pixel value, shifting towards the value determined for bare soil, and therefore decreased canopy coverage in those areas.

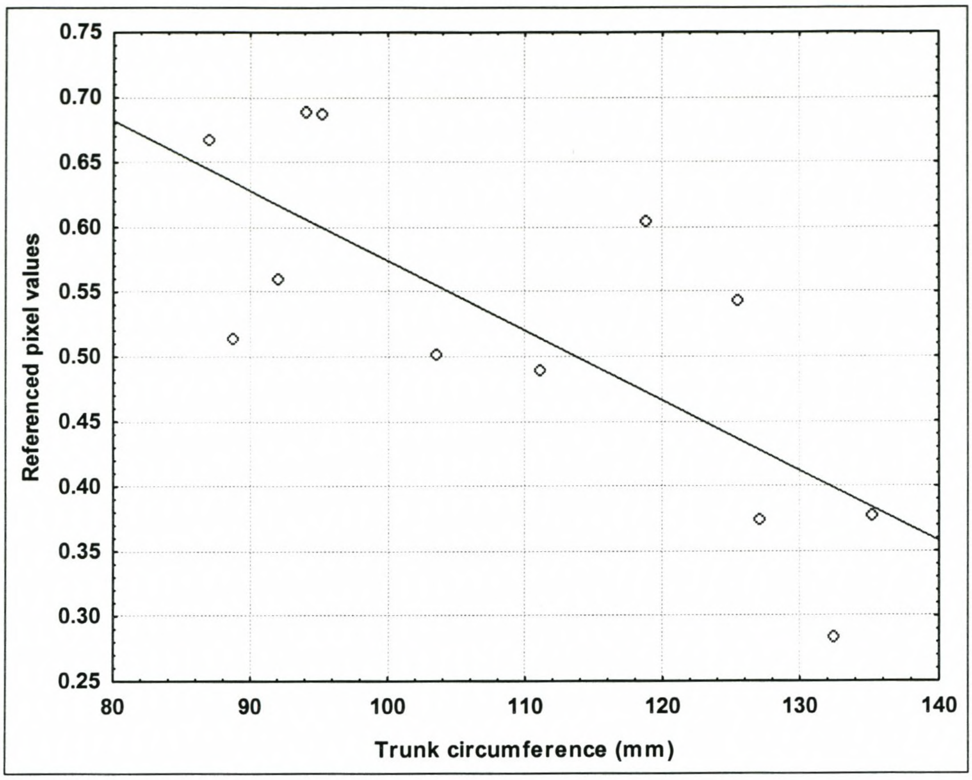

Figure 4.6 Relationship between the mean trunk circumference per plot and the referenced pixel values per plot in a Chenin blanc/R99 vineyard, Perdeberg (plot layout C) (r^2 = 0.56; r = -0.75; p = 0.005).

4.3.1.2 Canopy measurements

The higher vigour areas produced significantly larger leaves than the lower vigour areas, also having the largest lateral shoot- as well as main shoot leaf area (Table 4.3). The average ratio of lateral shoot leaf area/main shoot leaf area was 0.84 for the higher vigour areas, while a ratio of 0.73 was determined for the lower vigour area.

Table 4.3 Differences (Welch t-test) in leaf area measurements between plots with comparatively higher (H) and lower (L) vigour in a Chenin blanc/R99 vineyard, Perdeberg (plot layout C). Shaded values are significantly different at the $p \leq 0.05$ level.

	Mean H	Mean L	t-value	df	p
Area/leaf on main shoots (cm^2)	91.4	71.09	2.51	17	0.0224
Lateral shoot leaf area (cm^2)	1909.8	962.23	4.03	17	0.0009
Main shoot leaf area (cm^2)	2287.2	1315.86	5.49	17	0.0000
Total leaf area per shoot (cm^2)	4197.0	2278.09	5.17	17	0.0001
Total leaf area per vine (cm^2)	100828.7	47716.28	4.64	17	0.0002

	Valid N H	Valid N L	Std.Dev. H	Std.Dev. L	F-ratio Variances	p Variances
Area/leaf on main shoots (cm^2)	7	12	14.84	18.09	1.49	0.6502
Lateral shoot leaf area (cm^2)	7	12	567.37	449.24	1.60	0.4750
Main shoot leaf area (cm^2)	7	12	407.13	351.21	1.34	0.6342
Total leaf area per shoot (cm^2)	7	12	803.64	767.67	1.10	0.8448
Total leaf area per vine (cm^2)	7	12	29817.27	20293.92	2.16	0.2547

	Separate variance estimates		
	t-value	Df	p (2-sided)
Area/leaf on main shoots (cm^2)	2.65	14.84	0.0182
Lateral shoot leaf area (cm^2)	3.78	10.43	0.0033
Main shoot leaf area (cm^2)	5.27	11.19	0.0002
Total leaf area per shoot (cm^2)	5.10	12.20	0.0002
Total leaf area per vine (cm^2)	4.18	9.31	0.0022

Figs. 4.7 to 4.10 show how the measured parameters for leaf area differ per plot. From this it could be seen that plot 4 showed significantly higher leaf area per lateral shoot than the other plots, while also showing the highest difference in leaf area of the main shoots. Plots 2 and 4 also showed the largest differences in total leaf area per vine. Leaves were much smaller (as measured by the area/leaf) in the lower vigour areas than in the higher vigour areas, except at plots 5 and 6 (Fig. 4.7).

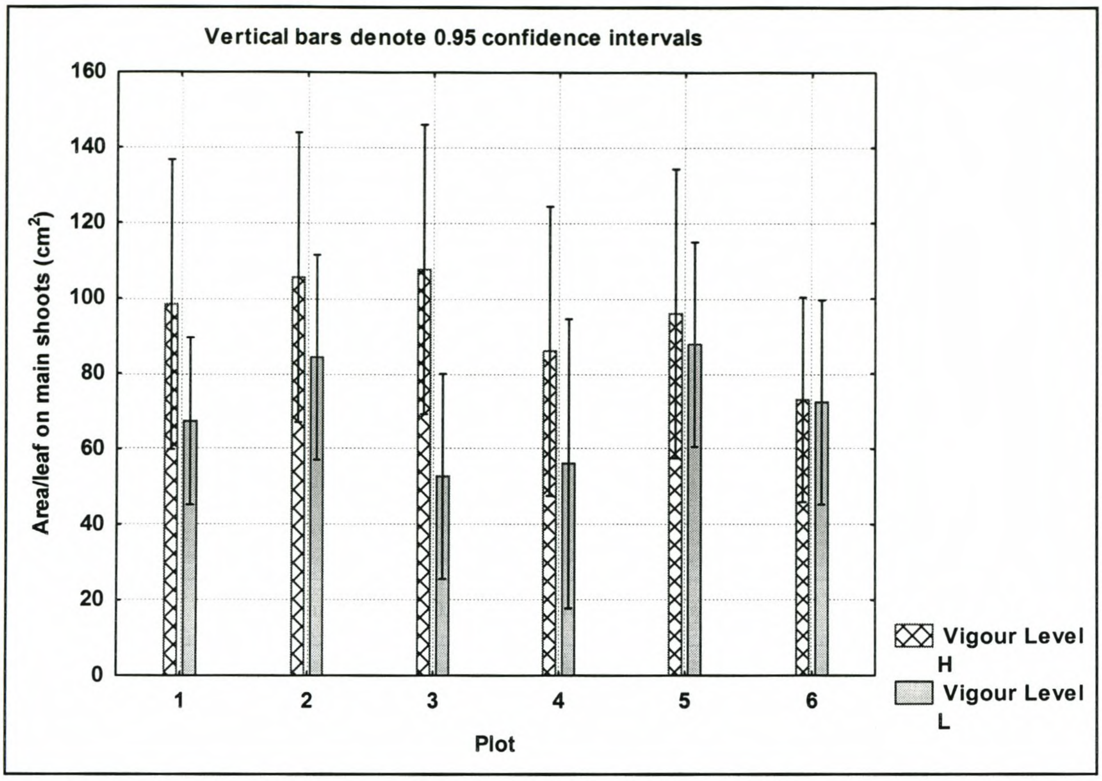

Figure 4.7 Differences in the area/leaf of the main shoots between plots with comparatively higher (H) and lower (L) vigour in a Chenin blanc/R99 vineyard, Perdeberg (plot layout C).

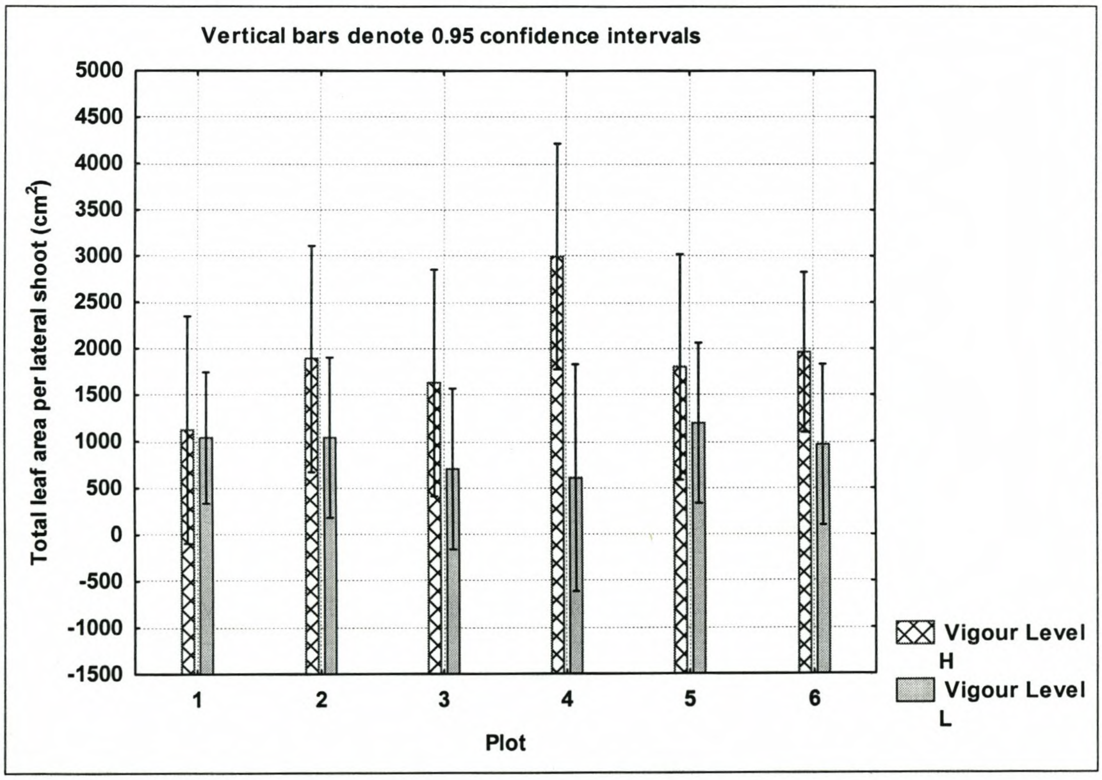

Figure 4.8 Differences in the total leaf area per lateral shoot between plots with comparatively higher (H) and lower (L) vigour in a Chenin blanc/R99 vineyard, Perdeberg (plot layout C).

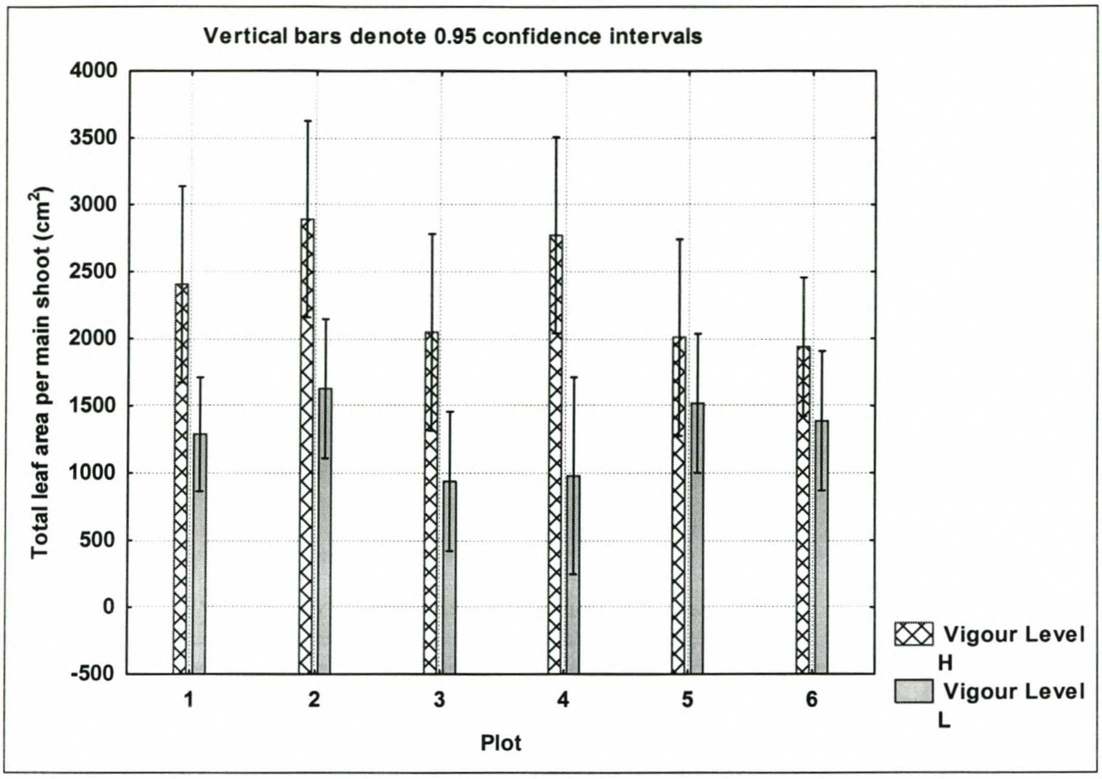

Figure 4.9 Differences in the total leaf area of the main shoots between plots with comparatively higher (H) and lower (L) vigour in a Chenin blanc/R99 vineyard, Perdeberg (plot layout C).

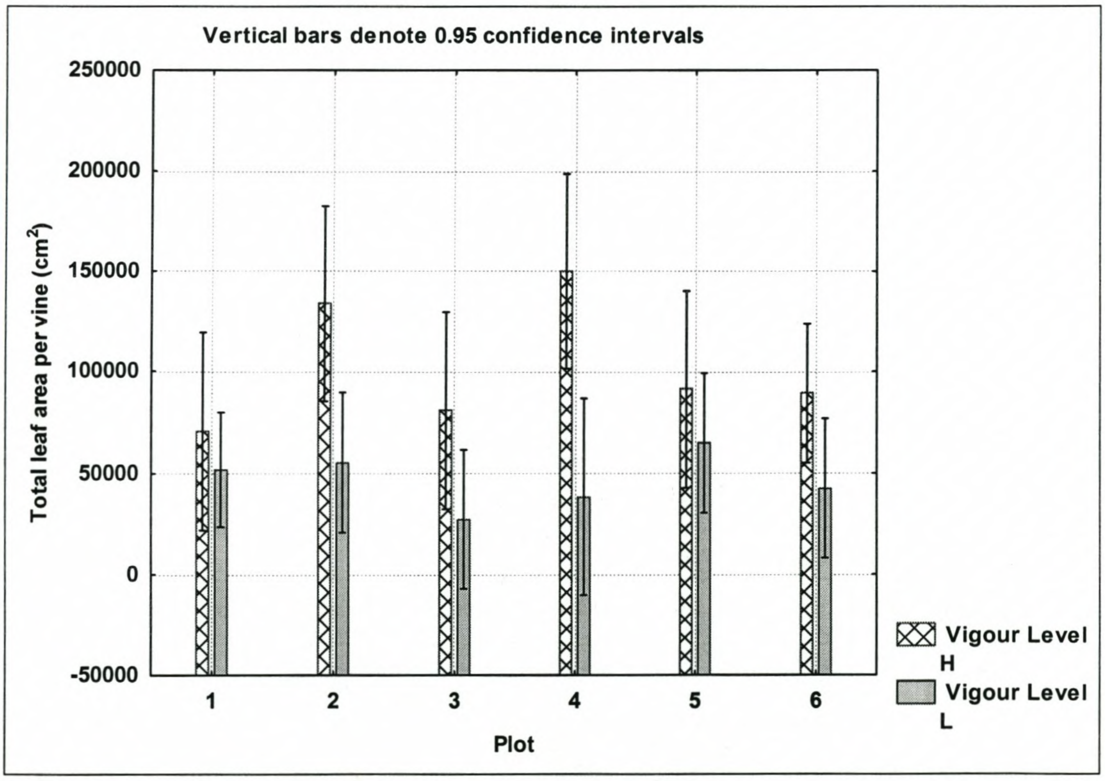

Figure 4.10 Differences in the total leaf area per vine shoots between plots with comparatively higher (H) and lower (L) vigour in a Chenin blanc/R99 vineyard, Perdeberg (plot layout C).Differences in the total leaf area per vine between plots with comparatively high and low vigour according to plot layout C.

An excellent correlation was also found between leaf area per vine and trunk circumference (Fig. 4.11). This showed that, for this vineyard, trunk circumference was an excellent measure of vine vigour owing to its relationship with leaf area, an important parameter with respect to fruit quality. It was also a very useful measurement, considering its link to both the sources (soil properties) and some of the effects (leaf area change) as well as shoot length (Section 4.3.13) of vigour variability. The correlation between leaf area per vine and the referenced image pixel values was however weak (r^2=0.24). This result was surprising, as it was expected that this parameter would be best correlated with the image data. The result implicates that the image reacted better to changes in soil conditions than plant canopy conditions. Possibly the type of image used in the image pixel value extraction (the red channel image) may have responded better to soil colour differences as well as topsoil structure between the vigour levels than differences in plant canopy biomass.

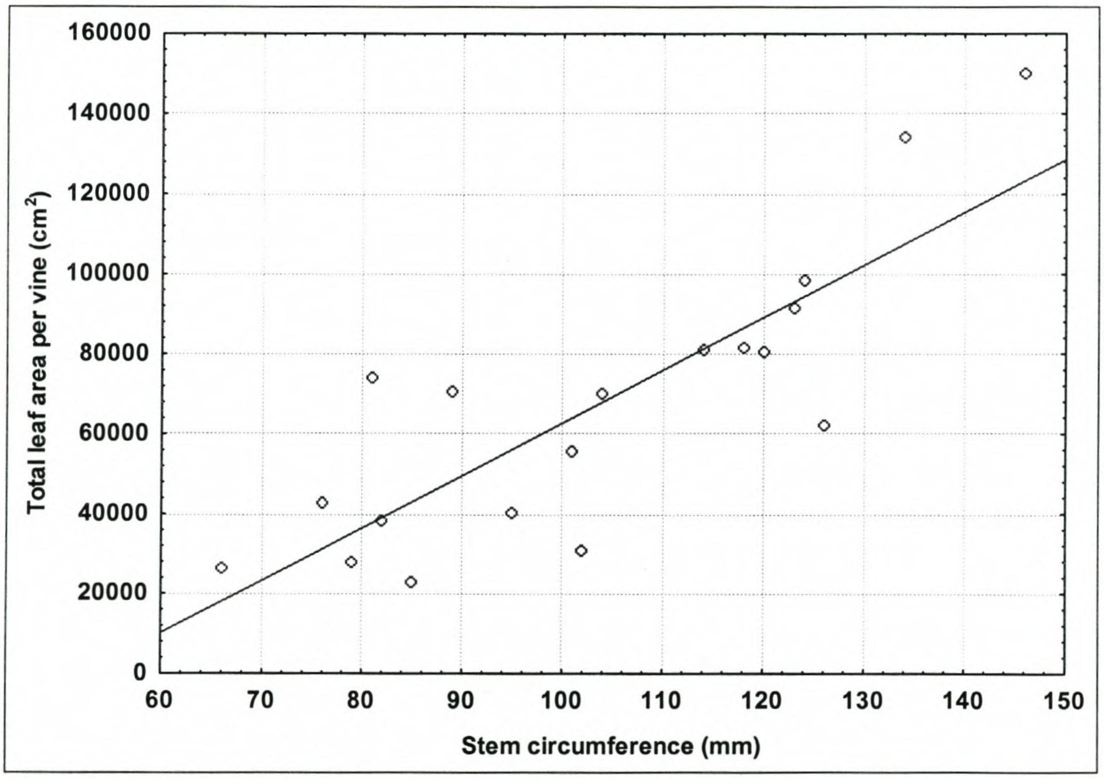

Figure 4.11 Relationship between the total leaf area per vine and trunk circumference in a Chenin blanc/R99 vineyard, Perdeberg (plot layout C) (r^2 = 0.70; r = 0.84; p = 0.00001).

The light measurements showed that of the 2945 $\mu E.m^{-2}.s^{-1}$ ambient radiation, some vines in the higher vigour areas received less than 100 $\mu E.m^{-2}.s^{-1}$, but that this was also the case for some vines in the lower vigour area. Although the average difference between the vigour levels was not significant, the measurement variability was very large as can be seen on Fig. 4.12. This could be explained by the fact that the canopies were not vertically shoot positioned, causing complications with the light measurements.

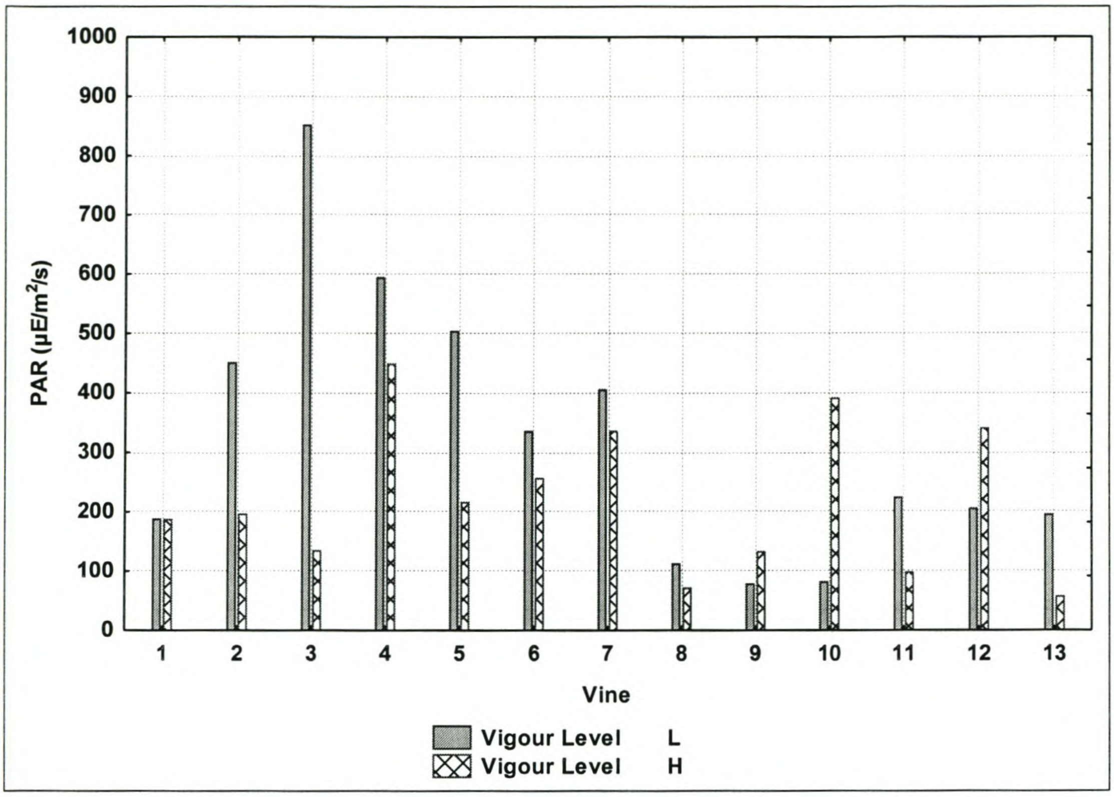

Figure 4.12 Measurements of the amount of photosynthetically active radiation (400-700 nm) conducted in the bunch zone of the canopy in areas of comparatively higher (H) and lower (L) vigour levels in a Chenin blanc/R99 vineyard in the Perdeberg area (plot 2, plot layout C).

Differences in shoot length were highly significant between the vigour levels, and therefore the amounts of nodes counted per main shoot (Table 4.4). Significant differences were not found for the lengths of the unripe shoot tips, but unripe shoot tips were found to be quite prominent in both vigour levels. This probably indicates that all vines are affected to a certain extent by the high salt content of the soil as well as water stress.

The high levels of variability in shoot length found in this vineyard can cause differing fruit ripeness levels, enhancing variability in fruit quality (Archer, 2001). In this case, however, it may have been countered by the more optimal fruit exposure levels in the lower vigour canopies.

Less lateral shoots per main shoot were counted in the lower vigour areas. The amount of lateral shoots found per main shoot for every plot is shown in Fig. 4.13. It is notable that the highest number of lateral shoots was found in the higher vigour areas at plots 2 and 4.

Shoot length was also found to be correlated well with trunk circumference, again underlining the excellent relationship found in this vineyard between trunk circumference and vine vigour (Fig. 4.14).

Table 4.4 Differences (Welch t-test) in measured shoot data between plots in comparatively higher (H) or lower (L) vigour areas in a Chenin blanc/R99 vineyard, Perdeberg area. Shaded values are significantly different at the p ≤ 0.05 level.

	Mean H	Mean L	t-value	df	p	t-value	df	p (2-sided)
Main shoot length (cm)	144.75	88.83	5.76	17	0.00002	5.04	8.55	0.0008
Unripe shoot tips (cm)	9.96	10.79	-0.29	17	0.7777	-0.27	10.24	0.7945
Nodes per main shoot	25.36	18.75	4.35	17	0.00044	3.67	7.80	0.0066
Mean number of shoots per vine	23.71	20.67	1.63	17	0.1210	1.78	15.89	0.0951

	Valid N H	Valid N L	Std.Dev. H	Std.Dev. L	F-ratio Variances	p Variances
Main shoot length (cm)	7	12	26.71	15.95	2.80	0.13185
Unripe shoot tips (cm)	7	12	7.05	5.45	1.67	0.43670
Nodes per main shoot	7	12	4.45	2.23	3.98	0.04605
Mean number of shoots per vine	7	12	3.15	4.29	1.86	0.46070

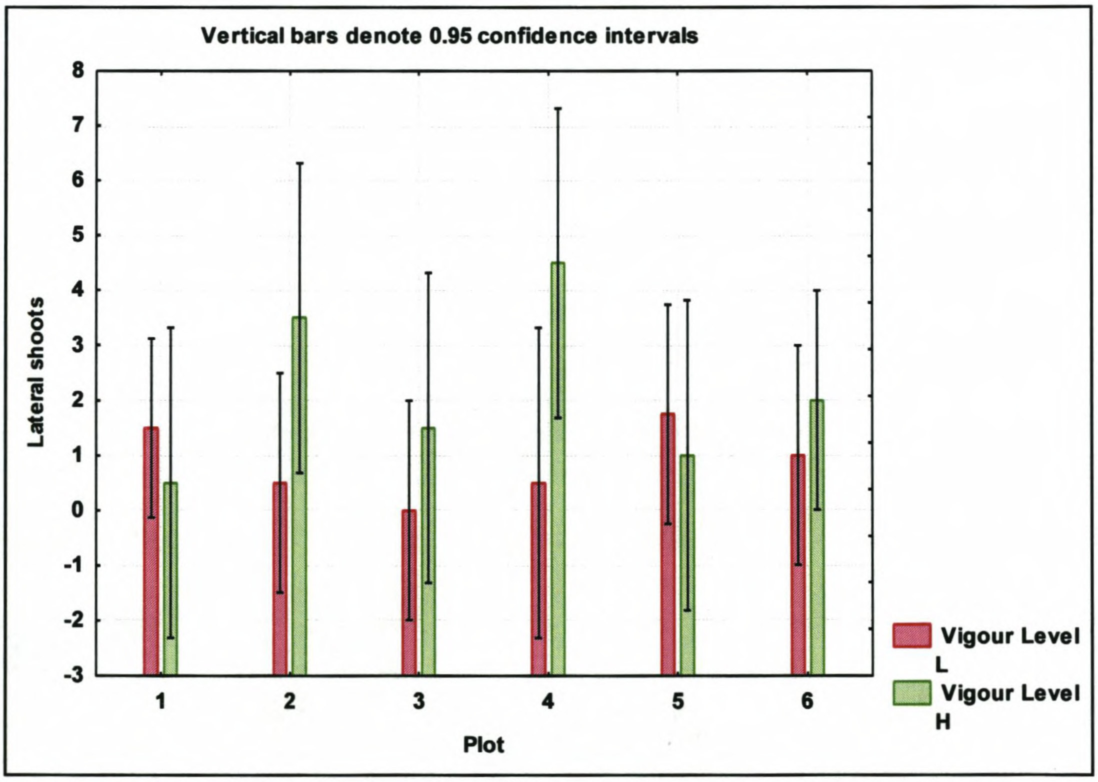

Figure 4.13 Differences in the number of lateral shoots found per main shoot between plots with comparatively higher (H) and lower (L) vigour in a Chenin blanc/R99 vineyard, Perdeberg (plot layout C).

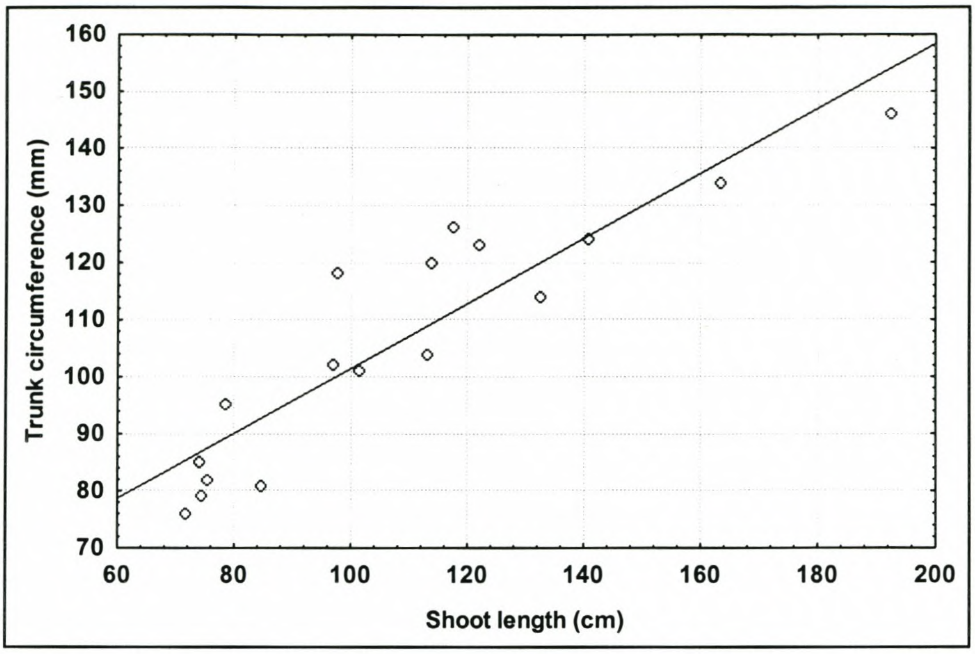

Figure 4.14 Relationship between the main shoot length and trunk circumference in a Chenin blanc/R99 vineyard, Perdeberg (plot layout C) ($r^2 = 0.83$; $r = 0.91$, $p = 0.0000004$).

4.3.1.3 Leaf water potential

Smart (1974) reported that the critical leaf water potential value where stomatal closure is induced is approximately -1.3 MPa. Results from this study, which yielded highly significant differences between vigour levels, suggest that the lower vigour vines may reach stomatal closure quite early in the morning on a relatively hot day, which may lead to reduced levels of photosynthetic activity in these vines (Table 4.5). The results found here also confirmed that low vigour vines were definitely more moisture-stressed than the high vigour vines.

Table 4.5 Differences (Welch t-test) in leaf water potential between plots in comparatively higher (H) or lower (L) vigour areas in a Chenin blanc/R99 vineyard, Perdeberg area. Shaded values are significantly different at the $p \leq 0.05$ level.

	Mean	Mean				p
	L	H	t-value	df	p	(2-sided)
Leaf water potential (Mpa) (Pre-dawn)	-1.019	-0.748	8.29	16	0.000000	0.000000
Leaf water potential (Mpa) (Midday)	-1.815	-1.466	3.00	7	0.0199	0.0168

	Valid N	Valid N	Std.Dev.	Std.Dev.	F-ratio	p
	L	H	L	H	Variances	Variances
Leaf water potential (Mpa) (Pre-dawn)	9	9	0.07	0.07	1.26	0.7516
Leaf water potential (Mpa) (Midday)	4	5	0.14	0.20	2.00	0.5944

As expected, much more consistent results were obtained with the pre-dawn leaf water potential measurements.

4.3.2. HARVEST MEASUREMENTS

4.3.2.1 Yield

Yield per vine showed highly significant differences between the higher and lower vigour areas (Table 4.6). It can be seen on Fig. 4.15 that yield seems to increase steadily with resistance increase. Although more data would be needed to confirm this, it may point to a very strong yield:salt content relationship, which shows an exponential trend.

The leaf area/fruit mass ratio was also determined for each plot (Fig. 4.16). Smart *et al.* (1990) proposed the ratio leaf area/fruit mass to ideally be around 10 $cm^2.g^{-1}$, with an acceptable range of about 6-15 $cm^2.g^{-1}$. Archer & Beukes (1983) found a value of 11,5 $cm^2.g^{-1}$ to be optimal in a suckering experiment. These norms were easily attained and also highly exceeded by most of the vines in the vineyard, which is also visible in the differences of the mean values between vigour levels (Table 4.7). Considering that vines in most of the plots actually operate under luxurious conditions with respect to available leaf area for the manufacturing of grape components, this may hold the key to the surprisingly high wine quality obtained. It has to be considered however, that in the higher vigour areas, a significant amount of these leaves may be shaded.

Table 4.6 Differences (Welch t-test) in yield per vine between plots in comparatively higher (H) or lower (L) vigour areas in a Chenin blanc/R99 vineyard, Perdeberg area. Shaded values are significantly different at the $p \leq 0.05$ level.

	Mean H	Mean L	t-value	df	P	p (2-sided)
Yield per vine (kg)	7.71	4.03	3.02	10	0.013	0.0002

	Valid N H	Valid N L	Std.Dev. H	Std.Dev. L	F-ratio Variances	p Variances
Yield per vine (kg)	6	6	1.65	2.49	2.27	0.3901

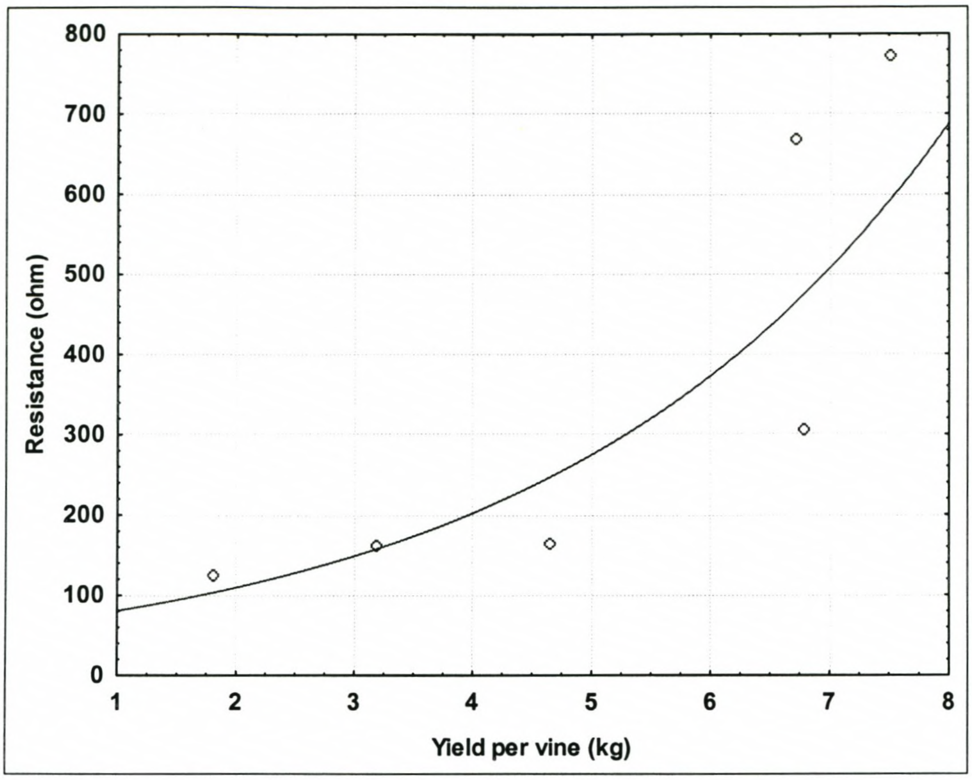

Figure 4.15 Relationship between soil resistance (average over 0-120 cm measured according to plot layout D) and yield per vine in a Chenin blanc/R99 vineyard on Swartland/Glenrosa soils, Perdeberg (plot layout C) ($r^2 = 0.67$; $r = 0.82$; $p = 0.0457$).

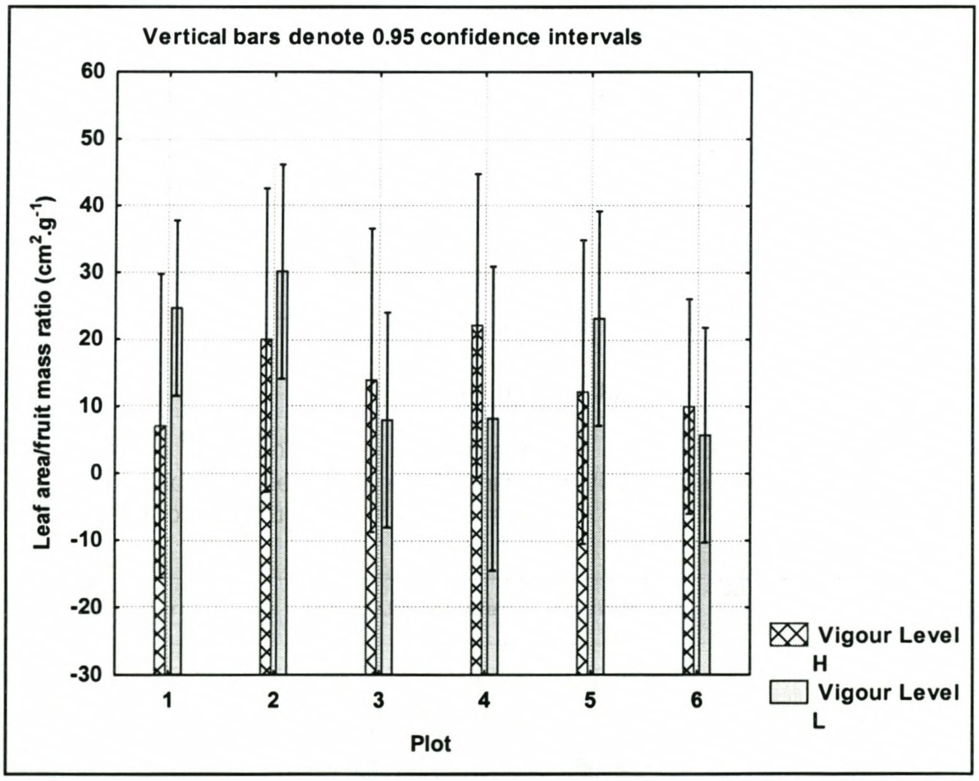

Figure 4.16 Differences in the leaf area/fruit mass ratio between plots with comparatively higher (H) and lower (L) vigour in a Chenin blanc/R99 vineyard, Perdeberg (plot layout C).

Table 4.7 Differences (Welch t-test) in leaf area/fruit mass relationship between plots in comparatively higher (H) or lower (L) vigour areas in a Chenin blanc/R99 vineyard, Perdeberg area. Values were not significantly different at the $p \leq 0.05$ level.

	Mean	**Mean**				**p**
	H	**L**	**t-value**	**df**	**p**	**(2-sided)**
Leaf area / fruit mass ($cm^2.g^{-1}$)	13.60	18.03	-0.88	17	0.394	0.305

	Valid N	**Valid N**	**Std.Dev.**	**Std.Dev.**	**F-ratio**	**p**
	H	**L**	**H**	**L**	**Variances**	**Variances**
Leaf area / fruit mass ($cm^2.g^{-1}$)	7	12	5.60	12.51	5.00	0.061

4.3.2.2 Bunch mass and berry mass

The lower vigour levels induced smaller bunches and berries than the higher vigour levels (Table 4.8). Evidently, huge variation in bunch and berry mass occurred in this vineyard. The smaller berries in the lower vigour areas may be another important factor in the achievement of high wine quality. Even for white cultivars, wine composition is normally favoured by a higher skin/pulp ratio in the berries.

Table 4.8 Differences (Welch t-test) in bunch mass and berry mass between plots in comparatively higher (H) or lower (L) vigour areas in a Chenin blanc/R99 vineyard, Perdeberg area. Values were not significantly different at the $p \leq 0.05$ level.

	Mean	**Mean**				**p**
	H	**L**	**t-value**	**df**	**P**	**(2-sided)**
Bunch mass (g)	295.36	199.70	3.31	38	0.0021	0.0024
g per100 berries	81.88	75.63	2.82	8	0.0226	0.0271

	Valid N	**Valid N**	**Std.Dev.**	**Std.Dev.**	**F-ratio**	**p**
	H	**L**	**H**	**L**	**Variances**	**Variances**
Bunch mass (g)	20	20	112.09	64.72	3.00	0.0211
g per 100 berries	5	5	4.23	2.59	2.66	0.3659

4.3.2.3 Juice chemical analysis

Large differences in titratable acid levels were found between the vigour levels. The values were relatively high in the vigorous areas (Table 4.9). More lateral growth, as well as larger and more leaves in the higher vigour canopies, may have contributed to the higher acid levels in these canopies due to a shading effect (Archer & Strauss, 1989; Jackson & Lombard, 1993).

The sugar concentration was slightly higher for the lower vigour vines. Much larger differences was expected due to the higher level of exposure of the lower vigour canopies, but it is possible that the stress experienced by these vines led to respiratory loss of sugar in the berries. This was confirmed by leaf water potential measurements, suggesting that the vines of the lower vigour areas experienced higher levels of water stress, potentially leading to increased levels of stomatal resistance and decreased levels of photosynthesis.

Table 4.9 Difference in chemical composition of the juice from grapes harvested from differing vigour levels in a Chenin blanc/R99 vineyard, Perdeberg area.

Component	Higher Vigour (H)	Lower Vigour (L)	Difference (H-L)
Sugar (°B)	22.8	23.3	-0.5
Titratable Acid (g.L^{-1})	9.43	8.05	1.38
pH	3.1	3.18	-0.08

4.3.3. WINE ANALYSES

4.3.3.1 Wine chemical analyses

Wine chemical analysis showed a slightly higher pH and total acid for the wine made from higher vigour vines (Table 4.10). Wines from the higher vigour vines contained much higher concentrations of malic acid than that from the lower vigour vines, indicating much higher levels of fruit exposure in the lower vigour areas and subsequent higher levels of malic acid respiration in these areas. Alcohol production was also slightly more in the lower vigour wine, probably due to a higher initial sugar concentration of the grapes.

Table 4.10 Difference in chemical composition of wines made through microvinification from differing vigour levels in a Chenin blanc/R99 vineyard, Perdeberg area.

Component	Higher vigour	Lower vigour
pH	3.81	3.58
Total Acid (g.L^{-1})	4.72	3.41
Malic Acid (g.L^{-1})	3.64	1.75
Acohol % (v/v)	13.9	14.6
Volatile Acid (g.L^{-1})	0.22	0.18
Lactic Acid (g.L^{-1})	0.42	0.3
Fructose (g.L^{-1})	0.85	0.73

4.3.3.2 Wine sensory analysis

The wines differed in terms of aroma and palate (Table 4.11). Panel members also agreed that these wines actually had a lot of character, considering the fact that they were produced according to small-scale winemaking procedures, and considering the use of a neutral cultivar and a neutral yeast strain. Some members of the panel noted interesting differences in character in the wines, such as “interesting stony/mineral-like touches” and a “muddy taste”.

Only one of the volatile compounds analysed was found to be above its threshold value. This was ethyl caprate, for which the flavour may be described as floral, sweet, fatty, nut-like or Cognaq-like (Table 4.12). The levels of this compound analysed in the wine made from the whole vineyard block (data not shown) was 0.95 mg.L^{-1}, which was much higher than both of the experimentally produced wines were. The yeast strain used in the commercial winemaking process therefore produced more of this ester.

Table 4.11 Results from sensory evaluation of wines made through microvinification from differing vigour levels in a Chenin blanc/R99 vineyard, Perdeberg area.

Judge	Vigour Level	Comments
1	L	Ripe fruit Interesting stony/minerally touches Hint of honey – very typical High acid, off-dry, high glycerol – good fruit concentration Should age well
	H	Less forthcoming on nose Some 'green' notes on nose, though not in any way unripe Hint of 'pear-drops' Tastes drier, less glycerol – less everything. Good fruit, less finish
2	L	Fresh, very crisp More fruit than the other wine
	H	Rather watery and a bit of a muddy taste.
3	L	Slightly green on nose, apple – lacks intensity. On palate a bit hard and short. Also lacking in acid.
	H	Shy nose, fresher on palate and has more length.
4	L	Guava palate. Grapefruit finish.
	H	More layered. Slight sweaty character.

Table 4.12 Results from volatile aroma analysis of wines made through microvinification from differing vigour levels in a Chenin blanc/R99 vineyard, Perdeberg area.

GC analysed component	**Mean L ($mg.L^{-1}$)**	**Mean H ($mg.L^{-1}$)**	**p (2-sided)**	**Threshold ($mg.L^{-1}$)**	**Detectable**	**Aroma / Taste** [c]
Acetaldehyde	0.0082	0.0153	0.04912	100 [a]	No	
Ethyl valerate	0.0004	0.0008	0.07459	0.0015 (water) [c]	No	Strong fruity, apple like
Benzaldehyde	0.2179	0.2109	0.93508	3 [d]	No	Bitter almond
Ethyl caproate	0	0	0	0.08 [a]	No	
Furfural	0.0075	0.0032	0	65 [d]	No	Almond
Linalool	0.0101	0.02	0.29468	0.05 [b]	No	Rose
Terpineol	0.0108	0.0118	0.1943	0.4 [b]	No	Lily of the valley
Ethyl caprylate	0.0046	0.0052	0.33704	0.58 [a]	No	
Citronellol	0.0054	0.0035	0.00158	0.018 [b]	No	Rose
Nerol	0.0042	0.0035	0.12624	0.4 [b]	No	Rose
Geraniol	0.0026	0.0029	0.74994	0.13 [b]	No	Rose
Ethyl pelargonate	0.0035	0.0032	0.45956	0.85 [c]	No	Fatty, oily, nut-like
Ethyl caprate	**0.4329**	**0.5278**	**0.00674**	**0.5** [a]	**Yes**	**Floral, sweet, fatty, nut-like, winey Cognaq odour**
Ethyl laurate	0.0093	0.0184	0.00321	2 (beer) [c]	No	Oily, fatty, floral with fatty fruity taste
Ethyl myristate	0.0114	0.0163	0.31328	2 (beer) [c]	No	Weak, fatty odor
Ethyl palmitate	0.0118	0.0117	0.97635	2 (water) [c]	No	Faint, waxy, sweet odor; nearly tasteless; creamy mouthfeel

a) Lambrechts & Pretorius (2000)
b) Ribéreau-Gayon *et al.*, (2000)
c) www.leffingwell.com/esters1.htm
d) www.winechina.com/Italia-Cina/vi2b.html

4.3.4 HYPERSPECTRAL MEASUREMENTS

4.3.4.1 Hyperspectral image analysis

The results for the normalised image pixel values (P_B, see Section 4.2.4.2) at the respective positions along the rows of Plot 2 are presented in Fig. 4.17. Except for the notable difference in the values between the two vigour levels, there was also a significant amount of variation along the row of a vigour level.

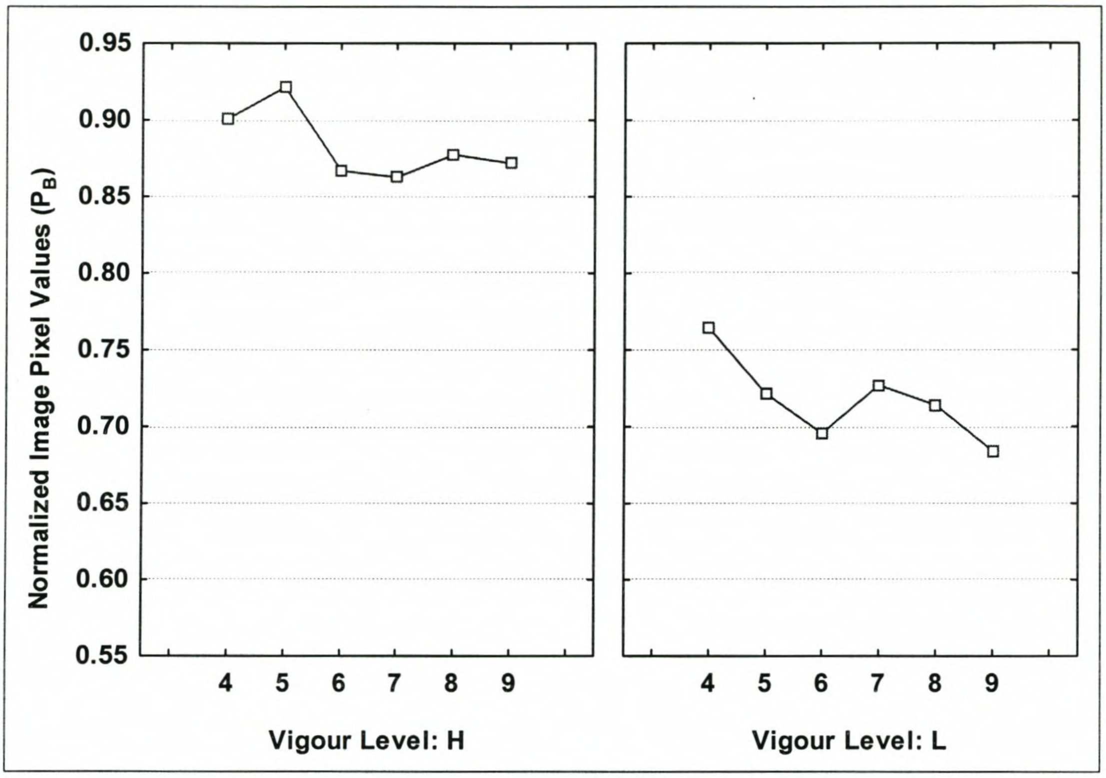

Figure 4.17 Normalised average image pixel values for the positions corresponding with those used in hyperspectral measurements conducted at plot 2 (Plot layout C) in a Chenin blanc/R99 vineyard, Perdeberg area. Individual vines are indicated on x-axis by numbers from 4 to 9 (vine numbers in section of the row).

The narrow-band NDVI values that were determined with the hyperspectral field instrument are shown in Fig. 4.18 for comparison with Fig. 4.17. Similarities can be seen in both the forms and relative values of graphs. However, a much lower narrow-band NDVI value was measured with the spectrometer at position 4. The measurement position for this result corresponds approximately with the position of a vine with a trunk circumference of only 50 mm (less than half of most of the other vines). In the aerial image, this single vine's image signal was probably mixed with some of the signals from the surrounding vines, which were much more vigorous, explaining why it did not affect the values shown in Fig.4.17.

These results therefore underline the value of narrow-band NDVI measurements as an indication of vine vigour, but more importantly shows the similarities between the simple image analysis methods used, and sophisticated hyperspectral measurement techniques. The hyperspectral field instrument has, potentially, wider application than this, which will be discussed in the following paragraph.

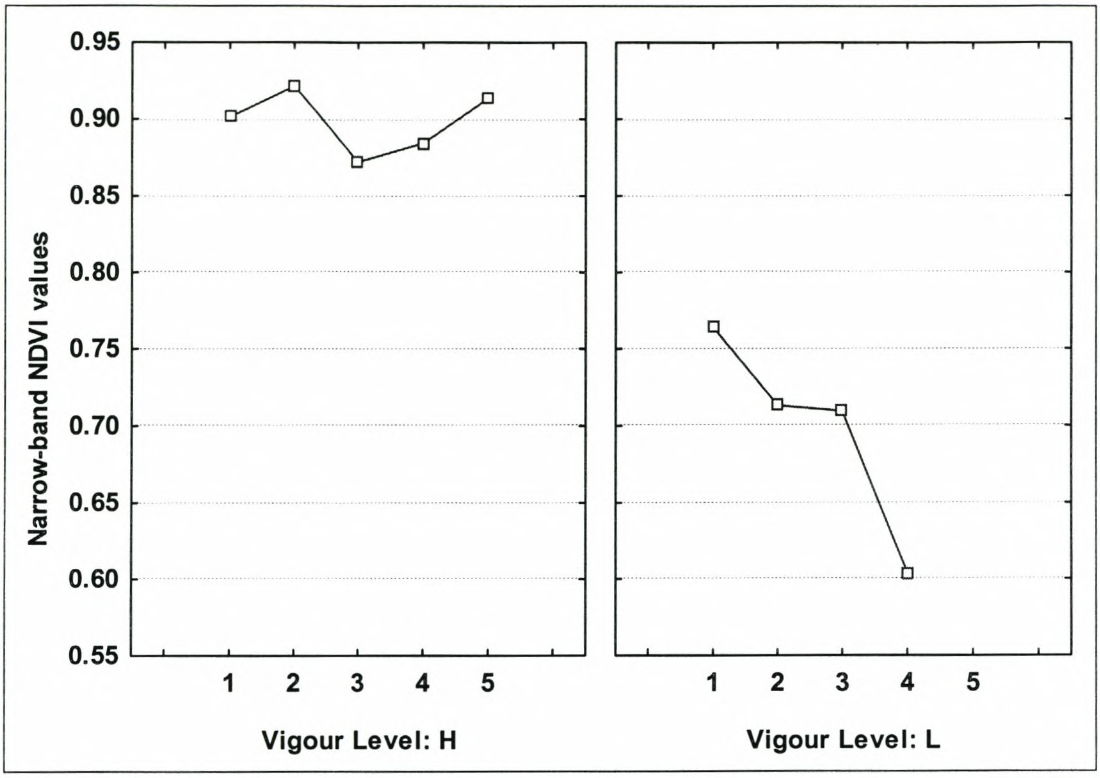

Figure 4.18 Narrow-band NDVI values calculated from hyperspectral measurements conducted at plot 2 (Plot layout C) in a Chenin blanc/R99 vineyard, Perdeberg area. Numbers on x-axis represent measurement positions corresponding to the vine positions indicated on the x-axis in Fig. 4.17.

4.3.4.2 Hyperspectral data analysis

In the previous section (4.3.4.1), hyperspectral canopy measurements were used to show the relationship between image values and a narrow-band NDVI index. However, this is a significant under-utilisation of the capabilities of this technology, which will be shown in this section.

A graph summarising all hyperspectral measurements for the different target types and different vigour levels is shown in Fig. 4.19. The canopies absorbed much more light than single leaves all over the electromagnetic spectrum, especially in the infrared regions. This is expected due to the internal scattering of light in the canopy environment, as opposed to light reaching a single leaf. The lower vigour canopy absorbed less light in the visible- as well as the infrared regions. Single leaves absorbed much less light in both regions due to lower total chlorophyll concentration as well as enhanced infrared light reflection (Smart, 1987). The individual leaves of both vigour levels showed more absorption of visible light by the adaxial (top-sides) of the leaves due to the presence of more chlorophyll in the adaxial mesophyll of the leaf. However, less light was absorbed in the infrared region for the adaxial sides of the leaves. This may be explained by the increased reflection of near-infrared light with an increase of intercellular air spaces, caused by the scattering of light when passing from hydrated cell walls (refractive index of 1.47) to air spaces (refractive index of 1.0) (Gausman & Allen, 1973). When the abaxial side of the leaf is the target, incident infrared radiation is firstly met by the relatively loose cell structure found here owing to a large number of intracellular spaces, as well as the increased number of stomata (Archer, 1981) and therefore shows increased reflectance.

Supplementary to Fig. 4.19, Table 4.13 explain some reflectance or absorption features associated with certain wavelength regions (also refer to Section 2.4.2).

Table 4.13 Reflectance or absorption features associated with certain wavelength regions as observed on Fig. 4.19.

Letter indicated on Fig. 4.19	**Approximate wavelength position**	**Associated feature**
A	550 nm	Green peak **
B	690 nm	Chlorophyll absorption well **
C	960 nm	Secondary water absorption feature*
D	1150 nm	Secondary water absorption feature, slightly past the 1120 nm reported in literature*
E	1450 nm	Major water absorption feature*
F	1940 nm	Major water absorption feature, heavily affected by the noise-rich region around 1850 nm*

* According to Ustin, 1997.

** Refer to Section 2.5.11

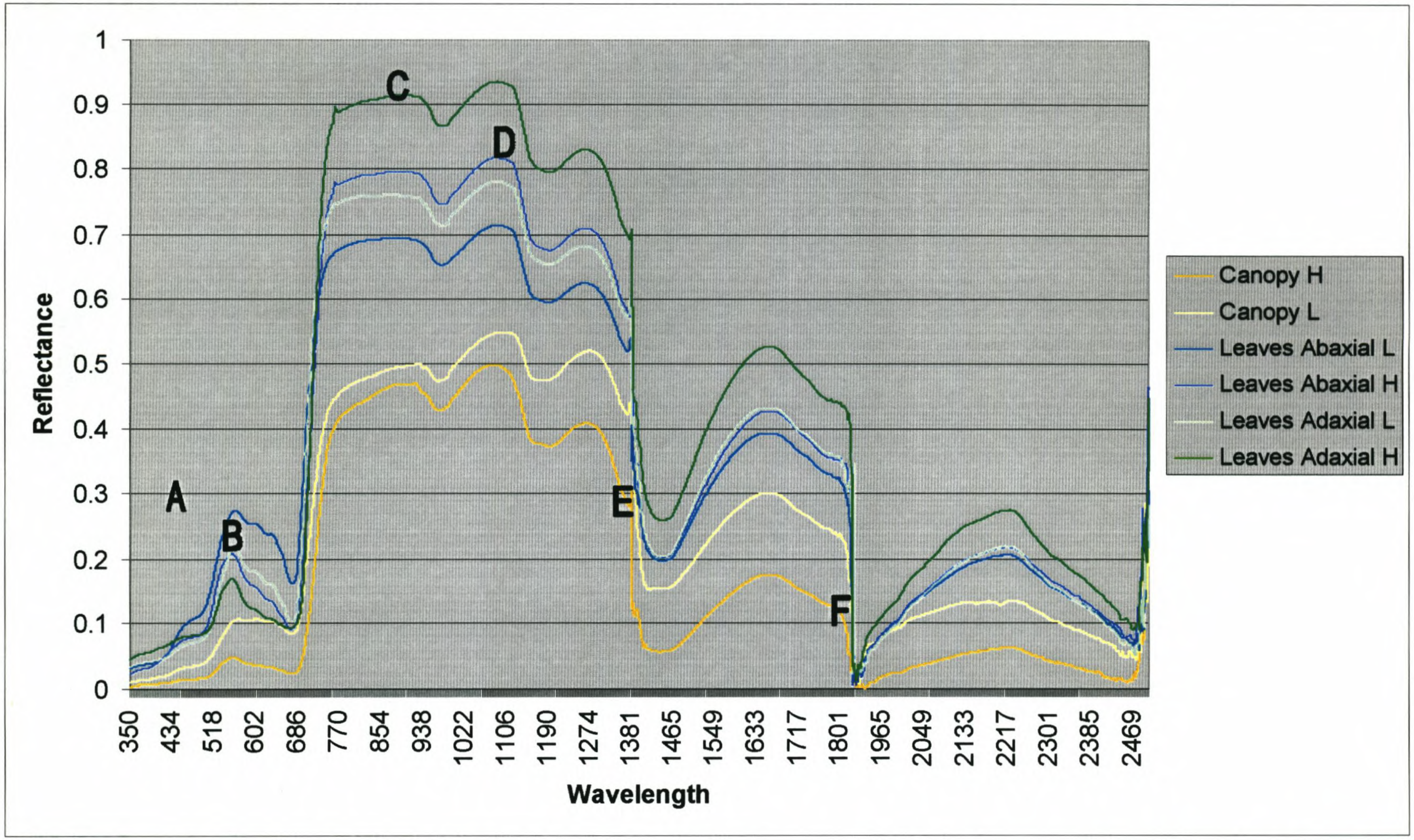

Figure 4.19 Hyperspectral reflectance data determined for different vegetation targets (canopies and leaves) at Plot 2 (plot layout C) in a Chenin blanc/R99 vineyard, Perdeberg area. (H – higher vigour; L – lower vigour; the letters A to F is explained in Table 4.13).

In the normalised reflectance data, the largest differences in all the targets occurred in the regions of chlorophyll and possibly also carotenoid absorption. The relative quantities of these components also differed considerably between the vigour levels: low vigour targets contained less of these components than high vigour targets. The region between 350 and 420 nm was the only region of higher absorption for the lower than the higher vigour targets (Fig.4.20), which can be ascribed to a higher concentration of these components in the adaxial leaf sides at the lower vigour areas.

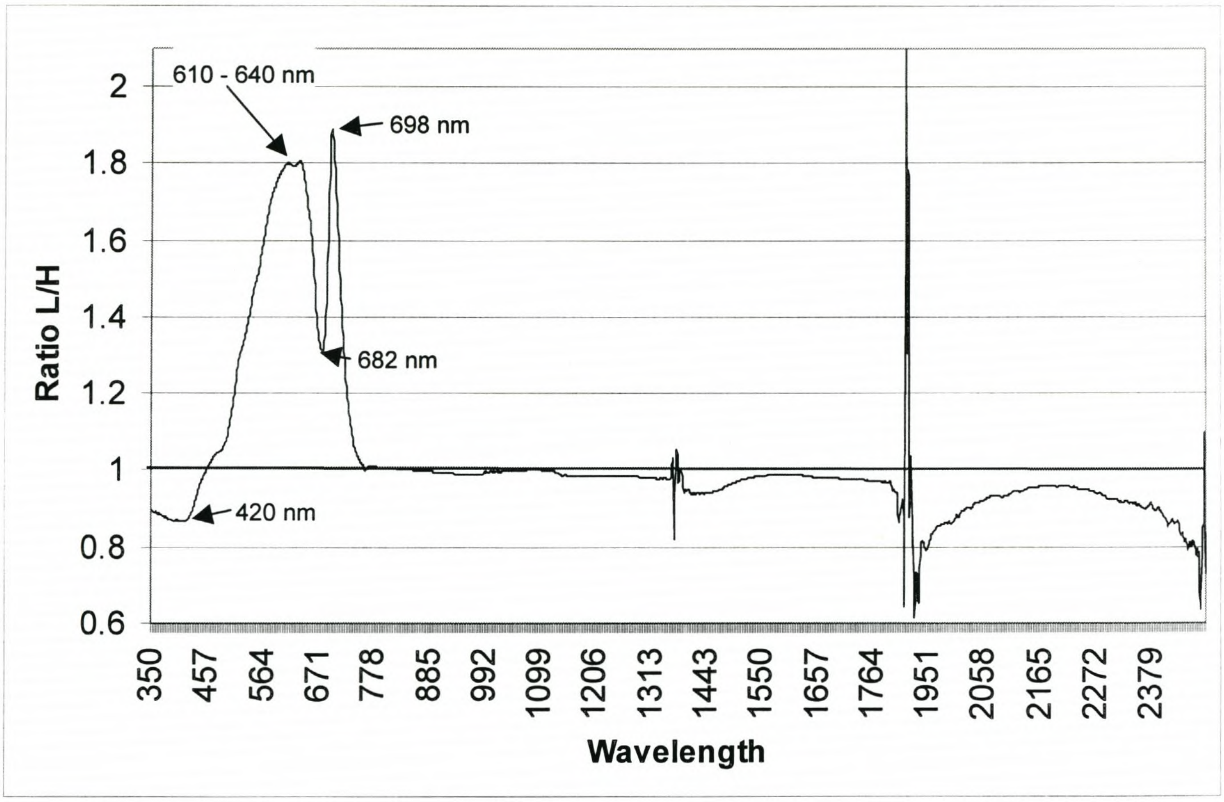

Figure 4.20 Normalised reflectance ratio (L = Lower vigour, stressed / H = Higher vigour, normal or less stressed) for the adaxial sides of the leaves measured in a Chenin blanc/R99 vineyard, Perdeberg area. The spectral ranges of certain wavepeaks or –troughs are indicated with annotated arrows.

This is probably caused by a regulatory process described by Taiz & Zieger (1998), where high-light regimes lead to activation of the de-epoxidase enzyme, which converts xanthophylls, a type of carotenoid, to the zeaxanthin form. The latter component normally has an absorption peak around 440 nm. The conversion of xanthophylls takes place to protect photosystem II from over excitation, which may be the case here, considering the high temperatures and light intensities during measurement.

The abovementioned process did not take place in the abaxial sides of the leaves, not being exposed to these high sunlight regimes (more than 2900 $\mu E.m^{-2}.s^{-1}$) (Fig. 4.21).

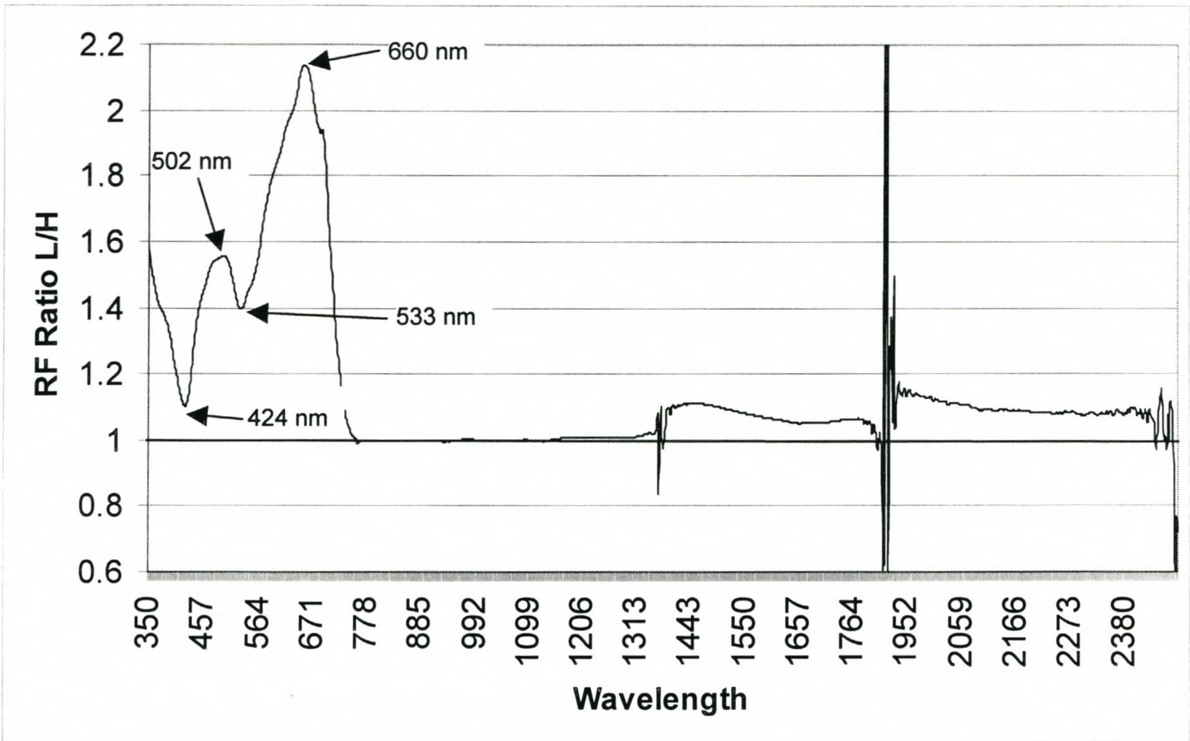

Figure 4.21 Normalised reflectance ratio (L = Lower vigour, stressed / H = Higher vigour, normal or less stressed) for the abaxial sides of the leaves measured in a Chenin blanc/R99 vineyard, Perdeberg area. The spectral ranges of certain wavepeaks or –troughs are indicated with annotated arrows.

The large differences in canopy structure (e.g. more exposed shoots, soil and trunk parts in the signal in addition to leaves) are probably responsible for the large differences in the reflectance ratio for the different canopies (Fig. 4.22). Further experimentation is underway in which the spectra of different stress levels will be investigated under controlled as well as field conditions.

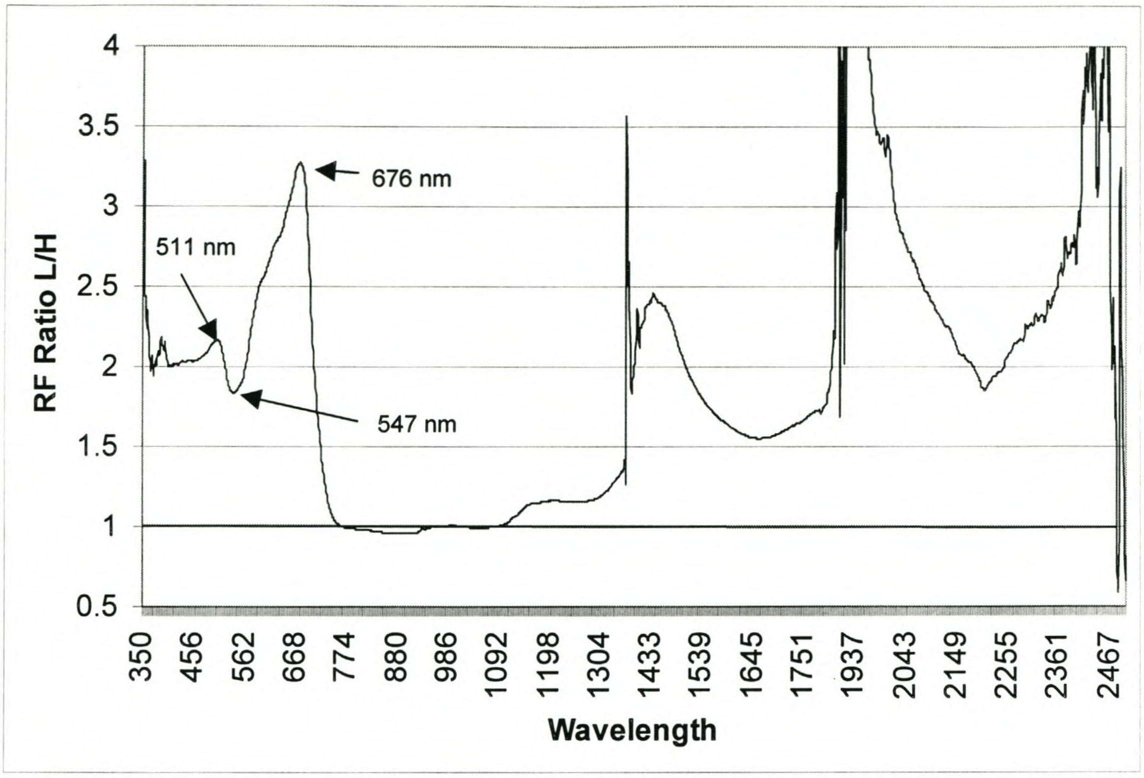

Figure 4.22 Normalised reflectance ratio (L = Lower vigour, stressed / H = Higher vigour, normal or less stressed) for the vine canopies measured in a Chenin blanc/R99 vineyard, Perdeberg area. The spectral ranges of certain wavepeaks or –troughs are indicated with annotated arrows.

4.4 CONCLUSIONS

Some of the vegetative measurements yielded highly significant differences between the vigour levels and confirmed that the vineyard was very well suited to the study of within-vineyard variability. Some of the measurements also correlated very well with soil salinity, being the largest source of the variability in this vineyard, as well as with the image pixel values. For this vineyard, trunk circumference proved to be an excellent link between canopy characteristics, soil conditions and the image pixel values.

Harvest data and wine analysis showed the same trend concerning differences between the vigour levels, but also emphasised the effect that these differences can have on grape and wine quality.

Grape composition (especially sugar concentration) was anticipated to vary much more in view of the large differences in canopy structure. In the lower vigour areas, however, it seemed as if the possible respiratory loss of sugar under stress could have decreased a potentially higher sugar concentration, leading to similar results between the vigour levels.

Wine evaluation yielded no clear preference for any of the wines, but the wine from the lower vigour vines was considered to have more fruit. If the positive comments from both wines are however combined, it can be understood why the wine from the whole block could be of excellent quality, especially considering that experimental winemaking techniques were used.

Hyperspectral measurements also emphasised the vigour differences through its effect on a calculated narrow-band NDVI index, but in addition it showed marked differences concerning the "quality" of the canopies. Different regions of the leaf- as well as canopy spectra showed marked differences in reflectance between the presumably stressed and less stressed vines. Regions corresponding to carotenoid, chlorophyll a and chlorophyll b showed different spectral reactions under stress conditions and these observations are well worth investigating in further studies.

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Chapter 5

GENERAL DISCUSSION AND CONCLUSIONS

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Precision viticulture has brought about new ways of looking at spatial variability in growth vigour within a vineyard and its management. It shows great promise worldwide, but particularly in South Africa, owing to the large variability found in geology and land form, leading to large differences in soil types over short distances. Obtaining images of variability in a vineyard and taking steps to recognise the cause of the variability may provide the viticulturist with a powerful tool not only to facilitate differential harvesting, but also to serve as a scientific basis to differentiate management techniques between different parts of the block. This may therefore provide a sound basis to eradicate variability when the aim is to achieve the desired uniformity necessary for top quality grapes. The goal may also be not to eradicate variability, but to manage it in such a way that the result is wine complexity, rather than variability in fruit quality that causes lower wine quality in general. It also offers the possibility of targeting vineyard sampling strategies in addition to providing an improved basis for soil profile pit placement used in vineyard layout.

Remote sensing, however, does not necessarily provide direct solutions for problems related to within-vineyard variability in growth vigour, but it may provide different ways of looking at the factors leading to the variability. This may in turn lead to a better understanding of the aspects affected by these factors along the chain of physiological events, leading to a specific grape quality level. It is therefore important that research should focus on gaining an increased understanding of the link between vine spectral signatures and biophysical parameters that may lead to variability in fruit quality (Arkun *et al.*, 2001).

The time has definitely arrived in both research and production environments to start accepting within vineyard variability as an inevitable property of nature, and to focus efforts on the extraction of useful data from this variable system through the utilisation of remote sensing tools. The challenge in research is to process the large amount of data acquired with the aid of these technologies into useful packets of information, while also investigating relationships between the different types of data acquired (eg. image data with data from yield monitoring and field trials). The challenge on the production side is to use the acquired information in day-to-day management, but also to restart the cycle by reporting the results back to the research environment.

This study aimed to analyse the causes and effects of within-vineyard vigour variability in a "patchy" vineyard, through the utilisation of both conventional and advanced techniques. While conventional methods of soil, vine and grape sampling were used to aid in the description of the high levels of variability found in the vineyard, advanced methods of image data extraction and hyperspectral data collection were evaluated regarding their link to the measured variability.

Selective image colour replacement could for instance be used to identify the areas worst affected by the unfavourable soil conditions. Differences in image pixel values determined for experimental plots, demarcated according to different plot layouts, corresponded very well to the vigour variability expected. Soil pH and resistance analysis, as well as the analysis of aboveground growth and productivity-related components, consistently showed significant differences between the higher and lower vigour plots (Fig. 5.1). Soil profile analyses revealed limiting soil physical conditions in both vigour levels, but suggested that, in the lower vigour areas, these conditions combined with soil chemical conditions to lead to dramatic vigour reduction over short distances. The largest effect of the high pH and resistance prevailed in the upper soil layer (0-30 cm), which is considered to have a significant effect on the soil structure and permeability to moisture in this layer.

Relationships between several factors, either causing or being the result of variability, could be shown after correlating the image pixel values with these factors (Fig. 5.2). Trunk circumference played a central role in these relationships, responding strongly to the effect of long-term exposure of the vine to high salt content. A dissapointing result, however was the non-significant correlation found between leaf area per vine and the image pixel values (r^2=0.24), which was actually expected to be the parameter best correlated with the image data. Instead, the image data showed the best correlation with soil resistance values, suggesting that the image reacted better to changes in soil conditions than plant canopy conditions. An explanation for this is the sampling method used for leaf area per vine determination, which only included a few vines randomly selected per vigour level and per plot for grape harvesting. Considering the levels of variability in canopy size and configuration between vines within vigour levels and plots, these vines probably could not give an accurate representation of the leaf area per vine average for a plot, which would presumably have yielded a much better correlation. For this type of correlations it is therefore needed to either measure leaf area from a lot more vines within treatments (a laborious task) or to have access to high-resolution geo-corrected images, where the position of a single vine and its representative pixel value could be extracted.

Table 5.1 Summary of 2-sided p-values (Welch t-test) determined for selected vigour variability measurements in a Chenin blanc/R99 vineyard block on Swartland/Glenrosa soils in the Perdeberg area. Values significant at the $p \leq 0.05$ level are shaded.

Parameter	**Mean H**	**Mean L**	**p-values (2-sided)**
pH (KCl) (plot layout B)	7.57	8.20	0.0049
Resistance (ohm) (plot layout B)	1338.99	292.23	0.0001
pH (KCl) (plot layout D)	7.46	7.61	0.2720
Resistance (ohm) (plot layout D)	582.33	137.50	0.0000
Trunk circumference (mm)	125.25	93.39	0.0000
Main shoot length (cm)	144.75	88.83	0.0008
Unripe shoot tip (cm)	9.96	10.79	0.7945
Nodes per main shoot	25.36	18.75	0.0066
Average shoots per vine	23.71	20.67	0.0952
Total leaf area per vine (cm^2)	100828.70	47716.28	0.0022
Leaf area / fruit mass ($cm^2.g^{-1}$)	13.60	18.03	0.3053
Yield per vine (kg)	7.71	4.03	0.0002
Bunch mass (g)	295.36	199.70	0.0024
g per100 berries	81.88	75.63	0.0274
Leaf water potential (Mpa) (Pre-dawn)	-0.75	-1.02	0.0000
Leaf water potential (Mpa) (Midday)	-1.47	-1.82	0.0168

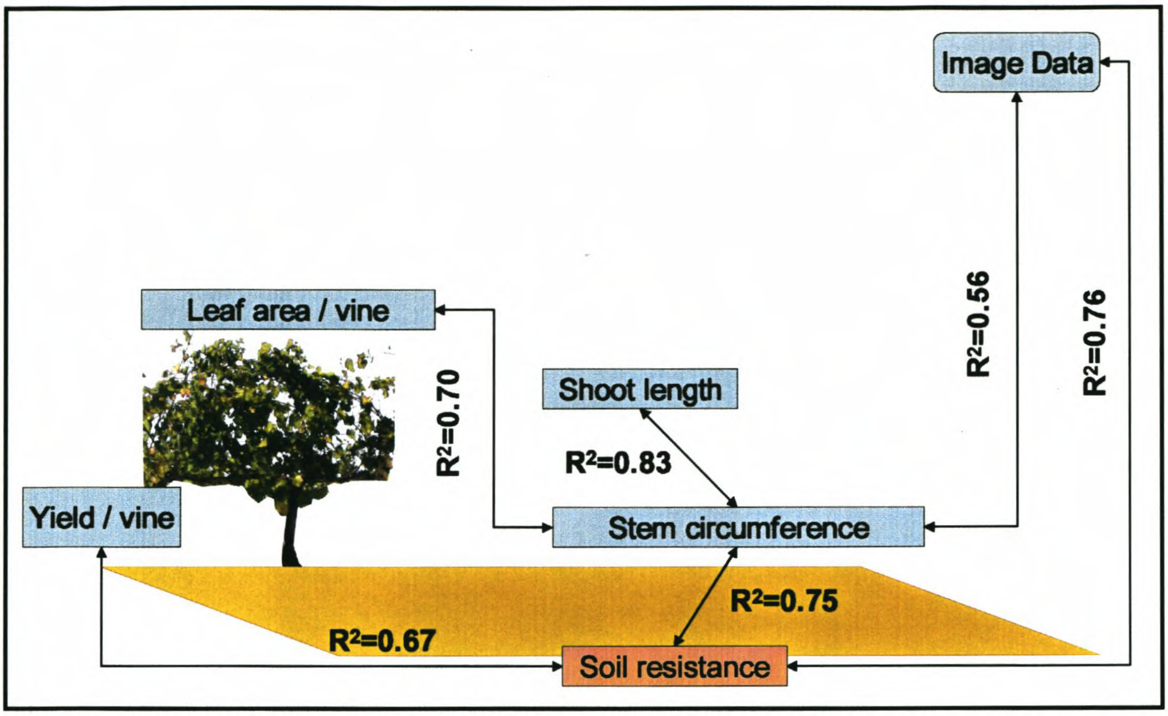

Figure 5.1 Correlations between selected parameters that can be related to vigour variability, as well as image data (referenced image pixel values) in a Chenin blanc/R99 vineyard block on Swartland/Glenrosa soils in the Perdeberg area.

In order to understand the relationships between some of the parameters measured at the higher and lower vigour plots in this study better, an adaptation of Fig. 2.3 (Chapter 2) has been made for the lower vigour level, showing how the factors that may have contributed to a vigour reduction may be interrelated (Fig. 5.2). In spite of all the factors that were shown to differ significantly between the vigour levels, and its interrelated nature, it must still be considered that differences in wine quality (as opposed to wine character) were not significant, in other words, both vigour levels had the potential of producing high quality wine. The yield reduction in the stressed parts of the vineyard may also play a significant role here, considering that the block produced nearly 18 $tons.ha^{-1}$ one season, causing the wine from the block to be rendered useless.

Reflectance measurements for different targets could be evaluated anatomically as well as physiologically, and results suggested that future studies into stress reactions in vines could benefit a lot from these measurements. However, the measurements should be confirmed with conventional physiological measurement techniques, which should be verified on vines grown under controlled stress environments (glasshouse). The narrow-band NDVI index corresponded well with values for vegetation targets found in literature, and succeeded in confirming image pixel analysis.

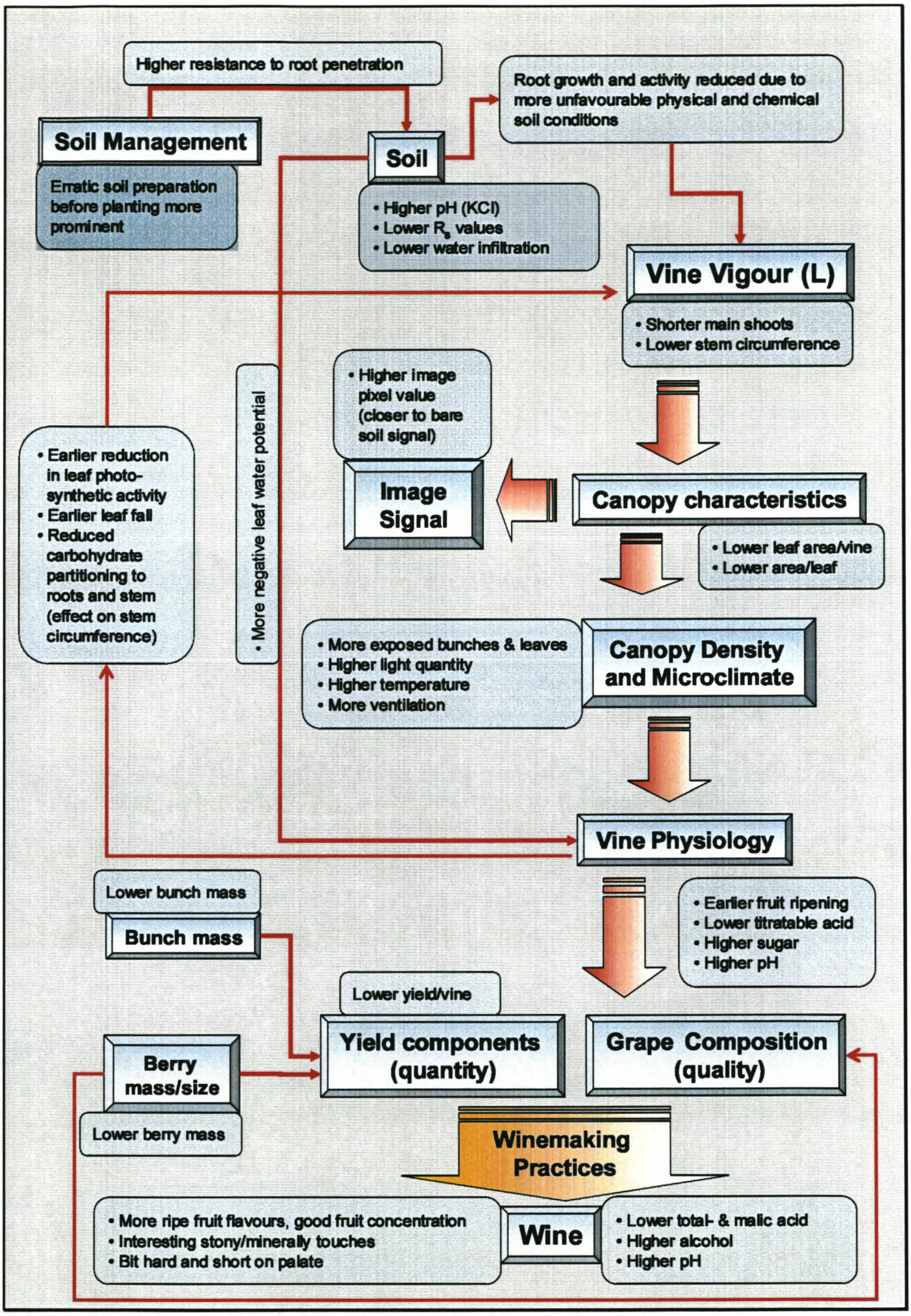

Figure 5.2 Factors possibly leading to the vigour reduction observed in the low vigour areas of this study in a Chenin blanc/R99 vineyard, Perdeberg area, and possible effects of these factors on wine quality.

The author of this study is confident that although the levels of variability found in this vineyard may exceed the levels found in most other vineyards, improved technologies such as high-resolution multispectral remote sensing and the creation of NDVI or similar images may have the ability to show variability in vineyards that were previously considered relatively homogenous. In a preliminary study aimed at such vineyards, it has been shown that vigour grouping and separate harvesting in a vineyard considered to be fairly homogenous produced red wines which significantly differed with respect to ageing potential and wine character.

It is believed that remote sensing technologies are opening new doors in viticultural research as well as vineyard management. The advantages of the technology strongly outweigh the disadvantages and criticism, but it has to be acknowledged that a significant amount of research is still needed to explain the nature of variability without the need for a significant amount of ground truth information.

5.2 LITERATURE CITED

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