

Identification of terroirs in the Robertson valley for Chardonnay and Shiraz: a focus on soil and roots

by

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Thesis presented in partial fulfilment of the requirements for the degree of
Master of Agriculture Sciences

at

Stellenbosch University

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February 2011

Declaration

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

Date: 18 February 2011

Summary

The grapevine must constantly find a balance between two continually changing environments, the rhizosphere (i.e. soil) and the troposphere (i.e. macroclimate). The adaptations are extremely complex because they encompass complicated and interrelated processes that are not yet fully understood.

In terms of water-use behaviour, differences between cultivars have been described in the literature. In this study, the water status and stomatal conductance of four cultivars (Shiraz, Grenache, Pinot noir and Chardonnay) grafted onto R99 were studied. Diurnal cycles of water status and stomatal conductance, from 07:00 to 19:00, were followed for a single day at the end of the 2009 season. The results showed that, at the end of the season, Shiraz was subjected to water stress conditions, losing leaves and showing symptoms of berry shrivelling. The other three cultivars had a much better canopy status and no symptoms of berry shrivelling were observed. Based on the canopy observations and a comparison of the curves of stem water potential (Ψ_s) and stomatal conductance (g_s), it seems that Pinot noir and Chardonnay are closer to the water-use behaviour of Grenache noir, which is known as a “pessimistic” cultivar, than to Shiraz, which is an “optimistic” cultivar.

A study of four plots each of Chardonnay/101.14 Mgt and Shiraz/101.14 Mgt was carried out in eight commercial vineyards in the Robertson region in order to investigate the relationship between soil and root morphology, and the influence thereof on canopy development and berry growth. These plots had different soil types. Important soil properties are reported to limit root growth, individually or as a combination of restrictions. It was found that the size of the root system of 101.14 Mgt is defined by soil physical and chemical properties. The roots of 101.14 Mgt under irrigation can grow to a depth of 100 cm or beyond if the soil physical and chemical properties allow it.

Because the soil properties define the root system and the water storage/drainage, they greatly influence the plant water status, even under irrigation. In an arid zone like Robertson, irrigation is an important management tool. The balance between canopy growth before véraison and the ability of the root-soil system to maintain that canopy size during the ripening process is crucial in an area with a high evaporative demand. In this regard, not all the soil properties-root system combinations showed satisfactory performance in maintaining the canopy functioning, which affected berry sugar loading and berry volume.

In another study that is presented, forty soil profiles were characterised in the Robertson valley. The root systems were considered as a product of the soil properties, and thus the morphology of the root systems was used as a starting point to group soils together. The importance of soil depth has been described well, thus the root systems were first classified according to rooting depth – into shallow and deep root systems. The deep root systems were then subdivided, creating two subgroups of high root density and low root density. The two extreme groups (i.e. shallow roots, and deep roots with high root density) have particularly different soil properties. The soil characteristics found in these extremes are represented up to certain point by families of the South African soil taxonomy, mainly due to the restrictive function of the B horizon. This restrictive function is related to soil properties that are taken into consideration in the South African soil classification and that are important for grapevine root growth, as well as the

thickness of the described horizons and the physical and chemical differences between the horizons.

Soil properties have an important influence on root morphology. Due to the fundamental role played by the root system in the overall plant functioning, soil properties are of critical importance. In an arid area, the low water pressure in the atmosphere and the high temperature greatly affect the plant water status. The soil-root system combination plays an important role in the ability of the root system to supply the plant with water during times of high evaporative demand. Different cultivars will react differently due to differences in transpiration control. The maintenance of an adequate water status will have an immense influence on canopy development and maintenance, and on normal and steady berry ripening. In this study it was found that not all the soil-root combinations can fulfil this satisfactorily. Thus, the grapevine balance determined by the combination of the soil-root-canopy complex and the influence of management techniques is extremely important for the favouring of a good canopy:root system ratio, a functional canopy throughout the season and a steady berry ripening curve.

This thesis is dedicated to my parents, Alfredo Erazo-Rojas and Nancy Lynch-Becerra, “the fire
from which I’m a spark”,
and to two extremely special persons in my life, Maria Rojas-Bustamente and
Eufemia Becerra-Rebolledo

Biographical sketch

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Acknowledgements

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

- Dr Victoria Carey, for her invaluable advice and contribution, her time and disposition, and for her clear thoughts. Thank you for guiding me throughout the whole process of this research, despite the distance in the last stages.
- Prof Alain Deloire, for his always suitable questioning, kind advice and extremely valuable ideas. Thank you for showing me a different way of reasoning viticulture.
- Prof Freddy Ellis, for his enormous contribution to this research; without his help this research would not have been possible. Thank you for the invaluable talks, precise advice, time and willingness to help. Thanks for introducing me to the exciting field of soil science.
- Mr Braham Oberholzer, for his crucial help in the soil descriptions, and for finding the time to help me with the field work, for his passion about soil. Thank you for helping me in the understanding of soil formation and the interpretation of the landscape.
- Prof Martin Kidd, for all his help and time with the analysis of the data
- Mr Albert Strever, for also helping me with some data, but more importantly for his valuable comments and discussion.
- Tinake CR van Zyl and Zelmari Coetzee, for all their help throughout with the measurements, for being there for the long drives, and for always having encouraging words. Also for many breakfasts after long nights of measurements. Thanks.
- The academic and technical staff of the Department of Viticulture and Oenology, for their assistance, for always being willing to talk, and for all the advice I received, but mainly for all the smiles. Thanks a lot to everyone.
- All the owners of the farms where this study was conducted. Without their valuable help, this research would not have been possible.
- The Department of Viticulture and Oenology of Stellenbosch University, Winetech and Thrip, for their financial support.
- My parents, for all their support and understanding in all these years I have been away from home.
- My Chilean friends Ignacio Serra and Felipe Cruzat, for lending an ear more than once and for suggesting more than one idea. Thank you guys.
- To my friend Alejandro Erazo-Lynch, for his technical assistance while taking holidays, for his visits, and for being here.

Preface

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

Chapter 1 **General Introduction and project aims**

Chapter 2 **Literature review**

The importance of grapevine roots in a warm dry climate

Chapter 3 **Research results**

Diurnal water status of Chardonnay and Shiraz: a comparison

Chapter 4 **Research results**

The influence of soil properties in Robertson on the development of 101.14 Mgt roots and the consequences thereof for canopy development and berry growth of Chardonnay and Shiraz

Chapter 5 **Research results**

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Chapter 1

Introduction and project aims

Introduction and project aims

In an increasingly standardized, mechanized and computerized world, fewer things remain that are truly individual. Wine is one of them. Despite the high technology of its production, wine remains essentially a natural product, with infinite variation from area to area, maker to maker, grape variety, and even bottle to bottle. It has a sensual fascination which takes it far beyond a mere alcoholic beverage (Gladstones, 1992).

1.1 Introduction

Terroir has been defined by many authors as the interaction between soil, climate and grapevine cultivar, these being the most important parameters determining wine typicality (Saayman, 1977; Morlat, 1996; Carey, 2001; Fregoni *et al.*, 2003; Van Leeuwen *et al.*, 2003; Van Leeuwen & Seguin, 2006). Due to the close interaction between these components, no single component can be studied in isolation (Carey, 2001). These parameters are not easily modified by the producer. Although management decisions will aid in defining the characteristics of the final product, they do not form part of the intrinsic definition (Carey, 2001).

A good terroir can be considered as one in which quality grapes (that can be converted into quality wine) are the result of the matched combination of soil, grapevine and cultivar, with minimal input from management practices.

There are two key points that define the quality of grapes in a determined terroir, and they are: the water status of the plant through the season (Fregoni, 1977; Morlat *et al.*, 1992; Choné *et al.*, 2001; Ojeda *et al.*, 2001, 2002, 2004; Van Leeuwen *et al.*, 2003, Deloire *et al.*, 2006), and the berry composition at the harvest date (Gladstones, 1992; Dokoozlian & Kliewer, 1995). Both are the result of the complex interactions between the terroir components to deliver a certain berry composition at a specific date.

1.1.1 The Breede River valley

The Breede River Valley is a warm climate region that can be very dry and arid in some places. The climate is influenced by the presence of mountains to a great extent: it is separated from the continental climate of the interior by the Langeberg mountain range, which is situated directly north of the Breede River valley, and from the maritime influence by the Du Toitskloof-Sonderend mountains to the south (Oberholzer, 2007). Consequently it neither presents a continental climate nor a truly maritime climate.

The average maximum temperature during January and February for most of the area is just above 30°C. Due to the presence of the mountains there is a restriction to the maritime influence during night time and the temperature drops more than in the coastal areas (Oberholzer, 2007), but it does not become as cold as in the continental areas. According to the heat summation of Amerine & Winkler (1944), the Robertson area falls in region IV, with 2170 degree days (Saayman & Van Huyssteen, 1980).

More than 70% of the rainfall occurs between April and September, but the distribution differs along the valley, decreasing from west to east. Around 1000 mm per annum has been measured at Du Toitskloof, an average of 600 mm per annum at Botha's Halt, but to the west, in the rest of the Breede River Valley, the rainfall seldom measures above 250 mm per annum (Saayman & Van Huyssteen, 1980; Oberholzer, 2007).

The soil characteristics of the area can change dramatically due to different soil-forming processes, which have had a tendency to differentiate the materials on which they act into horizons (Oberholzer, 2007).

In terms of distribution of wine grape as percentage Robertson represent 14% of the total wine grape vineyard surface in South Africa. In Robertson the surface planted with Chardonnay represents 24.32 % of the total planted with white grapes cultivars, and Shiraz represents 22.01% of the total surface planted with red grape cultivars (SAWIS, 2009).

1.1.2 Grapevine and environment

The grapevine survives by continuously accommodating both structure and function to the two environments in which it grows, namely soil (rhizosphere) and atmosphere (troposphere). Different cultivars have different strategies to adapt to those changing environments and important differences have been reported in their water use strategies (Schultz, 1996; 2003). Two important stimuli from the troposphere on grapevine metabolism are the temperature and the atmosphere water vapour deficit (Davies *et al.*, 2002; Loveys *et al.*, 2004; Wilkinson, 2004). These two have a considerable influence on the two aspects mentioned previously, i.e. the plant water status and the berry composition at harvest, as a result of complex processes and interactions among them.

The grapevine accesses the atmosphere by opening the stomatal pores in the leaf to take up gaseous CO₂ for photosynthesis. However, the plant inhabits an environment in which the leaves are subjected to a high evaporative demand, particularly during the middle of the day (Loveys *et al.*, 2004; Wilkinson, 2004). This means that the grapevine is also at constant risk of dehydration via unavoidable transpirational water loss. Transpiration requires energy for the water molecules to change their state (De Jager & Van Zyl, 1989), and the driving force is the difference between water vapour pressure at the evaporating surface and in the surrounding atmosphere (Allen *et al.*, 1998).

The stomatal control couples leaf transpiration to leaf photosynthesis as a result of a very complex process that can vary between cultivars. The response can be very finely tuned to soil drying, and a restriction of stomatal conductance can become apparent even when the soil water status changes by only a few kPa (Allen *et al.*, 1998; Davies *et al.*, 2002; Taiz & Zeiger, 2002).

The roots are the organ for water and nutrient uptake and the soil properties are essential in determining the root system characteristics (Morlat & Jacquet, 1993; Taiz & Zeiger, 2002). Due to the nature of its function and structure, the root system determines the performance of the grapevine (Southey & Archer, 1988). The size of the root system, and the availability of water and nutrients (both functions of the soil), will determine the canopy size (Archer *et al.*, 1988; Southey &

Archer, 1988; Van Huyssteen, 1988; Swanepoel & Southey, 1989). Consequently, improved water relations stimulate shoot and leaf growth (Smart *et al.*, 1985), but when water is less abundant, the matric potential of the water retained by the soil particles increases and promotes the synthesis of ABA in the plant, provoking a decrease in the rate of vegetative growth (Zacarias & Reid, 1990; Champagnol, 1997; Coombe, 2001) and stomatal closure (Trejo *et al.*, 1993; Zhang & Outlaw, 2001). This reaction has also been reported throughout the day, depending on the cultivar (Schultz, 1996, 2003; Rogiers *et al.*, 2009; Vandeleur *et al.*, 2009), as a response to a high evaporative demand (Trejo *et al.*, 1995).

1.1.3 The relation berry composition-canopy vigour

The dynamics of berry ripening is a rather complex process involving many metabolic routes, but there is a great deal of proof that it is highly affected by temperature (Coombe, 1987; Jackson & Lombard, 1993; Ferrini *et al.*, 1995; Hunter & Bonnardot, 2004), sun exposure (Smart, 1987; Jackson & Lombard, 1993; Dokoozlian & Kliewer, 1995; Price *et al.*, 1995) and the plant water status (McCarthy, 1999; Ojeda *et al.*, 2001, 2002). Temperature and sun exposure in the bunch microclimate are influenced by the canopy size and the trellis system (Smart *et al.*, 1985; Smart, 1988; Reynolds *et al.*, 1994; Kliewer & Dokoozlian, 2005; Cortell *et al.*, 2008).

Consequently, depending on the predominant climatic conditions and the grapevine cultivar, the soil will play a key role in the supply/restriction of water to the plant in order to match the atmospheric pressure deficit (VPD), which, depending on the phenological stage of the grapevine, can be beneficial or detrimental from a grape quality point of view. This difference is due to the big influence on the vegetative growth and berry metabolism discussed above. Therefore, soil properties are central to the whole-plant response to the atmospheric stimuli.

1.2 Project aims and hypothesis

The maximum temperature during the day exerts a great influence on grapevine and berry development and, if coupled with a high atmospheric water demand (and low air humidity), provoke a high potential evapotranspiration rate in the Breede River valley. The first hypothesis is that cultivars differ in their response to the high vapour pressure deficit, and thus in their water use strategy, and that Chardonnay and Shiraz will differ in this respect. The second hypothesis is that the size and distribution of the root system, and thus the ability of the grapevines to meet the demand for water stimulated by the high evapotranspiration rate, will be influenced highly by the soil characteristics and the genetic material. Following this, the third hypothesis is that the soil properties and characteristics will play a core role in the performance of the grapevine under the demanding atmospheric conditions in Robertson, and that these elements will affect grape berry composition and the potential wine style

The aims of this project were:

1. To compare the water status of Chardonnay and Shiraz after a season under dry-land conditions.

2. To determine the soil types and describe the root system of 40 reference vineyards of Chardonnay and Shiraz in the Robertson valley.
3. To characterise the viticultural performance of Chardonnay and Shiraz on four soil types each in the Robertson valley during the 2008-2009 season.

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Chapter 2

Literature review

The importance of grapevine roots in a warm,
dry climate

Literature review

2.1 Introduction

Grapevines survive by continuously accommodating both structure and function to the two environments in which they grow: the soil and the atmosphere (troposphere). The adaptation is extremely complex because it encompasses complicated and interrelated processes, namely transpiration, gas exchange and water losses, and the uptake of water and nutrients.

Probably the most important aspect is found in “the ways in which vegetation accommodates the supply of water provided to the root system by the soil to the demand for water imposed on the foliage by the atmosphere” (Monteith, 1993). In this regard grapevine water status is a key factor to understand the effect of the terroir, because it integrates the main terroir factors: climate, soil and grapevine (Van Leeuwen & Seguin, 2006).

Figure 2.1 provides a diagram of the relationships between these factors, acting over the grapevine vegetative growth period and influencing the ultimate product, namely, berry composition and thus wine quality.

This literature review integrates the environmental factors acting on the grapevine in the troposphere and rhizosphere; how the plant manages to integrate all of these stimuli to deliver one integrative response at a predetermined moment; and how this response affects long-term grapevine growth (canopy and root system) and the qualitative and quantitative seasonal yield.

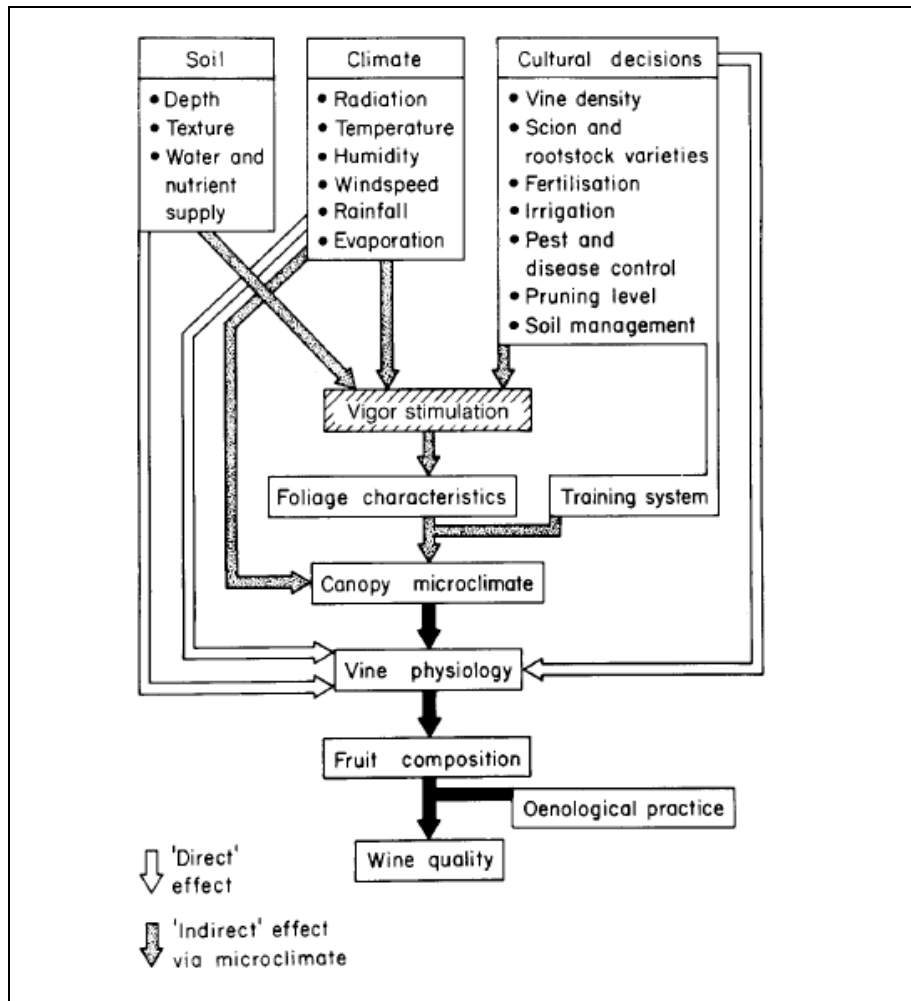


Figure 2.1 Conceptual model (from Smart *et al.*, 1985) that shows how soil, climate and cultural practices can affect canopy microclimate and therefore wine quality.

2.2 A brief introduction to troposphere

The earth is enveloped by a cocktail of gases, which form a band extending from the earth's surface to a height of about 1000 km, called the atmosphere. The atmosphere is divided into five layers, with the lowest one, over the surface of the earth, being the troposphere. This is where life exists and all weather events occur. All weather phenomena result from an interaction between solar energy, air and water vapour carried in the air (Luhr, 2004; Allaby *et al.*, 2008).

The climate of a particular area is the pattern of weather occurrences day by day and season by season over a long period of time (Allaby *et al.*, 2008). The climate (including micro-, meso- and macroclimate) affects the grapevine metabolism.

2.2.1 Evapotranspiration (ET)

Evapotranspiration is a term that brings together evaporation and transpiration (Allen *et al.*, 1998). Evaporation is defined as the physical process by which a liquid or solid is transferred to the gaseous state and removed from the evaporating surface (Allen *et al.*, 1998; De Jager & Van Zyl, 1989). The process of evaporation requires energy to change the state of the water molecules, or it can take place due to molecular escape without a change in temperature (Allen

et al., 1998; De Jager & Van Zyl, 1989). The main energy source is solar radiation, and the difference between water vapour pressure at the evaporating surface and that of the surrounding atmosphere is the driving force (Allen *et al.*, 1998).

The process of transpiration entails a vaporisation of liquid water from the plant tissues and the removal of the vapour (Allen *et al.*, 1998), and is controlled by means of the stomata. Exactly the same factors that act on evaporation act on transpiration.

Evapotranspiration is affected by: weather parameters (De Jager & Van Zyl, 1989), crop factors and cultivation practices, important in the determination of the transpiring surface (Myburgh, 2003), and of high value in determining irrigation strategies (Van Zyl & Fourie, 1988; Myburgh *et al.*, 1996).

Transpiration is beneficial because it cools leaves, accelerates the ascent of sap, and increases the absorption of minerals. However, it can also be regarded as an “unavoidable evil” (Kramer & Boyer, 1995; Allen *et al.*, 1998; Taiz & Zeiger, 2002), as nearly all the water taken up is lost by transpiration (Allen *et al.*, 1998). According to Taiz & Zeiger (2002), a leaf will exchange up to 100% of its water in a single hour on warm, dry, sunny day. Stomatal control couples leaf transpiration with leaf photosynthesis. The stomatal response depends on soil water status. Stomatal conductance can decrease even when the soil water status changes by only a few kilopascal (Allen *et al.*, 1998; Davies *et al.*, 2002; Taiz & Zeiger, 2002).

2.2.2 Weather parameters that influence evapotranspiration

2.2.2.1 Radiation

The most important source of energy in the earth-atmosphere system is the sun’s radiation. Radiation plays an essential role in the energy balance and in the physical processes that take place in the earth-surface systems (Pearcy *et al.*, 1989).

2.2.2.2 Temperature

The temperature in the troposphere is the result of an exchange of energy between the rays of the sun and the atmosphere, and it can be quantified (Luhr, 2004). Warmth from the sun provides energy for water to evaporate and, in a very simplistic generalisation of a much more complex process – the warmer the day, the greater the evaporation rate. Factors that influence the degree of heating are season (time of the year), geographical degree of latitude, nature of the surface, and slope inclination (Luhr, 2004; Allaby *et al.*, 2008).

2.2.2.3 Wind

The wind is a mass of air that moves, as a result of differences in atmospheric pressure, from a region of high pressure toward a region of low pressure. The air continues to move until the pressure differences are eliminated (Luhr, 2004). Evaporation from a surface is determined by the saturation deficit of the layer directly above the transpiring surface. The movement of the air constantly removes the vapour phase, thus saturation is avoided and evaporation continues to occur. In general terms, wind will increase losses due to evaporation (Huschke, 1959).

2.2.2.4 Humidity (vapour content of the atmosphere)

Less than 1% of the atmosphere is vapour. The amount of vapour that can be held in the atmosphere is dependent on the temperature: the warmer the air, the greater the amount of vapour that can be absorbed and that will prevail at saturation (Huschke, 1959; Luhr, 2004).

The saturation deficit is the difference between the saturation vapour pressure and the actual vapour pressure at a determined temperature, and indicates the vapour supplementation that is required to achieve complete saturation under those conditions of atmospheric pressure and temperature. The saturation vapour or maximum (E_m), is the point at which evaporation from a clear surface will cease: this is related to a given temperature. Consequently, the amount of vapour in the atmosphere influences evaporation and, as soon as the airspace is saturated with vapour, no further evaporation can take place (Huschke, 1959).

2.2.3 Effect of temperature on the metabolism of the grapevine

Temperature is acknowledged as probably the single most significant environmental factor influencing viticulture (Coombe, 1987). Each physical process (enzyme reaction, membrane field, transport process, phase transition) is subjected separately to the influence of temperature, some subtly and some dramatically (Coombe, 1987).

2.2.3.1 Temperature effect on photosynthesis.

Temperature affects all the biochemical reactions of photosynthesis, thus it is not surprising that the responses are complex (Leegood & Edwards, 1996). When the photosynthetic rate is plotted as a function of temperature, the curve has a characteristic bell shape. The ascending arm of the curve represents a temperature-dependent stimulation of photosynthesis up to an optimum, and the descending arm is associated with deleterious effects, some of which are reversible, while others are not (Taiz & Zeiger, 1998).

According to Taiz and Zeiger (1998), the optimal point is reached when the capacities of the various steps of photosynthesis are balanced optimally, and some of the steps become a limit as the temperature increases or decreases. Optimal temperatures have a strong genetic and physiological component. Furthermore, plants of the same species, grown at different temperatures and then tested for their photosynthetic responses, show temperature optima that correlate with the temperature at which they were grown (Taiz & Zeiger, 1998). This could suggest a difference in the optimum between grapevine cultivars from genetic expression or the capacity of adaptations to different environmental conditions.

Ferrini *et al.* (1995) compared Trebbiano grapevines grown at 20°C, 27.5°C and 35°C in separated chambers and found the lowest net photosynthesis values in vines grown at 35°C. The effect of temperature on stomatal conductance was less marked and the accumulation of dry matter was correlated with the average photosynthetic rate.

Zufferey *et al.* (2000) found that the photosynthetic activity of the leaves of Riesling below 20°C was higher than that of Chasselas. Similar results for photosynthesis in both cultivars were obtained in the range between 20° and 30°C, and Chasselas has a better response when temperatures exceed 30°C. Bertamini *et al.* (2007) reported cultivar differences in the exposure

to low night temperatures (LNT) provoking important reductions in photosynthesis in Lagrein, while Müller-Thurgau was not affected. They reported that chilling temperatures can limit photosynthesis via stomatal closure, the inhibition of thylakoid electron transport and photophosphorylation, RuBPC inactivation, the inhibition of key enzymes in sucrose, and starch biosynthesis and phloem loading.

Kliewer (1970) reported that photosynthesis is 90% to 100% efficient between 18°C and 33°C. Alleweldt *et al.* (1982), found the optimum net assimilation rate by photosynthesis to be at 25°C. Hunter & Bonnardot (2004) argued that a range between 20°C to 35°C is optimal for key physiological processes.

2.2.3.2 Influence of temperature on respiration.

Respiration is as important for the plant as photosynthesis. In very broad terms it makes the energy and C skeleton units fixed during photosynthesis available for other metabolic processes in the plant.

In the physiological temperature range, respiration is temperature dependent. The increase in respiration rate for every 10°C increase in ambient temperature, commonly referred to as the Q₁₀, is slightly greater than 2. Because respiration increases exponentially with temperature, the Q₁₀ value represents the difference in respiration rates over 10°C interval (Taiz & Zeiger, 1998).

2.3. A brief introduction to the rhizosphere

The rhizosphere is the environment where the roots grow, function and die. The effect of soil on vine behaviour and berry composition is complex because the soil offers many constraints to the development of the root system (Saayman & Van Huyssteen, 1980; Van Huyssteen, 1988a). The environment where roots develop is dominated by the influence of the soil physical conditions (Van Huyssteen & Weber, 1980). The term soil potential has been developed to rank soils, but only becomes meaningful if it is specified in terms of a specific crop (i.e. a soil not suitable for dryland maize production can be ideal for pastures).

2.3.1 Soil agronomic potential

Soil agronomic potential is defined as the soil aptitude to ensure plant vegetative growth, provided that the soil can fulfil the need for water, minerals and oxygen at the root level (Champagnol, 1997). Three aspects are important in relation to soil agronomic potential:

- a) The physical aspect of fertility, determined by the soil aggregates, and their influence on the porosity and consequently the capacity of the specific soil to retain water, exchange air and ensure drainage.
- b) The chemical aspect of fertility: a function of the necessary mineral nutrition for the plant that extracts the minerals from the soil solution (Champagnol, 1997).

- c) The hydraulic aspect of fertility, which depends on soil physical properties and depth (Champagnol, 1997; Van Zyl, 1988). Agronomic fertility can be confused with hydraulic fertility (Champagnol, 1997).

2.3.1.1 The three most important soil properties that explain soil agronomic potential

The three components of soil fertility can be explained by three soil properties:

- a) Texture. This is the expression of the predominant size, or size range, of the soil particles (Hillel, 1971). It determines the energy with which the water is held, and therefore the ease of extraction by the grapevine, and plays an important role in the gas exchange between the soil and the atmosphere, in soil water storage, and in the speed of drainage (White, 2009). The fraction that determines the physical behaviour of the soil is the colloidal clay, since it has the greatest specific surface area and is therefore the most active in the physicochemical processes that play an important role in the hydraulic balance. The total soil surface depends upon the type of clay as well on its total amount (Hillel, 1971).

Sand and silt have relatively small specific surface areas and consequently small physicochemical activity. Hillel (1971) calls sand and silt the “skeleton” and the clay the “flesh” of the soil.

- b) Structure is generally defined as the “mutual arrangements, orientation, and organization of particles in the soil” (Hillel, 1971). Sometimes the term is also used when referring to the geometry of pores. Unlike soil texture, structure is highly dynamic and may change greatly in response to changes in natural conditions, biological activity, and soil management practices (Hillel, 1971).

Structure greatly affects water storage and drainage, air content (through changes in porosity), heat regimes, stable aggregation and soil strength, which plays an important role in the ease with which roots can push through the soil (Hillel, 1971; White, 2009). The layers with high bulk density present a high resistance to root penetration, regardless of textural class (Saayman & Van Huyssteen, 1980). The threshold of soil resistance for root growth has been defined as 3 MPa. A penetrometer was used in a soil at field capacity, because soil strength changes with water content. For soil resistance values greater than 3 MPa, the soil will need amelioration to ensure sufficient root growth (Cass, 1999). According to White (2009), in duplex soils with dense B horizons, less than 5% of vine roots penetrate into the dense horizon.

- c) Chemical composition. This is a function of the total specific surface area that is able to exchange minerals, and the presence of the necessary minerals for plant growth in the soil solution in an optimal concentration (Champagnol, 1997). The balance and availability of mineral nutrients is affected by soil pH (Conradie, 1988).

2.3.2 The importance of hydraulic fertility

Hydraulic fertility has a large influence on the agronomic fertility, provided that there are no nutritional deficiencies. Two important concepts must be taken into account when considering the hydraulic fertility of a soil (Champagnol, 1997).

- a) The total amount of available water matched to plant necessity.
- b) The extractability of that water, which takes into account the soil matric potential developed over the soil particle surface.

Champagnol (1997) described three representative soil models in the Languedoc area in terms of their hydraulic fertility:

- a) Important water contribution, ease of extraction, small water constraint during the season.

Two different types are identifiable within this category.

1. Deep soils with or without a water table, but with a high water budget of more than 15 cm/m, due to an important concentration of clay and silt. They do not exert any water constraint, therefore inducing a great vegetative growth. They have two characteristics properties, namely an important percentage of the fine fraction (clay and silt), and a structure that facilitates deep rooting exploration.
 2. Shallow soils, which present a depth of around 50 to 80 cm and a texture dominated by sand. They retain very little water, around 2 cm/m, but are constantly fed water from rain or fluctuating water tables.
- b) Water retention that allows enough reserves, with progressive regulation, as a consequence of high water retention by the soil particles.

This is a characteristic of deep soils with a water content of between 4 and 8 cm/m. The water supply of the soil is high at the start of spring, although it progressively dries out, especially in the top horizons, where a high root concentration promotes a water constraint around or after flowering. During maturation the deep roots provide water from deeper layers, although slight signs of stress, like the senescence of leaves, can be identifiable. In these soils the water is restricted by the matric potential of the soil particles, more than by the total amount in the soil.

- c) Insufficient water reserves, severe water stress.

The third type of hydraulic behaviour includes soils with a good water reserve but that are shallow due to an impenetrable layer, hard pan, or close to unweathered parent rock.

The water availability during the spring is expressed in a high rate of vegetative growth in a few weeks, but the water may start to be depleted from the profile around flowering, establishing a drought condition towards véraison and ripeness.

2.4 The grapevine root system

The root system is essential in determining the performance of the grapevine, due to the nature of its function (Southey & Archer, 1988).

2.4.1 Root development

Roots have evolved to grow through the soil, an environment that challenges them with many constraints. They do so in order to absorb the water and nutrients that are vital for plant functioning and survival (Van Zyl, 1988; Morlat & Jacquet, 1993; Taiz & Zeiger, 2002). They also serve as an important source of nutrient reserves (Conradie, 1988). One of the root growth adaptations has been the lack of production of lateral organs by the apical meristem, in order to facilitate penetration through the soil pores. Branched roots only grow from mature or non-growing regions. Root hairs are produced behind the growing zone, where they enhance the absorption of water and minerals (Morlat & Jacquet, 1993; Taiz & Zeiger, 2002). Roots also provide structural support (Smart *et al.*, 2006).

Roots grow and develop from their distal ends and four developmental zones can be distinguished in the root tip: the root cap, the meristematic zone, the elongation zone and the maturation zone. These boundaries overlap considerably (Taiz & Zeiger, 2002). The root cap protects the apical meristem from mechanical injury. The meristematic zone lies just under the root cap and it generates only one organ, the primary root. The elongation zone is the site of rapid and extensive cell elongation, and the maturation zone is the region in which cells acquire their differentiated characteristics (Taiz & Zeiger, 2002).

The growth or formation of all the organs is according to the "cycle of vegetative growth". In the case of the grapevine, two peaks of growth are normally described in the literature (Van Zyl, 1984; Conradie, 1988); one occurs at flowering and the other in the postharvest period, irrespective of the soil moisture regime. Although contrary to generally accepted beliefs, Eissenstat *et al.* (2006) found little evidence that any root growth takes place after harvest, showed that root growth is not bimodal and saw that the timing of root growth can be quite variable from one year to the next, bringing some controversy to the accepted peaks of root growth. These findings were made when comparing two sites, one in Oakville (California) characterised by a hot, dry growing season (May-August average daily maximum temperature of 30.7° C; average precipitation = 1.8 cm), and the other in Fredonia, New York, characterised by a cool and moist growing season (May-August average daily maximum temperature = 24.7°C; average precipitation = 41.7 cm).

Van Zyl (1984) also pointed out that very little growth takes place in mid-summer, the time that water uptake reaches its maximum, and suggested that the white unsuberised roots "are not the only pathway for water movement from soil to vine" and that the suberised root may also play an important role in water and nutrient uptake.

2.4.2 Root distribution

The grapevine's root system in particular may have evolved in order to compete with the root system of its host tree, and in these terms a low density seems to be a good strategy to reach potential water sources, as is the employment of hydraulic redistribution to sustain the root system's growth and viability (Morano & Kliewer, 1994; Smart *et al.* 2006).

In the development of the root system, soil properties exert a strong influence over the phenotypic expression of the roots. According to Southey & Archer (1988), spatial root distribution is affected by soil environment and the root density is a function of the rootstock

cultivar. Others, like Morlat & Jacquet (1993), also ascribe a predominant role of soil characteristics in the root density. However, authors like Pongrácz (1983) give a higher importance to the genetic component.

The size and density of the root system is important in the plant's ability to explore the soil profile for water and nutrients, and determine the ultimate performance of the grapevine. Studies conducted in South Africa have shown how the size of the root system is reflected in the size of the canopy (Southey & Archer, 1988).

2.4.2.1 Effect of soil properties

2.4.2.1.1 Vertical distribution of the roots

The available soil volume is probably the single most important factor influencing root depth (providing that there are no other restrictions, such as chemicals or a fluctuating water table), and the vine roots could penetrate over five metres into soil with an unrestricted depth (Seguin, 1972; Archer *et al.*, 1988; Smart *et al.*, 2006). According to Van Zyl (1988), a two-year-old vine had already colonised the full soil depth and from then on only increases the root density.

Rooting depths of less than 60 cm are not able to develop a root system capable of sustaining optimal vine productivity under dry-land conditions (Saayman & Van Huyssteen, 1983). This concurs with the findings of Smart *et al.* (2006), who found that only about 60% of the roots in deep fertile soils are found in the upper 60 cm, consequently the other 40 % may contribute substantially to vine productivity by means of increasing the absorption surface. A deep soil profile, with a quality root system, increases the buffer capacity of the grapevine against unfavourable environmental conditions (Archer & Hunter, 2005). Deep and extensive root systems are an apparent strategy to ensure maximal water extraction from the soil. When the soil conditions become limiting the ability to continue to develop deep roots is an advantage (Bacon, 2004). Sharp & Davies (1985) reported that the more common response to soil drying is that roots show enhanced geo-tropism, which can be related to an attempt by the plant to find water in deep horizons.

It has also been shown by Nagarajah (1987) that root distribution is influenced by soil texture. He found that coarsely textured soil promoted deeper and well spread roots throughout the soil profile than moderately coarse and fine soil. High bulk density, in heavy clay layers, limits root penetration downward (Van Huyssteen, 1988a).

Although roots can reach deeper soil layers, they normally proliferate in a zone in the soil that has been called the preferential zone by Champagnol (1984). This preferential zone can be modified, enlarged or reduced, by means of cultivation practices (Archer *et al.*, 1988).

2.4.2.1.2 Lateral spread of grapevine roots

Saayman & Van Huyssteen (1980) reported that root densities were relatively high at 1.5 m from the trunk. Van Zyl (1988) found that the lateral spread of the root system is dependent on the area that is moistened by the irrigation system (the bulb of the irrigation). However, the extension shape of the bulb of irrigation is dependent on soil properties (Southey & Archer, 1988). It was also shown by Archer and colleagues that the lateral spread is highly dependent

on vine spacing (Archer & Strauss, 1985; Archer *et al.*, 1988). Van Huyssteen (1988b) furthermore showed that lateral spread of the root system can be highly affected by mechanical compaction due to tractor movement in the vineyard rows, but Van Zyl (1988) found that lateral roots growing into the inter-row space remained alive and were able to extract water once it was again available.

2.4.2.2 The effect of the genetic material

The hypothesis of Swanepoel & Southey (1989) was that in a soil with minimum restrictions to root penetration, genetic differences would be fully expressed, and exert an important influence on root density and distribution. They found that expressing the utilisation of the available soil volume in terms of the number of fine roots per m², Berlanderi 13/5, 101.14 Mgt and 1103 Paulsen performed best, while poor utilisation was obtained with 140 Ruggeri, US 16-13-26 and US 12-6-8. Southey & Archer (1988), in a different locality, with different soil and dry-land conditions, reported the opposite: a high root density was found for 140 Ruggeri, while 1103 Paulsen was in the low density group of rootstocks. Southey & Archer (1988) argued that the root distribution is mainly determined by the soil properties and that differences in root density seem to be a function of the rootstock. Taking the different results obtained by these authors into account, it would seem that other factors may play a more significant role than the genetic expression.

Swanepoel & Southey (1989) also reported that a good root distribution did not necessarily imply a good utilisation of the available soil volume. In the case of rootstock US 16-13-26 they reported that it colonised the soil volume to its maximum depth, but had a low percentage of fine roots. The root system function, and its influences over the whole plant functioning, is related to the rooting density, and to the root type. Important root functions that determine the grapevine performance are water and nutrient uptake, hormonal production and storage. Even though most of the root system can function as an absorbing surface, the effectiveness of different root types may differ (Atkinson, 1980). Thin roots are mainly responsible for the uptake of minerals (Swanepoel & Southey, 1989) and for the production of cytokinins and abscisic acid (Richards, 1983; Matthysse & Scott, 1984). Thick roots are more closely associated to storage (Taiz & Zieger, 2002), and have also been reported to have a better regenerative ability than thin roots and thus a better response to root pruning (Van Huyssteen, 1988b). Thick roots and the other perennial parts (trunk, cordons) of the grapevine act as nutrient stores for nitrogen and carbohydrates (Conradie, 1980). This storage capacity plays an important role at the beginning of the following season, before the formation of new roots and growth of new leaves. The perennial parts also play a storage role during water stress, with an increase of sugar at the expense of the starch accumulated and movement of nitrogen from the leaves to the permanent parts of the vine (Ndung'u *et al.*, 1997).

Thin roots, because of the nature of their function, are extremely important for grapevine functioning. According to Van Zyl (1984), the effectiveness of the root system can be indicated by the rooting index (the number of thin roots of less than 2 mm diameter divided by the number of thick roots of more than 2 mm of diameter). A high ratio will define a better root system. The threshold defined by Archer & Hunter (2005) was 3, and a root system with a rooting index of more than 3 will have a better buffer capacity when confronted by heat waves or periods of drought than one with a ratio of less than 3. This is a desirable quality under South African

conditions. However, for the rooting index to be meaningful, must be complimented by other data, as the total number of thin and thick roots.

Other authors have pointed out that the angle of root penetration is determined by the genotype (Guillon, 1905, cited by Smart *et al.*, 2006). They argued that the angle of root penetration would explained the tendency of certain rootstocks to present deep or shallow root distributions. Other authors (Archer & Strauss, 1985; Archer *et al.*, 1988; Hunter, 1998) have shown that the rooting angle can be modified with planting density, and that a higher number of plants provoke a steeper angle of penetration resulting in a deeper root system. A closer planting density also coincidentally increased the root density.

It has also been found that the differences in root distribution and number are reflected in shoot growth and yield, as the rootstock that better colonised the available soil had higher vegetative growth than those that had poor root distribution (Swanepoel & Southey, 1989; Morlat & Jacquet, 1993). This concurred with the observations of Koundouras *et al.* (2008), who found that canopy growth was strongly controlled by the rootstock genotype and its influence on the water status of the scion. They concluded that a rootstock such as 1103Paulsen – a water-efficient rootstock – would perform better under limited water conditions, and that SO4 would be better adapted to fertile soils under a non-limiting water supply, as it stimulated more balanced vegetative growth.

According to Smart *et al.* (2006), the differences between the performance of rootstocks could thus be explained by root density, rather than rooting depth, and this agrees with the earlier observations by Southey & Archer (1988) and Morano & Kliewer (1994), who found that the rootstock with the highest total root number coincided with the largest pruning mass. Root density may be the key difference in rootstock performance in terms of scion growth, in addition to other subtle factors such as root longevity and age-dependent nutrient absorption (Volder *et al.*, 2005). Other factors that will play a role in the performance of determined rootstock/scion combinations are: different degree of root tolerance to soil limiting factors such as pH (Conradie, 1983), differences in the rate of nutrient uptake (Freeman, 1983) and the rootstock's drought resistance (Carbonneau, 1985).

Daulta & Chauhan (1980) suggested that the scion may have an influence on root density, depth and rooting preference zone, but this aspect has not been widely studied.

2.4.2.3 The effect of management techniques

The close relationship between the aerial part and the root system has been reported by many authors. According to Archer *et al.* (1988) a direct correlation ($r = 0.97$) exists between the size of the root system and above-ground vine performance. Therefore, it is not strange that any cultural practice that improves or affects root growth and/or functioning, will have an effect over the canopy and vice versa. In very broad terms, this is explained by the functioning of the root system in terms of absorption of water and nutrients and by the capacity of the canopy to provide the roots with the products of photosynthesis, and a necessary and complex feed-back regulation between above and below- ground organs.

Increased trellis system size, resulting in an increased exposed leaf area have been shown to promote increases in the root density (Van Zyl & Van Huysteen, 1980; Archer *et al.*, 1988).

Improvements in the canopy microclimate by the means of leaf removal have also been shown to increase the root density (Hunter & Le Roux, 1992; Hunter *et al.*, 1995).

In terms of root distribution a better root colonization is obtained by increasing the soil available by means of ploughing (Saayman, 1982). The use of organic material as mulch has been shown to have an incremental effect on root number in the top soil, while the same effect was found with black plastic mulch, probably correlated with an increase in temperature and higher humidity (Van Huyssteen & Weber, 1980; Van Huyssteen, 1988b). Improvements in root distribution have been achieved by the performance of soil preparation prior to planting (Van Huyssteen, 1988a; Myburgh *et al.*, 1996).

Soil water content also has an effect on root distribution. A concentration of roots has been found under the drippers when compared to micro-sprinkler, but no differences in the total amount of roots were reported (Van Zyl, 1988, Araujo *et al.*, 1995). The water regime and the application of moderate water constraint have been shown to have an effect over root growth. An increase in root growth was reported at 50% of plant available water (PAW) in the soil, but a decline at 25% PAW (Van Zyl, 1988).

Tillage affects the roots present in the upper 20 cm of the soil (Van Huyssteen, 1988b), as well as the presence of a permanent cover crop (high competition for moisture) and clean cultivation, because repeated tillage means constant root pruning and an increase in compaction (Van Huyssteen & Weber, 1980).

Conradie (1988) has shown that root growth is seriously impeded at a pH 4.1, and by liming the soil to pH values of 5.0 and 6.0 the root mass was increased by 11% and 32% respectively.

2.5 The root system-grapevine canopy interrelationship

2.5.1 Plant water status

The soil progressively undergoes a drying process due to water extraction by the roots. This action exerts a range of influences on the roots as the extraction of water becomes increasingly difficult (Bacon, 2004; Loveys *et al.* 2004). Under dry atmospheric conditions, the rate of transpiration is highly dependent upon the ability of the roots to extend towards water sources, and upon the water movement by diffusion to the roots (Monteith, 1995). The consequences of these changes are not only restricted to the roots, but they are soon reflected in the aerial parts, and stomatal closure through the action of ABA (abscisic acid) is a common response to a drying soil (Loveys *et al.*, 2004). ABA action is discussed in more detail in Section 2.6.

Water constraints exert a great influence on the qualitative and quantitative responses of the grapevine (Ojeda *et al.*, 2004; Deloire *et al.*, 2006), and there is a close relationship between environmental conditions, grapevine gas exchange, plant water status,, yield and wine composition (Zsófi *et al.*, 2009).

The effect of water deficit is intimately related to the vegetative stage of the plant. During pollen formation, mother cell meiosis can provoke serious pollen sterility, thus affecting the fecundation and development of fruit (Passioura, 2004). During floral development, this can also be extremely harmful to seed set through pollen sterility or the abortion of embryos (Saini &

Westgate, 2000). According to Zinselmeier *et al.* (1995), this can be prevented by the infusion of a sucrose solution that replaces the substrate from photosynthesis, and therefore the response is due to starvation.

Water deficit reduces shoot growth and leaf area expansion, but root growth may be sustained or increased under stress (Munns & Sharp, 1993; Bacon 2004), and increases in the root/shoot ratio seem to be a common response (Wilkinson, 2004; White, 2009). This is certainly related to the ability of the plant to search for water through the soil profile, particularly when water availability in the soil declines.

2.5.2 Vegetative response (grapevine vigour)

The relationship between root growth and aerial growth has been discussed. The natural rooting pattern of rootstocks is important in determining the above ground performance of the vine (Swanepoel & Southey, 1989) and, consequently, limitations to the root system usually reduce top growth (Van Huyssteen, 1988a).

The vegetative vigour is dependent on the availability of the primary resources needed to grow, the environmental conditions and the timing during the growing period in which those resources are available. The consequences of the agronomic fertility discussed previously are reflected in the vegetative growth (Champagnol, 1997). Rapid shoot growth takes place between budbreak and anthesis, when the shoot increases in length and weight (Dokoozlian & Kliewer, 1995), and any constraints or stress during this period thus will have an effect on shoot growth, e.g. water deficits.

Baeza *et al.* (2007) found that shoot rate and CO₂ assimilation rate were correlated with plant water potential in Cabernet Sauvignon, and that shoot growth was zero for a predawn measurement of 0.48 MPa. Tardieu & Davies (1992) found that predawn plant water potential was correlated with the water availability in the soil and the concentration of ABA in the xylem.

Fertile soils support vigorous vines that can continue growing while the grapes mature. Less vigorous vines grown on soils of restricted fertility, generally as a consequence of restrictions on water and/or nitrogen supply, have a growth rate that diminishes towards véraison. This different behaviour is associated with hormonal balances and the regulation takes place through the balance in the syntheses of cytokinins and abscisic acid in the roots (Smart *et al.*, 1985; Champagnol, 1997).

Improved water relations will stimulate the synthesis of cytokinins, and shoot and leaf growth: as a consequence canopies of well-irrigated vines normally have more fruit and leaves in the shade (Smart *et al.*, 1985). When water is abundant the synthesis of cytokinins is high. However, as the water diminishes, the root environment does not get enough moisture and the synthesis of cytokinins decreases accompanied by an increase in the synthesis of ABA by the roots and the adult leaves, provoking a decrease in the rate of vegetative growth (Champagnol, 1997). This hormonal balance is compared with berry ripening in Figure 2.2 (from Coombe, 2001).

At a certain stage in the development of the grapevine it is desirable that the hormonal balance evolves synchronically between the vegetative growth and fruit development, promoting the

latter and restricting the former. The main factor in the evolution of the hormonal balance throughout the vegetative cycle is water availability in the soil (Champagnol, 1997). In fertile soils in which the water constraint happens to come late, the maturation process takes place while the conditions are still favourable for vegetative growth (Champagnol, 1997).

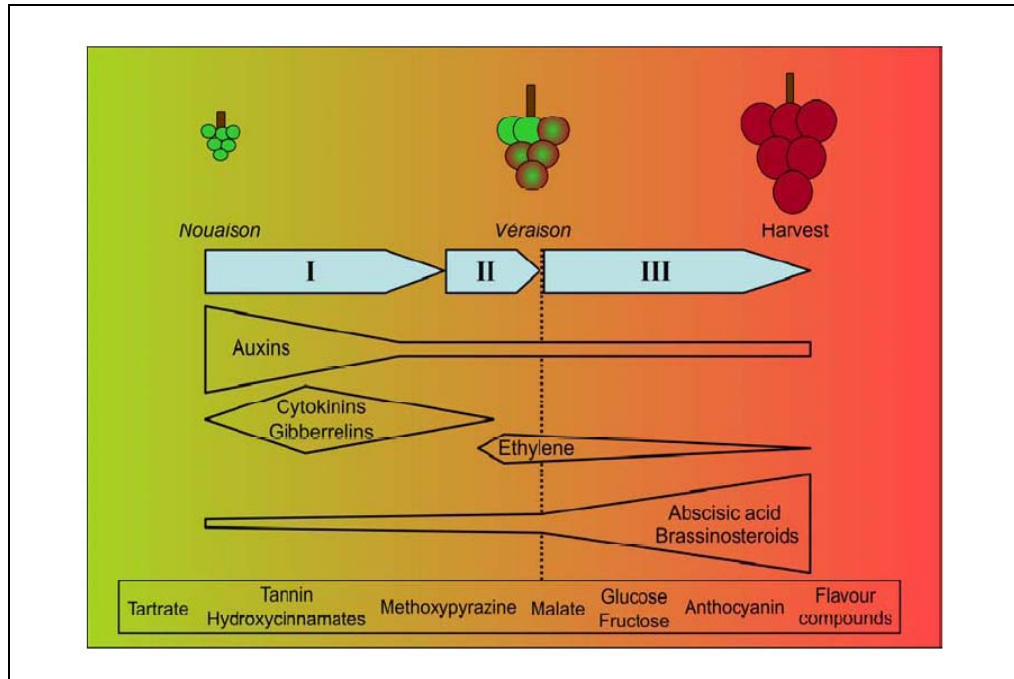


Figure 2.2: Hormonal regulation of grape berry development and ripening, and the hormonal content variation (Coombe, 2001).

Grapevines with high vigour tend to have numerous leaf layers and consequently dense canopies. In the case of mature Shiraz leaves, Smart *et al.* (1985) reported that only 9% of PAR is transmitted, while 6% is reflected. Therefore, in the presence of several leaf layers, the interior of the canopy will present leaves that are never in a position to be fully illuminated and are probably below the light compensation point, which has been determined to be between 15 and 30 $\mu\text{E}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. However, it is known that leaves can orient themselves, bending the petiole and lamina to fill canopy gaps to achieve maximum leaf illumination. This movement in dense canopies may not be enough to enable them to receive enough light (Gross & Chabot, 1979; Smart *et al.*, 1985; Smart, 1988; Cartechini & Pallioti, 1995).

Sunflecks are an important aspect of the light environment, as they can stimulate significant carbon assimilation in leaves growing in dense canopy shade (Dokoozlian & Kliewer, 1995).

The quantity of leaves or the size of the canopy in a determined space creates changes in the canopy microclimate, affecting vine physiology and thermal and phytochrome reactions (Mohr & Schopfer, 1995), as well as wind speed in the interior of the canopy. The degree of shading has been found to exert a major influence in reducing canopy yields and fruit quality (Smart, 1988).

2.5.3 Berry ripening

Most of the berry quality components considered as desirable for wine quality are synthesised *in situ*, as a product of a complex of interrelated metabolic pathways that are greatly influenced by phenological status. The root system influences the berry composition both directly and

indirectly – directly influencing berry physiology, and indirectly affecting canopy development, with consequences for bunch exposition.

2.5.3.1. Direct effect on berry physiology

Water constraints influence berry size affecting cell enlargement more than cellular division, depending on the intensity of the water constraint during the period between flowering and véraison (Ojeda *et al.*, 2001; Baeza *et al.*, 2007). Differences in the synthesis of phenolic compounds appear to be dependent upon the severity of the deficit and the stage at which it is applied (Ojeda *et al.*, 2002). Baeza *et al.* (2007), in another experiment involving water deficit, reported no differences in TSS (total soluble solids), total acidity or pH.

Increases in colour due to water deficit have been attributed to a change in the skin/pulp ratio in by many studies. However, Castellarin *et al.* (2007) found that water deficit in Cabernet Sauvignon triggers an earlier and greater expression of genes controlling the flux in the pathway of anthocyanin synthesis. They studied water constraint applied before and after véraison, finding that both increased anthocyanin accumulation and that early water stress accelerated the onset of anthocyanin synthesis.

2.5.3.2 Direct effect on canopy development; indirect effect on berry ripening

It is difficult to separate the effects of light and temperature on the berry, as they are intimately related. Treatments that increased fruit and leaf exposure to sunlight generally improved grape and wine composition, while sunlight-exposed fruits generally exhibited higher concentrations of sugars, anthocyanins and total phenolics, and lower levels of malic acid and potassium compared to fruits ripened in the canopy interior (Dokoozlian & Kliewer, 1995).

2.5.3.2.1 Effect on berry respiration

As most of the berry quality compounds of interest in wine quality are metabolised in the berry, berry respiration is a key process in the ripening process and, in the absence of oxygen, the berry would not ripen (Galet, 2000). The energy released by respiration is required to activate the chemical changes in the berry's constituents, namely enzymes, colour, aromas and flavours, tartaric and malic acids, tannins, glucosides and vitamins (Winkler, 1974). The dynamic of respiration is highly dependent on the temperature: an increase in temperature accelerates the respiration rate and a berry exposed to sunlight will have a higher temperature than one in the shade (Galet, 2000).

There are also cultivar differences, and some cool climate cultivars, such as Chasselas, Pinot noir and Riesling, have been reported to degrade malic acid more easily during respiration. This is an advantage in cool climates, but in warm regions gives rise to wines with insufficient acidity (Galet, 2000).

Hunter & Bonnardot (2004) argued that the temperature range from 25 to 30°C has a positive effect on respiration and that at temperatures over 30°C respiration will be too high.

2.5.3.2.2 Effect over the aromatic compounds

Carotenoids are precursors of aromatic compounds and their levels are dependent on light. The levels of the major carotenoids, β -carotene, lutein, neoxanthin-neochrome and flavoxanthin, decrease in the grapes between véraison and maturity (Marais, 1992). Others, like the level of C₁₃-norisoprenoids, seem to increase with sunlight exposure in the berry as products of photo-oxidation.

Deloire (2007) indicates the importance of cold nights (IH) (fresh nights index: $12^{\circ}\text{C} \leq \text{IH} \leq 14^{\circ}\text{C}$) as a favourable influence on aromatic expression. Hunter & Bonnardot (2004) define the optimum ranges for grape flavour development and maintenance as the following: a range of 20 to 25°C for the diurnal temperature between 06:00 and 18:00, and a night temperature range of 10 to 15°C between 18:00 and 06:00. These figures are similar to those suggested by other authors. For the good development of flavour/aroma, Jackson & Lombard (1993) proposed night temperatures of between 5 and 15°C, or mean temperatures of 9°C to 20°C, during stage III of ripening, while saying that there would be a negative influence at night temperatures above 15°C, or mean temperatures above 20°C. Higher temperatures accelerate the degradation of aromatic compounds, and lower temperatures could affect the metabolic pathway of its synthesis.

2.5.3.2.3 Effect on colour development

According to Kliewer & Torres (1972) temperature is the most important climatic factor influencing the degree of colouration. They found that the skins of Cardinal, Pinot noir and Tokay grapes ripened at a day temperature of 15°C had anthocyanin levels two to four times greater than those ripened at a day temperature of 35°C when the night temperature was the same. A day or night temperature higher than 35°C affected the amount of anthocyanins, apparently increasing their degradation, and a temperature lower than 10°C seemed to slow down their synthesis. The optimum for good anthocyanin synthesis appears to be between 20 and 25°C.

Kliewer & Torres (1972) suggested a strong thermoperiodicity effect on fruit colouration. They observed that differences between day and night temperatures of greater than 10°C generally depress fruit colouration. Colouration was always less at temperatures of 35/15°C or 35/10°C than at 35/25°C or 35/30°C. These results correspond with those obtained by Kobayoshi *et al.* (1967, cited by Kliewer & Torres, 1972), who found that the growth and colouration of 'Delaware' grapes was optimum when day/night temperatures were about equal, e.g. 20/20°C or 25/25°C. The reason for these as pointed out by Gladstone (1992) it may be in the optimal temperature for the enzymatic activity in the anthocyanins pathway, process that probably continue during the night.

A study carried out by Yamane *et al.* (2006) found that stage III (one to three weeks after the onset of colouring) is the most sensitive for anthocyanin accumulation in the berry skins of Aki Queen. A low temperature treatment (20°C) during stage III significantly enhanced colouring, and the concentration of ABA was 1.6 times higher than at 30°C. This resulted in the high expression of the gene VvmybA1 that participates in the synthesis of anthocyanins.

Spayd *et al.* (2002) found that excessive fruit temperatures reduced anthocyanin concentrations in sun-exposed grape berries. Haselgrove *et al.* (2000) found that the berries of Shiraz exposed to high levels of ambient light developed higher levels of quercetin-3-glucosides and reduced production of malvidin anthocyanins compared to berries developed in shaded bunches. This may be related to the phenolic compound pathway, in which light and temperature promote flux in the direction of some compounds.

2.6 The grapevine needs to integrate the above- and below-ground environments

The maintenance of the plant's hydraulic balance is a very complicated dynamic process and requires that the plant constantly integrates all the diverse environmental factors in a metabolic response.

The major viticultural areas of the world are located in hot and dry climates (e.g. Mediterranean), where high light, high temperatures and a high vapour pressure deficit (VPD) often co-occur with low soil water content (Costa *et al.*, 2007). These conditions can provoke high water losses because CO₂ and H₂O share the same diffusion pathway, but the diffusion gradient that drives water loss is about 50 times larger than that for CO₂ uptake (Chaves *et al.*, 2007). To be able to balance water loss with CO₂ uptake, the control of stomatal opening and closure is a key factor for plant survival (Jones, 2004; Loveys *et al.*, 2004; Wilkinson, 2004; Buckley, 2005). The modulation of the stomatal pore aperture and closure is the commonly observed plant response to a reduction in water availability in order to prevent potential desiccation rather than high temperature stress (it has been reported that a non-transpiring leaf could be 20°C above the air temperature (Loveys *et al.*, 2004). Stomata are controlled by a pair of guard cells and there are thousands of them per leaf (Loveys *et al.*, 2004; Wilkinson, 2004).

Plant growth and functioning are regulated in accordance with the control of stomatal behaviour. However, as the stomata close there is a non-linear correlation between the decrease in water loss that is achieved and the decrease in carbon assimilation that unavoidably occurs (Davies *et al.*, 2002; Wilkinson, 2004).

The plant has developed a signalling mechanism in order to balance itself as the soil dries out in the rhizosphere, or when the water demand from the atmosphere is higher than the water uptake/supply by the roots. The ability to respond dynamically to changes in available soil water usually improves the plant's long-term water-use efficiency, thus having an impact on growth and/or survival (Augé & Moore, 2002). These signals may be hydraulic (reduction in water transport through the plant as soil dries out) or local and long distance chemical signalling (Loveys *et al.*, 2004) and, at any moment, all of these factors are integrated to deliver a particular stomatal aperture (Bacon, 2004).

2.6.1 The role of abscisic acid (ABA) in coupling water supply to atmospheric demand

We have known for many years that excessive irrigation promotes vegetative growth in grapevines, especially with the availability of water when the peak of vegetative growth occurs (Dry & Loveys 1999, 2000a; Behboudian & Sing, 2001; Poni *et al.*, 2009).

Although in many situations the water supply may not be optimum, ABA plays an essential role in maintaining the hydraulic balance of the grapevine. The ABA concentration fluctuates

dramatically in specific tissues in response to the changing environment, whether or not it is “stressful”. It interacts with auxin, cytokinin, gibberellins and ethylene (Champagnol 1997; Wilkinson, 2004), usually as an antagonist, to influence many aspects of the response to stress. ABA is transported around the plant via both the xylem and phloem tissue. It induces reductions in leaf and stem growth rates, preventing the increase in the transpirable surface (Bacon *et al.*, 1998; Wilkinson & Davies, 2002), and also accelerates the senescence of leaves, while ethylene induces their abscission (Zacarias & Reid, 1990). It has also been reported that there is a high correlation between ABA concentration in the guard cell and the aperture of the stomata (Zhang & Outlaw, 2001).

2.6.2 High atmospheric vapour pressure deficit (VPD) related to stomatal regulation throughout the day

The environment surrounding the grapevine leaf can impose a high water demand. Even if the soil water content is high, the speed of water uptake and transport may not be sufficient to keep up a continuous transpiration stream. As a response to the daily fluctuation of VPD in the atmosphere, stomatal conductance can vary substantially over short periods of time due to climatic variables that have important effects on the sensitivity of the guard cells to ABA. Significant diurnal changes take place in leaf ABA and stomatal conductance in the grapevine (Loveys, 1984).

The stomata respond directly to changes in the evaporative demand, rather than to changes in the relative humidity (Costa *et al.*, 2007). The increase in VPD related to the increase in the temperature around the leaf and the presence of wind would, according to Trejo *et al.* (1995), accelerate the speed of the transpiration stream and therefore the delivery rate (flux) of ABA to the leaves. Similarly, Zhang & Outlaw (2001) demonstrated that VPD induced local increases in ABA around the guard cells. Cornic & Ghashghaie (1991) found that limitations in stomatal opening imposed by high concentrations of ABA can be rapidly and completely reversed by lowering the leaf temperature.

2.6.3 Root-shoot signalling as the soil dries

There are many reports that stomatal conductance (g_s) diminishes in drying soil, even when the shoot are hydrated adequately, and that some plants will regulate water status independently of hydraulic signals as the soil dries (Davies *et al.*, 1994; Augé & Moore, 2002; Davies *et al.*, 2002; Bacon, 2004; Wilkinson, 2004). Augé & Moore (2002) have also argued that the non-hydraulic inhibition of stomatal opening can be substantial, with a decline in g_s of up to 50%.

The increase in the xylem pH provokes the closure of the stomata via an ABA-based mechanism, as described by Schurr *et al.* (1992) and Davies *et al.* (2002), in terms of which the stomata’s sensitivity to xylem ABA increases with xylem pH. This subtle change in the ionic status of the xylem allows the plant to respond to small changes in soil water or nutrient availability, and is a very effective signalling mechanism without the need for the synthesis of extra hormones (Davies *et al.*, 2002).

The importance of chemical signalling in the absence of a shoot water deficit for the control of leaf and/or fruit growth has been demonstrated by the use of partial rootzone drying (PRD) (Loveys, 1991; Dry & Loveys, 1999, 2000a, 2000b; Stoll *et al.*, 2000; Loveys *et al.*, 2004) and

regulated deficit irrigation (RDI) (Goodwin & Boland, 2002; McCarthy *et al.*, 2002). Both of these irrigation strategies target a controlled application of water to the roots with the aim of modifying xylem/apoplastic pH, causing a decrease in stomatal conductance (Loveys *et al.*, 2004; Costa *et al.*, 2007).

2.6.4 Cultivar effect in the control of plant water status

The grapevine in particular presents a wide range of physiological responses between genotypes in the control of the plant water status (Schultz, 1996, 2003; Rogiers *et al.*, 2009).

Great differences have been reported for different grapevine cultivars in the control of stomatal conductance, and therefore in the maintenance of leaf water status. Rogiers *et al.* (2009) showed that Semillon would continue transpiring during the night, with values for stomatal conductance and transpiration up to four times higher than those for other varieties. Schultz (1996, 2003) classified Grenache (Mediterranean origin) as “drought avoiding”, and Shiraz (Mesic origin) as “drought tolerant”. In an ecological classification done by Jones (1980) he separated plants into “pessimists” and “optimists”. “Pessimists” are the *drought avoiding* or *isohydric* plants, showing strong control over the transpiration rate and a similar water potential between well-watered and drought-experiencing plants. On the other hand, “optimists” are the *drought tolerant* or *anisohydric* plants, which typically exhibit less stomatal control and consequently experience large fluctuations in leaf water potential during the day due to transpiration (Tardieu & Simonneau, 1998; Franks *et al.*, 2007).

Pessimists modify their physiology to conserve and control their demand for resources, whereas optimists use all their resources hoping that more will arrive (Schultz, 2003). According to Rogiers *et al.* (2009), Semillon can be classified as anisohydric due to its large stomatal conductance and the consequent significant water losses during the day and night.

Schultz (1996) reported that the optimist cultivar (Shiraz) achieved crop maturation although it exploited all the soil water, but also pointed out that there was a narrow line between production and death. The pessimistic cultivar, Grenache, failed to mature the crop, probably due to severe carbon starvation as a result of stomatal closure. This also represents a risk; the stomatal closure avoids the gas exchange and may deprive Grenache of electron acceptors provoking photoinhibition (Schultz, 1996; Chaves *et al.*, 2004).

Hydraulic conductance by roots was also found to affect drought tolerance in grapes (Vandeleur *et al.*, 2009). Vandeleur *et al.* (2009) reported physiological and anatomical differences in water transport across roots between Chardonnay and Grenache grown on own roots when they are faced with water stress: the hydraulic conductivity of the root cortex cells doubles in Chardonnay but remains unchanged in Grenache. This is related to different levels of aquaporin activity in the roots, where the expression of VvPIP1,1 in Chardonnay induces three-fold higher activity of VvPIP2,2, but is absent in Grenache (Vandeleur *et al.*, 2009). A summary of the concept is presented in table 2.1

Table 2.1 Summary of concepts use for different strategies of plant water use in grapevine cultivars.

Concepts		Definition (adapted from Jones, 1980; Tardieu & Simonneau, 1998; Schultz, 1996, 2003; Franks <i>et al.</i> , 2007)	Grapevine cultivar examples
Isohydic	Pessimistic (Jones, 1980)	Drought avoiding They exert a strong control over the transpiration rate. They modify their physiology to conserve water at the expense of having lower photosynthesis and risking increase in the internal temperatures, thereby posing a threat to plant metabolism.	- Grenache (Schultz, 1996).
Anisohydric	Optimistic (Jones 1980)	Drought tolerant They typically exhibit less stomatal control and consequently experience large fluctuations in leaf water potential during the day due to transpiration. They use all their resources, hoping that more will arrive.	- Shiraz (Schultz, 1996) - Semillon (Rogiers <i>et al.</i> , 2009)

2.7 Conclusions

A large influence is exerted by temperature and VPD on plant functioning. Temperature affects enzymatic activity, and therefore all of the plant's physiology, and the VPD imposes a constant loss of water by means of transpiration. The transpiration rate depends on climatic factors, such as solar radiation, temperature, wind and the humidity of the air. In areas with high temperatures and dry air, the water vapour deficit in the air surrounding the grapevine is higher, which provokes a higher evapotranspiration potential and eventually a higher loss of water by the plant. In this regard the size of the canopy plays an extremely important role, as it is the transpiring surface.

The grapevine needs to continuously integrate the influence of the rhizosphere and the troposphere in order to match the constant changes in those environments to a metabolic response. A short-term response is the daily regulation of stomatal functioning (closure/aperture), and a long-term response is the plant size (root and canopy). These regulations are mainly root-sourced, hence the root system plays a significant role in determining the growth and quality potential of the grapevine.

The plant's water deficit is a result of the process of soil drying. A drying soil will modify all aspects of a plant's growth, development, functioning and shoot growth, which will be restricted as the soil around the root dries. Under these conditions, soil properties play a fundamental role in the water supply, determining the development of the root system and the balance in the synthesis of hormones (cytokinins/ABA). The concept of hydraulic fertility effectively expresses how the availability of water greatly determines root functioning, vegetative growth and, consequently, canopy size.

Furthermore, berry composition is affected, directly and indirectly, by the root system and water constraints related to berry phenology. In a simplistic explanation of very complex processes, the direct effect of the water deficit is manifested in the size of the berry and in the influence of ABA on anthocyanin synthesis; the indirect effect on canopy size is therefore found in the exposure of the berry to light and temperature. Light exposure plays a role in the aromatic compounds and the anthocyanin pathway; and temperature plays a role in berry respiration, and the synthesis or degradation of aromatic compounds, colour and acids. Depending on each pathway, synthesis can continue for 24 hours if substrate is available and the temperature favourable for enzymatic activity. However, excessive temperatures may inhibit enzymes and accelerate the loss of volatile compounds, while low temperatures can inhibit metabolism and retard physiological ripeness.

Very relevant are the great differences that have been reported between cultivars in physiological terms: stomatal regulation, root density, root hydraulic conductivity, temperature ranges optimal for photosynthesis and berry physiology. These are probably the result of “human selection” over centuries in order to reproduce desirable characteristics in the grapevine and wine under determined climatic conditions, as many of these adaptations seem to be well-suited to the local environmental conditions under which those cultivars have traditionally been grown.

In warm and dry viticultural areas, there is an important relationship between tropospheric influences, the hydraulic behaviour of the cultivar and the hydraulic fertility of the soil for grapevine functioning, canopy development and, ultimately, berry composition. The root system plays a key role in integrating these factors, determining canopy growth and stomatal functioning by means of hormonal balance. The distribution of the root system is determined by the soil properties, and the root density by soil properties and the genetic potential of the rootstock.

The ability of a determined root system to provide enough water is determined by the water retention properties of the soil and is a function of the capacity of the roots to explore the soil profile. This is a key property in warm, dry areas, and is related to the scion’s degree of stomatal control, which, in times of high canopy growth rates, will determine the canopy size and subsequently influence berry composition.

2.8 References

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Chapter 3

Research results

**Diurnal water status of Chardonnay and Shiraz:
a comparison**

Chapter 3: Diurnal water status of Chardonnay and Shiraz: a comparison

3.1 Acknowledgements

To Mr Albert Strever for his help with the data analyses.

This research was financially supported by Winetech and THRIP, under grant number TP2008061300003. Any opinions, findings and conclusions expressed in this publication are those of the authors and do not necessarily reflect the views of these organisations.

3.2 Abstract

The water status and stomatal conductance of four cultivars (Shiraz, Grenache, Pinot noir and Chardonnay), all grafted onto Richter 99, were studied. Diurnal cycles of water status and stomatal conductance, from 7:00 to 19:00, were followed for a single day in March 2009. Two cultivars were chosen as references for two different strategies of water use, according to the current literature: Shiraz as a cultivar that uses an “optimistic” strategy, and Grenache as a cultivar that uses a “pessimistic” strategy. The four cultivars studied were planted in a single vineyard, which was not irrigated and was planted in a relatively spatially homogeneous soil. The measurements were done at the end of the season just before harvest. The results showed that Shiraz was subjected to water stress conditions, losing leaves and with symptoms of berry shrivelling. The other three cultivars had much better canopy health and no symptoms of berry shrivelling were observed. For Shiraz, minimum values for stem water potential (Ψ_s) of -2.0 MPa were reached at 15:00, and maximum stomatal conductance values of only 30 mmol H₂O/m²/s were measured at 13:00, confirming the water stress status of the grapevine. For Grenache, the minimum values for Ψ_s of -1.5 MPa were recorded at 13:00, which is also considered to be a water stress situation. For this cultivar, higher stomatal conductance values of 70 mmol H₂O/m²/s were recorded at 11:00. For Chardonnay and Pinot noir, similar values to those of Grenache were recorded, with Ψ_s values around -1.5 Mpa and stomatal conductance values around 80 and 70 mmol H₂O/m²/s respectively. Based on canopy observations and comparison of the curves of stem water potential (Ψ_s) and stomatal conductance (g_s), it seems that Pinot noir and Chardonnay are closer to the water-use behaviour of Grenache noir, which is known as a “pessimistic” cultivar, than to Shiraz, which is an “optimistic” cultivar. This, however, deserves further study over a full season.

Key words: Water potential, stomatal conductance, Chardonnay, Pinot noir, Shiraz, Grenache.

3.3 Introduction

In the whole of South Africa, the mean annual rainfall is less than 500 mm (Schulze, 1979). It is estimated that 8.6% of the rainfall is useable runoff, which is the lowest proportion worldwide (Davies and Day, 1998). The relatively small number of both subterranean resources and substantially sized rivers make South Africa (SA) fall under the 30% of countries globally that have the least water (Botha, 2010). Water scarcity is certainly one of “South African Agriculture’s biggest threats in years to come” (Botha, 2010).

In terms of climatic changes it has been reported by Bonnardot and Carey (2008) that, in the last 30 to 40 years, the annual maximum temperature in Stellenbosch has increased by 1.7°C, in Paarl by 1.1°C and in Worcester by 1.0°C. This increase in temperature implies an increase in evapotranspiration, which means a major water demand by the atmosphere and consequently more pressure on the plant water status and its regulatory system.

The grapevine presents a wide range of physiological responses to water scarcity between cultivars. In this challenging scenario, the most important aspect is the way in which the cultivars accommodate the supply of water provided to the root system by the soil to the demand for water imposed on the canopy by the atmosphere (Monteith, 1993). These responses are especially diverse in their drought tolerance, traversing the isohydric–aniso-hydric spectrum (Table 2.1) (Schultz, 2003; Rogiers *et al.*, 2009). Great differences have been reported for different grapevine cultivars in the control of stomatal conductance, and therefore in the maintenance of leaf water status (Schultz 1996, 2003; Rogiers *et al.*, 2009), but also in the hydraulic conductance of the roots (Vandeleur *et al.*, 2009) and in the changes in the osmotic potential at the turgor loss point (Park, 2001). Rogiers *et al.* (2009) showed that Semillon continues transpiring during the night, resulting in night values for stomatal conductance and transpiration up to four times higher than those for other varieties. This has consequences for the recovery of the water status, especially during warm nights, and, as a result, leads to more negative predawn leaf water potential values (Donovan *et al.*, 2001). Jones (1980) separated plants into “pessimists” and “optimists” in terms of ecological classification. “Pessimists” are *isohydric* plants. “Optimists”, on the other hand, are *aniso-hydric* plants (Table 2.1).

The aim of this study was to compare four cultivars. Two of them are well known for their differences in transpiration strategy (namely Shiraz and Grenache (Schultz 1996, 2003)) and were used here as reference cultivars. The other two cultivars, Chardonnay and Pinot noir, were studied to understand their behaviour in terms of water use and to try to classify them as “optimistic” or “pessimistic” cultivars.

3.4 Materials and methods

3.4.1 Study area

The study area was located at the Welgevallen cultivar collection vineyard of the University of Stellenbosch (Stellenbosch, South Africa). The planting distance is 1.40 x 2.40 m, and the grapevines are trained on a vertical shoot positioned (VSP) trellis system. The row orientation is east-west, the soil is Dundee according to the South African soil classification (Soil Classification Working Group, 1991). (Ellis, F; University of Stellenbosch; Personal communication, 2010). The Dundee form has an orthic A and a stratified alluvium B horizon (Soil Classification Working Group, 1991) and is a fluvi-cumulic soil (Fey *et al.*, 2010). The soil is considered to be spatially homogeneous across the vineyard, and no irrigation was applied.

3.4.2 Plot selection

Four plots with four different cultivars were selected. Each plot had three grapevines. The cultivars selected were *Vitis vinifera* L. cv. Shiraz noir, Grenache noir, Pinot noir and Chardonnay blanc. They were all grafted onto Richter 99 (*V. Berlandieri* x *V. rupestris*).

3.4.3 Grapevine water status

The plant water status was measured every two hours, in a 12-hour cycle from 07:00 to 19:00 in March, 2009. Three fully mature, exposed and healthy leaves from a primary shoot, located between nodes 4 and 7, were used for the measurements. The measured leaves were covered with tin foil and plastic bags for 30 min. before excision and measurement with a Scholander-type pressure chamber (stem water potential method according to Choné *et al.*, 2001).

3.4.4 Stomatal conductance

A leaf porometer manufactured by Decagon Devices was used to perform the stomatal conductance measurements on three fully mature, exposed and healthy leaves from a primary shoot, located between nodes 4 and 7 at the same time as the leaf water potential.

3.4.5 Experimental layout

Three vines each of Grenache, Shiraz, Pinot noir and Chardonnay (*Vitis vinifera* L.) were used. Every two hours, three leaves (i.e. one leaf per vine) were sampled for water status measurements and for stomatal conductance. A mixed-model repeated measures Anova analysis was applied to compare water status and stomatal conductance between the cultivars.

3.5 Results and discussion

3.5.1 Canopy morphological assessment

Towards the end of the season, the canopy of Shiraz showed extreme stress symptoms, resulting in yellowing and abscission of leaves, together with an extreme shrinking of berries. At the same time, the canopies of Pinot noir, Chardonnay and Grenache appeared to be much healthier. These cultivars showed a greater number of leaves, which kept the grape bunches shaded, none of which revealed signs of berry shrivelling, and the leaves were pale to yellowish green.

3.5.2 Vine water status

Shiraz was under stress conditions throughout the day. The measurements at 11:00 showed an average stem water potential (Ψ_s) of -1.5 MPa, which represents a stressed condition (Deloire *et al.*, 2004). From 15:00 to 17:00, an average value of -2.0 MPa (Ψ_s) was reached. At dusk the average value was -1.5 MPa, which means that the plant recovered slowly towards the end of the day, when the atmospheric demand decreased (Figure 3.1).

Pinot noir, Chardonnay and Grenache followed a similar evolution of water status through the day; the lowest values were reached between 13:00 and 15:00, with an average of -1.5 MPa (Ψ_s). The three cultivars finished the day with a water status of about -0.5 MPa (Ψ_s), which was almost equal to the early morning measurements (i.e. those done at 07:00). This means that these plants managed to recover much faster and equilibrated with the available water once the atmospheric demand decreased.

3.5.3 Vine stomatal conductance

Differences in the stomatal conductance (g_s) were found between the cultivars. Shiraz had the lowest g_s curve of all, reaching its maximum of only 30 mmol H₂O/m²/s at around 11:00 (average of the three measurements). The highest conductivity was registered in Chardonnay, with 80 mmol H₂O/m²/s, followed by Pinot noir and Grenache, with a peak of 70 mmol H₂O/m²/s each (Figure 3.1).

Flexas *et al.* (2002), as well as Galmés *et al.* (2007), suggested thresholds regarding the g_s in grapevines. These thresholds are as follows: for a well-watered plant a g_s of about 250 mmol H₂O /m²/s, for a plant under moderate water stress a g_s of about 150 mmol H₂O/m²/s, and for a plant under severe water stress a g_s of about 50 mmol H₂O/m²/s. According to these thresholds, the stomatal conductivity of Shiraz was much lower than the severe water stress value. Grenache, Chardonnay and Pinot noir had a slightly higher stomatal conductivity, but were still in a situation of moderate to severe water stress.

The increase in conductance in Grenache reached a peak at 11:00, at the same time that -1.0 Mpa (Ψ_s) was reached. The same was true for Chardonnay and Pinot noir. In Chardonnay and Pinot noir the stomatal conductivity stabilized from 11:00 to 15:00 around 70 mmol/m²/s. In the Grenache, the stomatal conductivity decreased after 11:00 together with the curve for water status, reaching -0.55 MPa (Ψ_s) at around 17:00, which was almost the same reading as early in the morning. This is a very fast recovery compared with the other cultivars, but it must be taken into account that the location of this plot in the experimental vineyard was closer to a row of trees. As light diminishes, so does the plant's need for CO₂. This may have also had an effect on the stomatal conductivity, through closure of the stomatal pores and favouring of the re-establishment of the water potential compared to Chardonnay and Pinot noir. Despite this influence, after a whole season without irrigation, Grenache managed to maintain a water status that allowed it to maintain a healthy canopy without signs of high water stress, and to ripen the grapes satisfactorily without sign of berry shrivelling (as did Chardonnay and Pinot noir). This was in contrast with the Shiraz grapevines.

An inflection point was found in the curve of g_s when the stem water potential reached values of -1.0 MPa (Ψ_s) for Chardonnay, Pinot noir and Grenache, but the inflection point for Shiraz was associated with a much lower stem water potential value, ca. -1.6 Mpa (Ψ_s). An inflection point in the curve of g_s being associated with stem water potential values of -1.0 Mpa (Ψ_s) was also observed in the study of Park (2001). This point is thus shared by cultivars such as Riesling, Chardonnay, Grenache and Pinot noir and may refer to a threshold where the stomatal conductivity is highly affected by plant water status. This could have consequences for the availability of CO₂, and for photosynthesis. Shiraz would appear not to have the same sensitivity. The stomatal conductance may also be influenced by differences in canopy structure (i.e. spatial distribution and size of leaves).

Opposite to what appears to be the case in this study, Vandeleur *et al.* (2009) argued that Chardonnay is an anisohydric cultivar. They showed that Chardonnay was able to increase the water absorption by its root system (Chardonnay on own roots) up to three-fold in response to water stress compared to Grenache. This was associated with the expression of different aquaporins that were not expressed in Grenache. This occurs on a diurnal basis and, according to Vandeleur *et al.* (2009), this aquaporin activity accounts for Chardonnay being an anisohydric

cultivar and Grenache being isohydric. In this regard, the optimistic-pessimistic concept (or iso-anisohydric range) seems to be complex, and it is discussed from different angles across the literature. It has been related to stomatal control, but also to root hydraulic conductivity (Schultz 1996, 2003; Rogiers *et al.*, 2009; Vandeleur *et al.*, 2009). The role of roots in plant water status is unquestionable, but their role in stomatal control is different from their role in hydraulic conductance. The roots' function in controlling stomatal aperture is related to root-to-shoot signalling, the synthesis of phytohormones (i.e. abscisic acid) (Loveys, 1984, 1991; Tardieu and Simonneau, 1998; Dry and Loveys, 1999; Stoll *et al.*, 2000), the uptake of ions (i.e. potassium) (Holbrook *et al.* 2002), and its ability to influence the xylem pH as a response of a drying soil influencing ABA availability (Davis *et al.*, 2002; Wilkinson, 2004). In terms of their hydraulic conductance, an extremely important role is played by the activities of the aquaporins, and their enhanced expression when the roots are confronted by water stress (Galmés *et al.*, 2007; Vandeleur *et al.*, 2009). This should perhaps better be described as drought resistance rather than being part of iso-anisohydric strategies. As has been defined by Carbonneau (1985), drought resistance, from an agronomical point of view, is considered as the ability of the root system to extract maximum water from the soil in order to maintain the photosynthetic system, allowing good crop production under stress. This is not related to the ecological concept of water saving as a survival strategy (i.e. xerophytes).

The rootstock of the four cultivars in this study was Richter 99, which allowed a relevant comparison. The differences found in this study between the cultivars can, therefore, be ascribed to the control of stomatal function (related to plant physiology), and combined with differences in plant vegetative growth and leaf morpho-anatomy (Chaves *et al.*, 2010 and references therein) that diverge between cultivars, more than to a difference in root functioning.

A mixed-model repeated measure Anova analysis was carried out in order to see whether there were differences between the cultivars in the evolution of water status and stomatal conductivity during the day (Figure 3.1). In both parameters, significant differences, reflected in low p values, were found. The Shiraz curve marks these differences in both cases. The other cultivars are grouped together as they have similar values.

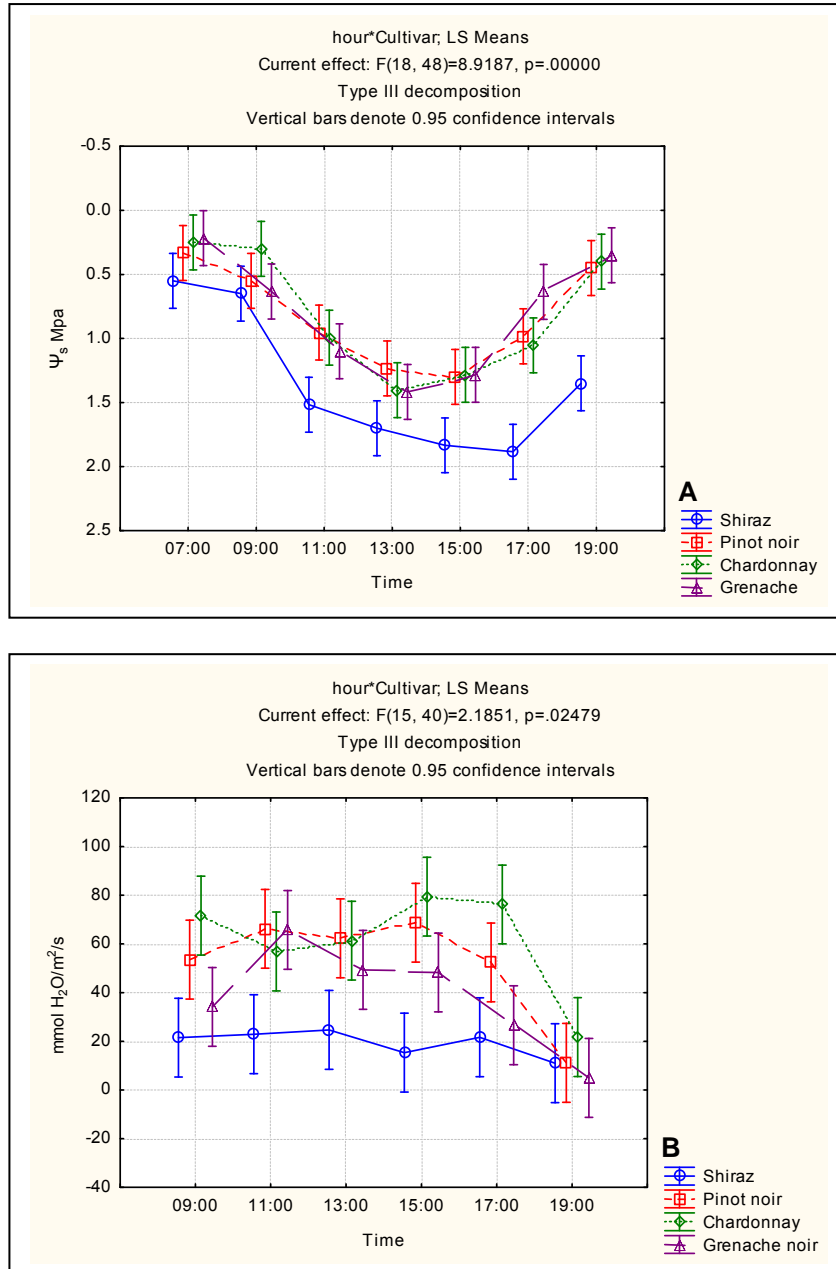


Figure 3.1 A & B. A mixed-model repeated measures ANOVA analysis comparing the evolution of the stem water potential (A) and stomatal conductance (B) of the four cultivars throughout the day on March 2009. The low p values show significant differences between the Shiraz curve and the curve for the other cultivars.

This analysis shows that Chardonnay and Pinot noir appear to be closer in behaviour to Grenache than to Shiraz in terms of water use. At the end of the season they showed very similar, healthy canopy conditions, with good recovery on the initial water status towards the end of the day, and with intact berries. In terms of stomatal conductance, Shiraz would have been expected to show a higher g_s compared to Grenache noir due to its optimistic behaviour, and probably that was the case throughout the season, but at the time the measurements were done (i.e. at the end of the season), the results can be assumed to reflect the consequences of optimistic water use without additional water resources being made available. The low stomatal conductivity found in this study can thus hypothetically be explained by an earlier depletion of

the soil water content by the Shiraz plants. The Shiraz plants were in an extreme water stress situation that was visually obvious, and that was a consequence of the reduction of water from the soil profile due to its optimistic behaviour, while Grenache, Chardonnay and Pinot appeared to be in a healthier situation with regards to their water status, which we assume to have been as a result of “pessimistic” behaviour resulting in more careful control of water resources throughout the season.

3.6 Conclusions

The comparison between four cultivars under dry-land conditions at the end of the 2009 season showed that Chardonnay and Pinot noir have some mechanisms that allow them to thrive under water stress conditions in a better way compared to Shiraz.

All of these cultivars were grafted onto R99, thus the differences in water use can be assumed to be related to different strategies of stomatal control, or to the way the plant architecture or leaf anatomy interferes with the movement of air adjacent to the stomatal cavities, or perhaps to a combination of these factors.

The similarities in the curves of stem water potential and stomatal conductance between Chardonnay, Pinot noir and Grenache suggest that Chardonnay and Pinot noir may have an ecological response that is closer to the isohydric plants, also known as “pessimistic”, than to the anisohydric or “optimistic” plants. This deserves further research, with measurements performed repeatedly through a season. This is an exciting field of research and much can still be done to obtain more conclusive results with these cultivars, and in relation to interactions with different rootstocks and different soil types.

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Chapter 4

Research results

The influence of soil properties in Robertson on the development of 101.14 Mgt roots and the consequences thereof for canopy development and berry growth of Chardonnay and Shiraz

The influence of soil properties in Robertson on the development of 101.14 Mgt roots and the consequences thereof for canopy development and berry growth of Chardonnay and Shiraz

4.1 Acknowledgements

This research was supported financially by Winetech and THRIP, under grant number TP2008061300003. Any opinions, findings and conclusions expressed in this publication are those of the authors and do not necessarily reflect the views of these organisations.

Thanks are due to Mr Albert Cloete, Mr Philip Jonker, Mr LA van Zyl, Mr Briaan Stipp, Mr David Rossouw, Mr Peter de Wet, Mr Hannes Erasmus and Ms Erna Blancquaert, for their valuable contributions to the research, and to Ms CR van Zyl and Ms Zelmari Coetzee, for their technical assistance.

4.2 Abstract

A study of four plots each of Chardonnay/101.14 Mgt and Shiraz/101.14 Mgt was carried out in eight commercial vineyards near Robertson, South Africa during 2009. These plots had different soil types. Root profile studies showed differences in root system morphology between the vineyards. Important soil properties reported in this study to limit root growth in the Robertson region were: the presence of hard pan carbonate, unweathered parent material, abrupt changes in texture or structure and, chemically, the exchangeable sodium percentage (ESP), the sodicity, the pH and the concentration of magnesium. These properties can influence root growth individually or as a combination of restrictions. It was found that the size of the root system of 101.14 Mgt is defined by soil physical and chemical properties. The roots of 101.14 Mgt under an irrigation regime can grow up to or beyond 100 cm depth without any problem if the soil physical and chemical properties allow it.

In terms of hydraulic fertility, because soil properties define the root system and the water storage/drainage, they greatly influence the plant water status, even under irrigation. The plant water status determines shoot growth before véraison (i.e. canopy size), and the maintenance and functioning of that canopy after véraison, and consequently influences berry sugar loading, which was observed to be an interesting indicator of grapevine functioning.

The balance between canopy growth before véraison and the ability of the root-soil system to maintain that canopy size during the ripening process is crucial in an area with a high evaporative demand, such as Robertson. In this regard, not all the soil-root system combinations showed satisfactory performance in maintaining the canopy functioning, which affected the berry sugar loading and the berry volume.

Keywords: root development, soil properties, Chardonnay, Shiraz, 101.14 Mgt, hydraulic fertility, sugar loading

4.3 Introduction

The rhizosphere is the environment where root development takes place. The effect of the soil on grapevine behaviour and berry composition is complex, because the soil offers many constraints to the development and functioning of the root system. This environment is determined by the soil physical and chemical conditions (Van Huyssteen & Weber, 1980; Conradie, 1988). The physical characteristics will also influence the balance between water and air and the supply of minerals to the grapevine's roots (Saayman & Van Huyssteen, 1980; Van Huyssteen, 1988b).

The soil agronomic potential is defined as the soil aptitude to ensure the plant's vegetative growth, providing that the soil can fulfil the need of water, minerals and oxygen at the root level (Champagnol, 1997). The three components of soil fertility (physical, chemical and hydraulic fertility) are explained by three soil parameters, namely texture, structure and chemical composition. These play an important role in determining the soil porosity and the "rooting soil depth", defined as the volume available where roots can grow (Champagnol, 1997). A clear tendency for better grapevine performance with increasing soil depth has also been established (Van Huyssteen, 1988a).

The roots are the organ for water and nutrient uptake and, due to the nature of its function and structure, the root system determines the performance of the grapevine (Southey & Archer, 1988; Morlat & Jacquet, 1993; Taiz & Zeiger, 2002). The size of the root system and the availability of water and nutrients will determine the canopy size (Archer *et al.*, 1988; Southey & Archer, 1988; Van Huyssteen, 1988a; Swanepoel & Southey, 1989). Water availability plays an important role in the grapevine growth cycle (Champagnol, 1997; Coombe, 2001). Improved water relations stimulate shoot and leaf growth, especially between budbreak and véraison (Smart *et al.*, 1985; Dokoozlian & Kliewer, 1995). When water is less abundant, the matrix potential of the water retained by the soil particles increases and promotes the synthesis of ABA; as a result of complex processes, which will provoke a decrease in the rate of vegetative growth and stomatal closure (Zacarias & Reid, 1990; Trejo *et al.*, 1995; Champagnol, 1997; Coombe, 2001; Zhang & Outlaw, 2001; Baeza *et al.*, 2007). This reaction has also been reported throughout the day, depending on the cultivar, as a response to a high evaporative demand (Trejo *et al.*, 1995; Schultz, 1996, 2003; Rogiers *et al.*, 2009; Vandeleur *et al.*, 2009). The canopy size determines the transpirable surface and plays an important role in the berry microclimate, influencing berry ripening.

The dynamic of berry ripening is a rather complex process involving many metabolic routes, but there is a great deal of proof that it is highly affected by temperature (Coombe, 1987; Jackson & Lombard, 1993; Ferrini *et al.*, 1995; Hunter & Bonnardot, 2004), sun exposure (Smart, 1988; Jackson & Lombard, 1993; Dokoozlian & Kliewer, 1995) and the plant water status (Ojeda *et al.*, 2001, 2002; McCarthy *et al.*, 2002; Deloire *et al.*, 2004). Temperature and sun exposure in the bunch microclimate are influenced by the canopy growth (Smart *et al.*, 1985; Smart, 1988).

Grapevine leaves in Mediterranean climatic regions are generally speaking exposed to high temperatures and subjected to a high evaporative demand, particularly during the middle of the day (Loveys *et al.*, 2004; Wilkinson, 2004). This means that the grapevine is also at constant risk of dehydration via unavoidable transpirational water loss. The stomatal control couples leaf transpiration to leaf photosynthesis as a result of a very complex process (Davies *et al.*, 1994,

2002; Buckley, 2005). This response can be very finely tuned to soil drying, and a restriction of stomatal conductance can become apparent even when the soil water status changes by only a few kilopascal (Allen *et al.*, 1998; Davies *et al.*, 2002; Taiz & Zeiger, 2002). The control of the stomatal aperture depends on the cultivar (Schultz, 1996, 2003; Loveys *et al.*, 2004; Rogiers *et al.*, 2009; Vandeleur *et al.*, 2009).

The grapevine's water-use strategy differs between cultivars, covering isohydric and anisohydric behaviour, which has been referred to by Jones (1980) as pessimistic and optimistic water-use management (see Table 2.1). Consequently, and depending on the predominant climatic conditions and the grapevine cultivar, the soil will play a key role in the supply/restriction of water to the plant in order to match the atmospheric vapour pressure deficit (VPD). The availability or restriction of water, depending on the phenology of the grapevine, can be beneficial or detrimental from a grape quality point of view. This difference is due to the important influence that soil properties exert over vegetative growth and berry metabolism. As a result, soil properties are central to the whole-plant response to atmospheric stimuli.

The objective of this study was to describe the relationship between soil characteristics and root system and to characterise the viticultural performance of Chardonnay and Shiraz on four plots with different soil types. This paper will deal first with the soil properties influencing root growth in the Robertson region so as to analyse the root systems observed in terms of root diameter, number of roots and depth. This will be followed by a discussion of canopy development and plant water status according to the root system observed. Plant water status will then be compared with the curves of sugar loading so as to discuss the possible role of berry sugar loading as an indication of grapevine functioning.

4.4 Materials and methods

4.4.1 Study area

The study area was the Breede River Valley. The climate is influenced to a great extent by the presence of mountains: it is separated from the continental climate of the interior by the Langeberg mountain range, which is situated directly north of the Breede River Valley, and from the maritime influence by the Du Toitskloof-Sonderend mountains to the south (Oberholzer, 2007).

The average maximum temperature during January and February for most of the area is just above 30°C. Due to the presence of the mountains there is a limit to the maritime influence at night and the temperature drops more than in the coastal areas (Oberholzer, 2007), although it does not become as cold as in the continental areas. According to the Winkler index, the Robertson area falls in region IV, with 2170 degree days, which is a warm climate region (Saayman & Van Huyssteen, 1980).

More than 70% of the rainfall occurs between April and September, but the distribution differs along the valley, decreasing from west to east. Around 1 000 mm per annum has been measured at Du Toitskloof, and an average of 600 mm per annum at Botha's Halt, but to the west, in the rest of the Breede River valley where the study plots were located, the rainfall seldom measures above 250 mm per annum (Saayman & Van Huyssteen, 1980; Oberholzer, 2007).

The soil characteristics of the area change dramatically due to different soil-forming processes, which have had a tendency to differentiate the materials on which they act into horizons (Oberholzer, 2007).

4.4.2 Selection of plots

Experimental vineyards were selected from amongst an existing network of commercial vineyards that had been monitored in the prior season. The criteria for selection were the following: The rootstock material chosen was 101.14 Mgt, which has been described as having a low vigour (Galet, 1998), well adapted to saline conditions (Southey & Jooste, 1981) and low-moderate lime tolerance (Galet, 1998). It also took into account similar age of the vines (was considered a mature vine if seven years old or older), the same trellis system, similar planting density and different soil types.

The location of each plot is shown in Addendums 4.10 to 4.13. In Table 4.1 age, orientation, trellising system and planting density, irrigation system and frequency, from data obtained from a survey carried out in Robertson in 2007 to 2008 are presented.

Table 4.1. Plots studied [CH (Chardonnay) and SH (Shiraz)]

Plot	Year planted	Planting distance	Trellis system	Irrigation Type	Irrigation frequency in peak time
KD CH	1995	1.5 x 2.2	4 wire ext. P	drip	2 x week
STV CH	1996	1.5 x 2.5	5 wire ext. P	drip	12 h x week
WPK CH	1995	1.5 x 2	4 strand edge	drip	1 x week
WB CH	1996	1.4 x 2.5	4 wire ext. P	drip	18 h x week
EX SH	2000	1.5 x 2.5	5 wire ext. P	drip	1 x week
WTBR SH	2000	1.2 x 2.4	5 wire ext. P	drip	1 x 2 months
WTRS SH	1999	1.2 x 2.5	5 wire ext. P	micro	*
WV SH	1998	1 x 2.4	4 wire ext. P	micro	6 h x week

* irrigation is only applied two or three times at the end of the season if needed

Three mini-plots were laid out within each vineyard with the aim to cover homogenous portions of the plot. Aerial images were available for two different dates and were used to map the vigour response in each vineyard block in order to avoid extreme differences in vigour as a consequence of possible extreme differences in soil profile or water retention, and to place the plots in areas of the vineyard that are fairly homogenous (addendums 4.10 to 4.13).

4.4.3 Canopy measurements

Destructive shoot measurements were done a week after véraison. Six representative bearer shoots were chosen per plot. The main shoot length and total secondary shoot length were measured, and nodes and leaves were counted. The main leaf area and secondary leaf area were calculated separately using a Delta-T leaf area meter (Delta-T Devices, Cambridge, UK).

4.4.4 Water status

Plant water status was followed every seven to ten days from one week before véraison. For each cultivar the measurements were done on the same day. In the case of Chardonnay, three measurements were done, and in the case of Shiraz five measurements were done. The Scholander-type pressure chamber was used. Predawn water potential (Ψ_{pd}) and midday stem (Ψ_{md}) water potential were measured (using the methods described in Choné *et al.*, 2001). Ψ_{md} was measured between 10:00 and 14:00. Each time, three fully expanded, exposed and healthy leaves from three separate bunch bearer shoots (one leaf per shoot), between the third and seventh node, which had previously been covered for 30 min, were measured.

4.4.5 Berry ripening

Berry samples were composite field samples per mini-plot consisting of 200 berries taken from the top, middle and bottom of the bunches, and from the sun side as well as the shade side of bunches. Samples were taken every five to ten days from véraison onwards. Berry mass was determined with an electronic balance. The berries were crushed with a Braun® blender and centrifuged for 10 minutes. The TSS (total soluble solid) was determined using a digital refractometer (Atago Pocket refractometer PAL-1) zeroed with distilled water. Titratable acidity (TA) and pH were measured with the Metrohm® 785 DMP Tritino automatic titration instrument, with sodium hydroxide (NaOH) at a dilution of 0.333 N. In order to harvest at a similar level of ripeness, the sugar-loading curves were calculated, as was the daily dynamic of sugar loaded into the berry. This method is based on the zero sugar loading point, which has been reported to be an important physiological point in the berry ripening process and the development and evolution of different aromatic compounds in the berry beyond this point, which is cultivar dependent (Brenon *et al.* 2005; Deloire *et al.* 2008). All these analyses were performed for Chardonnay and Shiraz. Tint angle was measured only in Chardonnay, using the Dyostem® developed by Sferis. In brief, the Dyostem operates combining different parameters as the berry volume, colour, and amount of sugar per berry to help to determine harvesting date (more information about Dyostem® is available at <http://www.sferis.com/dyostem.html>). The harvest decision was made according to the sugar-loading curve. The Shiraz plots were harvested 20 days after the zero sugar loading point was reached. The Chardonnay plots were harvested between five to seven days after zero sugar loading point. For Chardonnay, berry colour was also taken into consideration and grapes were harvested with an average hue of ca. 73. This value has been related to high concentrations of thiols in the aromatic profile of the wine (Deloire *et al.*, 2008; Deloire, 2009).

4.4.6 Soil profiles

Soil pits were dug in each mini-plot, perpendicular to the vineyard row at 30 cm from the vine. The pits were 1.5 m long and 1 m deep if no soil restriction was found beforehand.

4.4.7 Soil descriptions

The soil description and classification were done by an experienced soil scientist (Mr Braham Oberholzer, VinPro, 2008) according to the South African soil taxonomic system (Soil Classification Working Group, 1991).

4.4.8 Soil chemical analyses

A composite sample of each horizon was taken from the different faces of the soil pit and analysed according to standard methods by the laboratory of the Department of Agriculture: Western Cape (Eisenburg) according to methods described by The Non-Affiliated Soil Analyses Work Committee (1990). Particle size was done using the Bouyoucous method, boron (B) with the hot water method, copper (Cu), zinc (Zn) and manganese (Mn) with the di-ammonium EDTA method, and calcium (Ca), potassium (K), magnesium (Mg), sodium (Na) and phosphorus (P) with the citric acid method.

4.4.9 Root profiles

The root profiles were described following the method described by Böhm (1979), utilising a grid composed of 150 squares of ten cm² each. Roots were counted and classified according to their diameter into five categories (≤ 0.5 mm, 0.5-2 mm, 2-5 mm, 5-7 mm and ≥ 7 mm). Fine roots were considered to be between ≤ 0.5 mm to 2 mm, and thick roots from 2 mm to ≥ 7 mm.

4.4.10 Experimental layout

Four plots were studied per cultivar and three mini-plots were laid out on each plot, with each mini-plot consisting of ten vines.

4.4.11 Statistical analyses

The roots percentages were analysed with one way ANOVA, the root number per horizon and per plot were presented in a mean plot graph. Canopy measurements of main leaf area, secondary leaves area, total leaf area and number of bunches, together with shoot length are also shown in mean plot graphs with 0.95 confidence intervals using the Statistica® software. For the plant water status the three measurements done per mini-plot each time were averaged and the standard deviation was also calculated.

4.5 Results and discussion

4.5.1 The soil volume

The soil volume includes two concepts, the “soil volume” *per se* and the “rooting soil volume”. “Rooting soil volume” refers to the real soil volume available for the roots to grow and can only be smaller or equal to the “soil volume” (i.e. in duplex soils, abrupt changes in texture and soil structure between soil horizons make root penetration difficult, therefore the whole soil volume is not ready available for root growth). The rooting soil volume is limited by soil physical stresses that restrict root elongation, mainly because they affect the soil structure and penetrability (Bengough *et al.*, 2006). These characteristics will also influence the so-called “root preference zone” described by Champagnol (1984) in terms of root extension and colonisation of the soil.

The total volume of soil therefore represents the volume available for water storage, and the “rooting soil volume” represents the volume where roots are present.. This study describes which soil properties are limiting factors for root development in different soils types at Robertson.

4.5.1.2 The soil rooting depth and density

It has been reported in the literature that roots can penetrate to depths of greater than 80 cm (Champagnol, 1984), and even down to 6 m (Seguin, 1972). Despite the ability of the roots to grow deep, the majority of roots will group in the so-called root preference zone (Champagnol, 1984). The soil physical conditions exert a major influence on the root preference zone, as they dominate the environment in which roots develop and function (Van Huyssteen & Weber, 1977). Root distribution is predominantly a consequence of the soil environment, but rootstock characteristics cannot be totally excluded (Southey & Archer, 1988; Southey, 1992).

A summary with different root profiles of 101.14 Mgt described in the literature in South Africa are presented in Tables 4.2 and 4.3. Southey & Archer (1988) describe the morphology of 101.14 Mgt in different soil profiles and locations. In Vredendal, in an Oakleaf soil, they reported a high percentage the roots located between 80-100 cm and 140-160 cm depth (table 4.3), associated with the favourable conditions of a silty layer at those depths. In Lutzville, in a Hutton soil, 101.14 Mgt colonized to a depth of 1.5 m where the growth was restricted by the presence of a hard pan. A high root percentage was also found between 100 – 150 cm (Table 4.3). In Stellenbosch, in a Clovelly soil, they observed that 101.14 Mgt was limited by a massive (structureless) subsoil located at about 1.0 m depth. Southey (1992) observed that 101.14 Mgt grew relatively vigorously compared to other rootstocks but had low root densities. The root percentages reported by Southey (1992) in Robertson are presented in Table 4.3.

Table 4.2 Summary of different studies in South Africa involving the root distribution of 101.14 Mgt. Characteristics and cultural practices of each plot studied.

Location	Scion	Age (years)	Planting distance	Trellis system	Irrigation type	Irrigation frequency	Soil form	Author
Vredendal	Chenin Blanc	4	2.3 x 1.2	3 strand Perold	Flood	100 mm every 18 days	Oakleaf	1
Lutzville	Chenin Blanc	13	2.7 x 1.5	3 strand Perold	Sprinkler	50 mm every 14 days	Hutton	1
Stellenbosch	Chenin Blanc	6	3.0 x 1.5	1.2 m slanting	Dry-land	-	Clovelly	1
Robertson	Chenin Blanc	9	2.6 x 1.3	1.5 m slanting	Overhead sprinklers	60 mm every four weeks	Oakleaf	2

1. Southey & Archer (1988)
2. Southey (1992)

Table 4.3 Comparison of roots percentages of 101.14 Mgt in depth in different localities of South Africa.(data from Southey & Archer, 1988; Southey, 1992)

Depth cm	Vredendal	Depth cm	Lutzville	Depth cm	Robertson	Depth cm	Stellenbosch
0-30	2.52	0-25	12.7	0-20	35.13	0-20	15.46
30-60	1.74	25-50	15.5	20-40	25.93	20-40	21.31
60-90	2.74	50-75	6.1	40-60	24.13	40-60	13.9
90-120	19.21	75-100	7.6	60-80	10.63	60-80	22.82
120-150	51.41	100-125	25.7	80-100	1.67	80-100	21.66
150-180	22.38	125-150	32.4	100-120	2.51	100-120	5.05
-	-	-	-	-	-	120-140	0
-	-	-	-	-	-	140-160	0

The root distribution of a 101.14 Mgt seems from these results to be highly affected by soil properties, and, as has been mentioned by other authors, root distribution would appear to be mainly a function of soil properties. According to Galet (1998), 101.14 Mgt is a medium vigour rootstock. The vigour response is certainly the result of an interaction of many factors, namely, soil properties (physical and chemical), rootstock characteristics and cultural practices. Important rootstock characteristics are: the ability to overcome soil restrictions of a chemical nature (e.g. 101.14 Mgt is sensitive to low soil pH (Conradie, 1988) but performs better than others under saline conditions (Southey & Jooste, 1991)). Limitations can be of a physical nature (e.g. 101.14 Mgt was reported to stop growing when a massive horizon was found (Southey & Archer, 1988)). Important characteristics, also related to vigour expression, are the root functionality. This is related to the number of thin roots, which represent higher absorption rates, and play an important role in synthesis of plant growth regulators such as cytokinins (Van Zyl 1984; Southey 1992), but also to physiological differences between rootstocks, such as drought tolerance (Carbonneau, 1985), and in the different expression of aquaporins in roots (Galmés *et al.*, 2007). The latter characteristic may play an important role in the often seen differences in the performance of different grafting combinations, in combination with root system morphology (highly dependent on the soil properties) and modified to a certain extent by cultural practices such as soil preparation (Van Hussyteen, 1988a), irrigation system and amount of water applied (Van Zyl 1988), soil ameliorations (Conradie, 1988), planting density (Archer & Southey, 1985), trellis system (Van Zyl & Van Huysteen, 1980; Archer *et al.*, 1988), canopy management practices such as leaf removal (Hunter & Le Roux, 1992; Hunter *et al.*, 1995) and the degree of water deficit in the soil (Van Zyl, 1988).

In this study, the majority of roots were found in the top 60 cm of soil. The results are presented in Table 4.4. For the Chardonnay plots, an average of 90.3% of the roots were found in the top 60 cm of the soil profile, while the average for the Shiraz plots was 92.3%.

The plots in this study were all under irrigation. According to Soar and Loveys (2007), root distribution is altered by the type of irrigation, but this may be related to the extent of wetting of the surface. The optimum distribution of root length depends mainly on the distribution of water and nutrients in the soil (Bengough *et al.*, 2006). Araujo *et al.* (1995) also noted that root growth and branching proliferated in the wetted zone under the dripper. Van Zyl (1988) compared drip and micro-sprinkler irrigation, and also reported a high root density under the dripper, and a more homogeneous root distribution with the micro-sprinkler, but similar root density between the two. Sipiora *et al.* (2005) found no influence of two irrigation regimes on the density or distribution of roots in a Mediterranean fruit-growing region. However influence over the root number is exerted by the water deficit in the soil, which depends on the soil water retention properties but, also importantly, the frequency and amount of water applied. It was shown by Van Zyl (1988) that root number was increased with a moderate soil water deficit of 50% plant available water. In this study, soil water measurements were not followed which makes it difficult to speculate about this effect over the root number, as well as the long term effect provoked by the previous year's irrigation strategy. As has been described in the literature, irrigation and irrigation management play a role in the root distribution, but the effect is related to soil properties. It is shown in depth in this study (Chapter 5) that, under drip irrigation, 101.14 Mgt would grow deeper if no soil restrictions were present, decreasing the percentage of the total number of roots in the first 60 cm of soil from the reported average of over 90.26% to an average of 66.23%.

Table 4.4. The percentage of the total number of roots found in the top 60 cm of soil for selected plots of Chardonnay and Shiraz in Robertson

CH	% roots	SH	% roots
WB 1	88.60	WTBR 1	100.00
WB 2	97.84	WTBR 2	93.39
WB 3	95.27	WTBR 3	100.00
WPK 1	87.91	WTRS 1	87.97
WPK 2	100.00	WTRS 2	86.13
WPK 3	81.36	WTRS 3	92.47
STV 1	84.75	EX 1	80.94
STV 2	94.07	EX 2	93.69
STV 3	79.23	EX 3	72.49
KD 1	89.53	WV 1	100.00
KD 2	90.20	WV 2	100.00
KD 3	94.33	WV 3	100.00
Average	90.26	Average	92.26

In this study, the highest percentage of roots was found, on average, between 20 and 40 cm soil depth, with a high percentage also in the top 20 cm (Table 4.5). On average, for all the plots, 38.72% of the roots were found between 20 and 40 cm and 28.53% were in the top 20 cm, and together these depths accounted for more than 65% of the roots. This observation concurs with the findings of Southey (1992). He argued that this high percentage of roots in the top horizons may be related to soil restrictions to vertical growth. Similarly to the Southey study, this situation seems to be related to soil restrictions. Swanepoel and Southey (1989) reported that, in a soil with no vertical restrictions, only 10.3% of the roots were in the first 20 cm. This seems to be strongly related to the soil properties in this study, however due to the number of variables indicated in Table 4.1, all this discussion is speculative and it is difficult to draw definite conclusions.

In Table 4.5 the root percentages for every 20 cm depth in each mini-plot are presented. A one way ANOVA statistical analysis was performed separated for each cultivar. Due to the large differences between the mini-plots no significant differences between the plots are reported at any depth (data not shown) with the exception of the Shiraz plots between 60 to 80 cm, where the root percentages differed significantly (Fig. 4.1), determined for the marked differences in rooting depth between the shallowest root system of WV where a very low percentage of roots was found at this depth, compared to the EX plot that presented a high percentage of roots here. An important role is probably played by the heterogeneity within the plots. In Chardonnay different soil forms were reported in the same plot, while more homogeneity was found in the Shiraz plots, this is related to important properties in the soil that may define the percentage of roots found at different depths. The shallow soil of WV had the lowest and EX the highest percentage between 60 to 80 cm depth. The differences in soil forms and root distribution within plots suggested that an analysis using averages may not be very representative and may lead to misinterpretation of the results. It was opted thus to analyse each mini-plot separated.

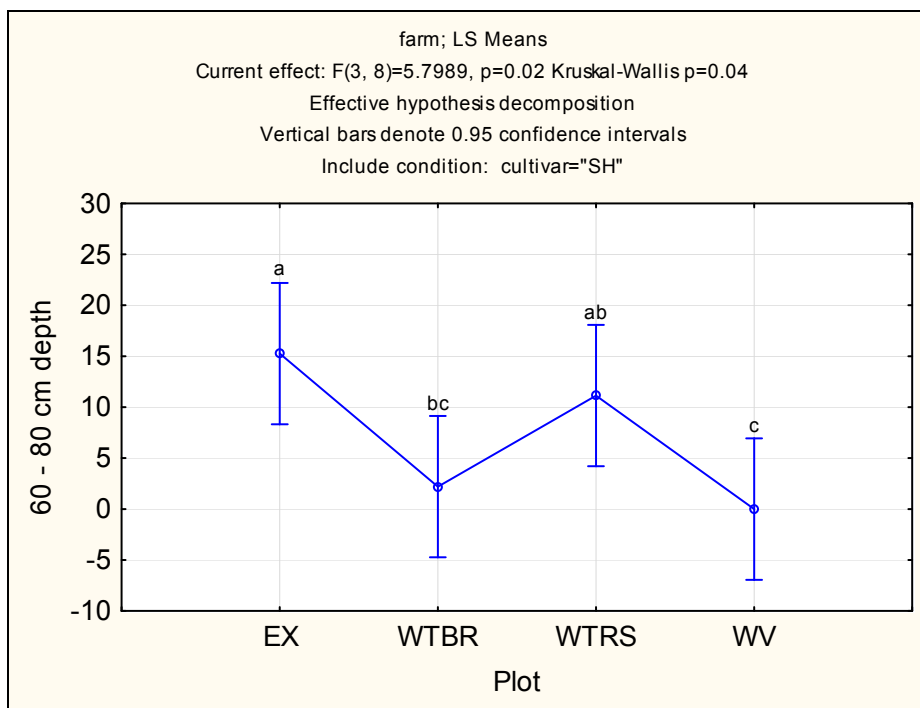


Figure 4.1 Differences between the percentages of roots between 60 to 80 cm depth between the Sihraz plots. Different letters denote significant differences at $p \leq 0.05$.

Table 4.5 Root distribution calculated as a percentage of the total root number per mini-plot for selected Chardonnay and Shiraz vineyards in Robertson

Plot	Depth in cm				
	0 - 20	20 - 40	40 - 60	60 - 80	80 - 100
WB CH 1	19.87	35.83	32.90	11.40	0.00
WB CH 2	34.63	35.93	27.27	2.16	0.00
WB CH 3	44.26	26.35	24.66	4.73	0.00
WPK CH 1	14.29	39.56	34.07	12.09	0.00
WPK CH 2	65.00	28.00	7.00	0.00	0.00
WPK CH 3	44.07	16.10	21.19	14.41	4.24
STV CH 1	31.67	30.50	22.58	13.20	2.05
STV CH 2	32.05	40.06	21.96	5.93	0.00
STV CH 3	15.30	39.34	24.59	17.49	3.28
KD CH 1	17.05	42.64	29.84	10.47	0.00
KD CH 2	35.29	37.91	16.99	6.54	3.27
KD CH 3	27.84	39.18	27.32	5.15	0.52
EX SH 1	19.40	33.11	28.43	19.06	0.00
EX SH 2	27.18	40.78	25.73	4.85	1.46
EX SH 3	21.01	23.96	27.51	21.89	5.62
WTBR SH 1	41.91	48.53	9.56	0.00	0.00
WTBR SH 2	19.01	47.11	27.27	6.61	0.00
WTBR SH 3	22.35	60.00	17.65	0.00	0.00
WTRS SH 1	20.89	33.54	33.54	12.03	0.00
WTRS SH 2	14.60	40.88	30.66	13.87	0.00
WTRS SH 3	30.14	46.58	15.75	7.53	0.00
WV SH 1	18.37	61.22	20.41	0.00	0.00
WV SH 2	23.08	35.90	41.03	0.00	0.00
WV SH 3	45.52	46.27	8.21	0.00	0.00

The following root properties reported by various authors were found in this study to exert an influence over vine root development in the Robertson region. They limit the rooting depth but also the rooting density. Figures 4.2 to 4.5 showed the total number of roots and the soil chemical properties versus depth in the four plots. The results for all the plots are presented in Tables 4.6 and 4.7. All the limiting soil properties were depth-weighted in layers of 20 cm.

In this study, physical restrictions were found to be the presence of rocks (WBCH, WTBRSH), hard pan (KDCH3, STVCH2), high bulk density WWSH, WTRSSH, STVCH1, 3) and abrupt changes in texture/structure (WPKCH1, 3). These restrictions have been reported in the literature (Morlat & Jacquet, 1993; Saayman, 1982; Richards, 1983; Van Huyssteen, 1988a; Southey 1992; Morlat & Jacquet, 1993). Chemical restrictions were: the ESP (exchangeable sodium percentage), which indicates levels of sodicity in WPKCH2,3, STVCH3, KDCH1, EXSH2,3 and WWSH2 – this restriction has been reported by Fitzpatrick *et al.* (1993) and Rengasamy and Churchman (1999), the salinity levels represented by the means of electrical resistance in WBCH3, STVCH, KDCH, EXSH2,3 and WWSH – this restriction has been reported in the literature by Groot Obbink and Alexander (1973), West and Taylor (1984) and Downton (1985); the pH, which may be involved to certain extent, since some values are close to the ideal limits reported in the literature by Conradie (1988) and Wooldridge *et al.* (2010); and the Ca:Mg ratio, specifically the concentration of

magnesium, as it plays an important role in soil structure (Conradie, 1994; Nicholas, 2004). As has been expressed well by Bengough *et al.* (2006 and references therein), the combination of these restrictions affect root growth to different degrees.

These restrictions can affect soil properties, but also root functioning, in the following ways:

The effects of high soil salinity on vine performance are: reduction of water availability (an osmotic effect), toxicity (toxic at low tissue concentration) and the promotion of nutrient imbalance (Neja *et al.*, 1978; Prior *et al.*, 1992; Cass *et al.*, 1996; Anon, 1997). Root growth, particularly of the fine roots, decreases with decreasing electrical resistance (Southey, 1992).

Sodicity occurs in the soil when sodium gradually displaces calcium from the exchange complex. Sodic soils generally have poor physical properties due to clay dispersion. They provide a very poor environment for root growth, because the aeration and drainage properties are limited and they tend to hold little of the available water (Fitzpatrick *et al.*, 1993; Rengasamy & Churchman, 1999). Sodicity is the cause of slaking and dispersion, the processes by means of which soil structure breaks down. Slaking involves the breakdown of soil aggregates into micro-aggregates smaller than 0.25 mm in diameter. Dispersion is the breakdown of micro-aggregates into individual constituents of sand, silt and clay (Nicholas, 2004).

Similar effects to those caused by high sodicity can be caused by high exchangeable magnesium levels, especially where the exchangeable Ca:Mg ratio is < 1. Grapevines can tolerate Ca:Mg ratios in the approximate range of 2:1 to 10:1.

In terms of the pH, soils are considered alkaline if $pH_w > 7.5$. According to Nicholas (2004), a distinction can be made between soils made alkaline by calcium carbonate alone, i.e. calcareous alkaline soils (pH_w 7.5–8.4), and alkaline sodic soils ($pH_w > 8.4$), which have significant concentrations of toxic sodium bicarbonates or clays with high exchangeable sodium percentages. He argued that little root growth can take a place where pH_w exceeds 9.2. The soil pH has an effect on mineral availability (see Addendum 4.5), and zinc and iron deficiencies have been reported in alkaline soils, particularly if the surface soil is highly calcareous, but this is less significant in the subsoils (Richards, 1954; Slattery *et al.*, 1999).

The plot WVSH has an overall small root system in the three mini-plots (Figure 4.2). Root growth was restricted to a depth of 60 cm. The dominant restrictions encountered for root growth appear to be soil salinity in all three mini-plots, with low resistance values from 30 cm down, and the ESP, which classified as a sodic soil in two mini-plots (WVSH1 and WVSH3) and highly sodic soil in WVSH2 (Figure 4.2 E). The small number of total roots in WVSH2 therefore seems to be the consequence of a combination between sodicity and salinity, and probably their joint effect on soil structure. The soil consistency was classified in the field as hard. A slightly high concentration of magnesium was also reported in WVSH3 (Figure 4.2 B).

The plot EXSH (Figure 4.3) has the highest root number of the Shiraz plots. No limitations of any kind were found in the top 70 cm. After 70 cm the number of roots decreased more markedly in EXSH3, and even disappeared, similarly to the mini-plot EXSH1. In EXSH3, a combination of low resistance (i.e. 250) and high ESP appeared to be the limitation for root growth at 80 cm depth, together with a low pH of 4.6.

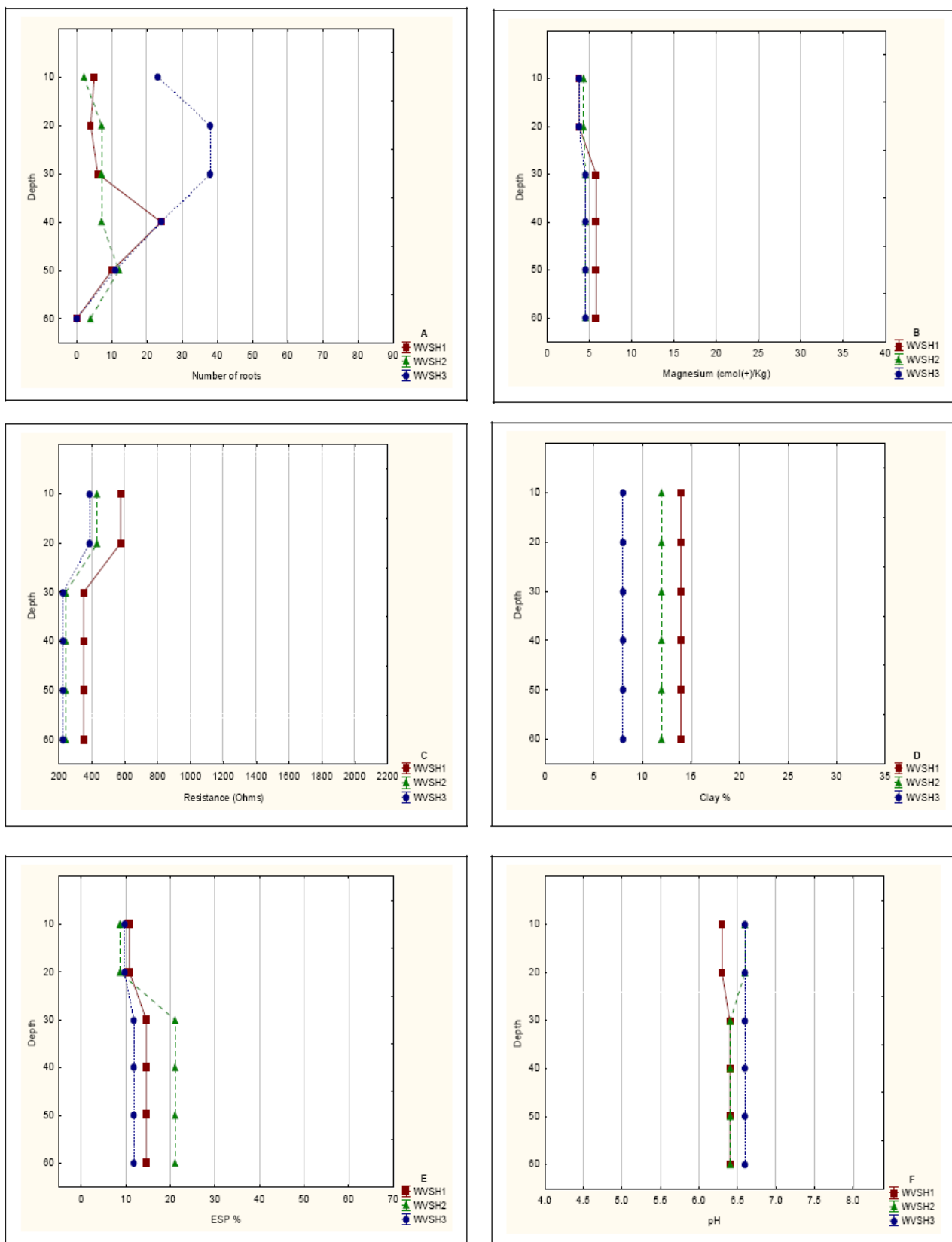
The WPKCH plot had the smallest total number of roots of the Chardonnay plots. Two mini-plots had a marked change in texture and structure from an E horizon into a B horizon, with higher clay content (Figure 4.4 D) and a strong prismatic structure. The change occurred at a depth of 40 cm. WPKCH1 had the greater change, from 12.5% depth weighted clay at 20 cm depth to 32% depth weighted clay from 40 cm downwards. WPKSH2 had the smallest number of roots of the mini-plots (Figure 4.4 A). The root development is probably affected by the ESP, which classified the soil in WPKCH2 as highly sodic.

STVCH had the largest number of roots of the Chardonnay and Shiraz plots (Figure 4.6 A). The larger number of roots is concentrated in the upper 60 cm in the three mini-plots. The restriction to root growth from 60 cm down is related to low values for resistance (i.e. salinity) in the three mini-plots (Figure 4.5 C), and high ESP in STVCH2 and STVCH3 (Figure 4.5 E). The consistency measured in the three plots in the field was classified as hard from 60 cm down. A high concentration of magnesium was found in the STVCH3 from 60 cm down, in STVCH1 throughout the entire profile, and in STVCH2 from the top until 60 cm (Figure 4.5 B). The high content of magnesium can have a similar effect on the soil structure as sodium (Nicholas, 2004).

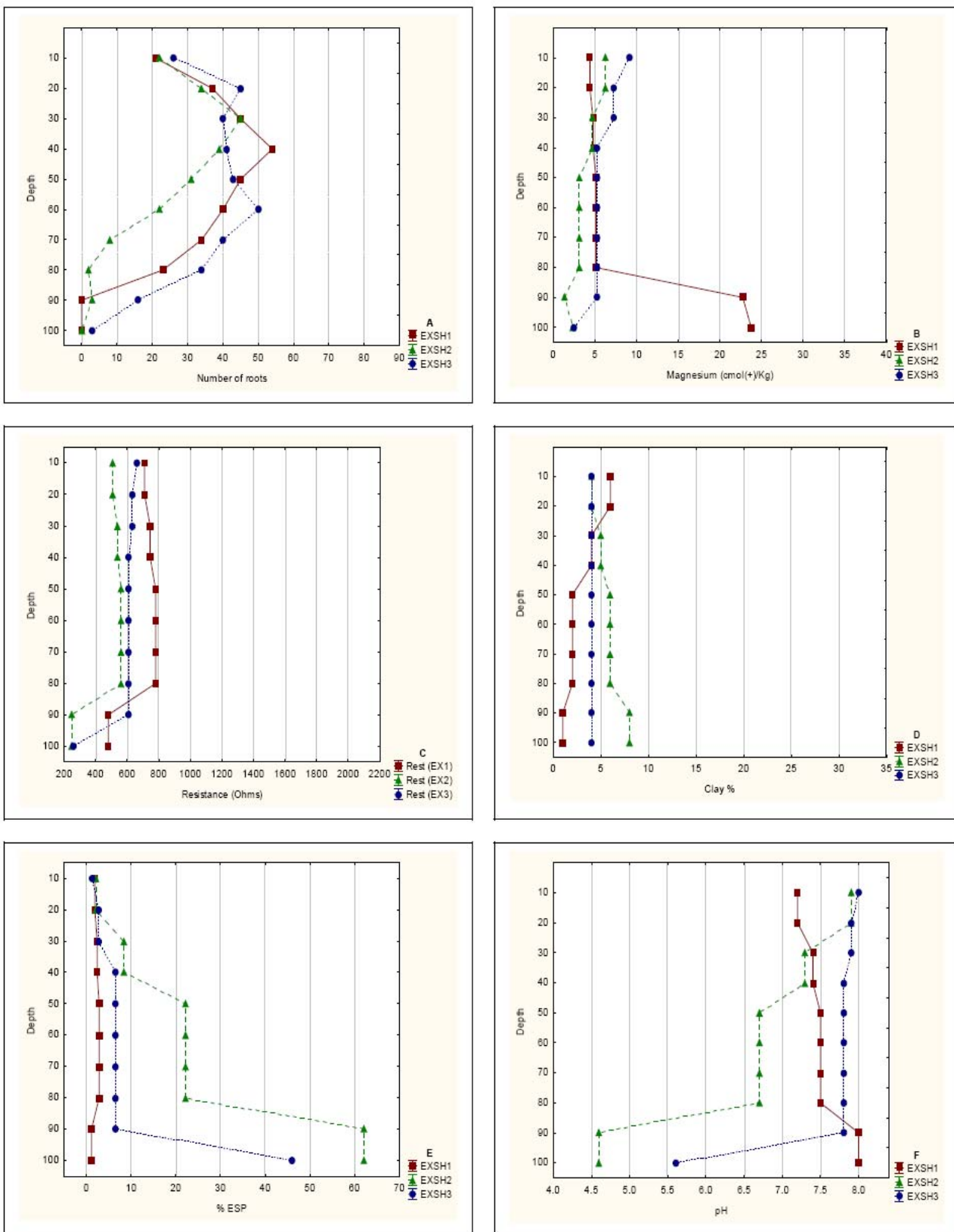
Two ratings, one for exchangeable cations and one for critical limits for soil degradation due to sodicity, are presented in Addendums 4.3 and 4.4.

The chemical impediments mentioned above are related to the low rainfall of the study area, which is on average 250 mm per annum (Oberholzer, 2007). Salinity and sodicity are related to the amount of rain (and slope), which allows these minerals to be leached out of the soil profile. Irrigation systems that use increasingly saline water, together with slow soil permeability, can reduce the leaching of these salts, and even promote their accumulation. Thus, salinity and sodicity are related to arid zones or the lower zones in the landscape. Low rainfall also relates to high pH, and alkaline soils are found mostly in areas with less than 500 mm annual rainfall (Nicholas, 2004).

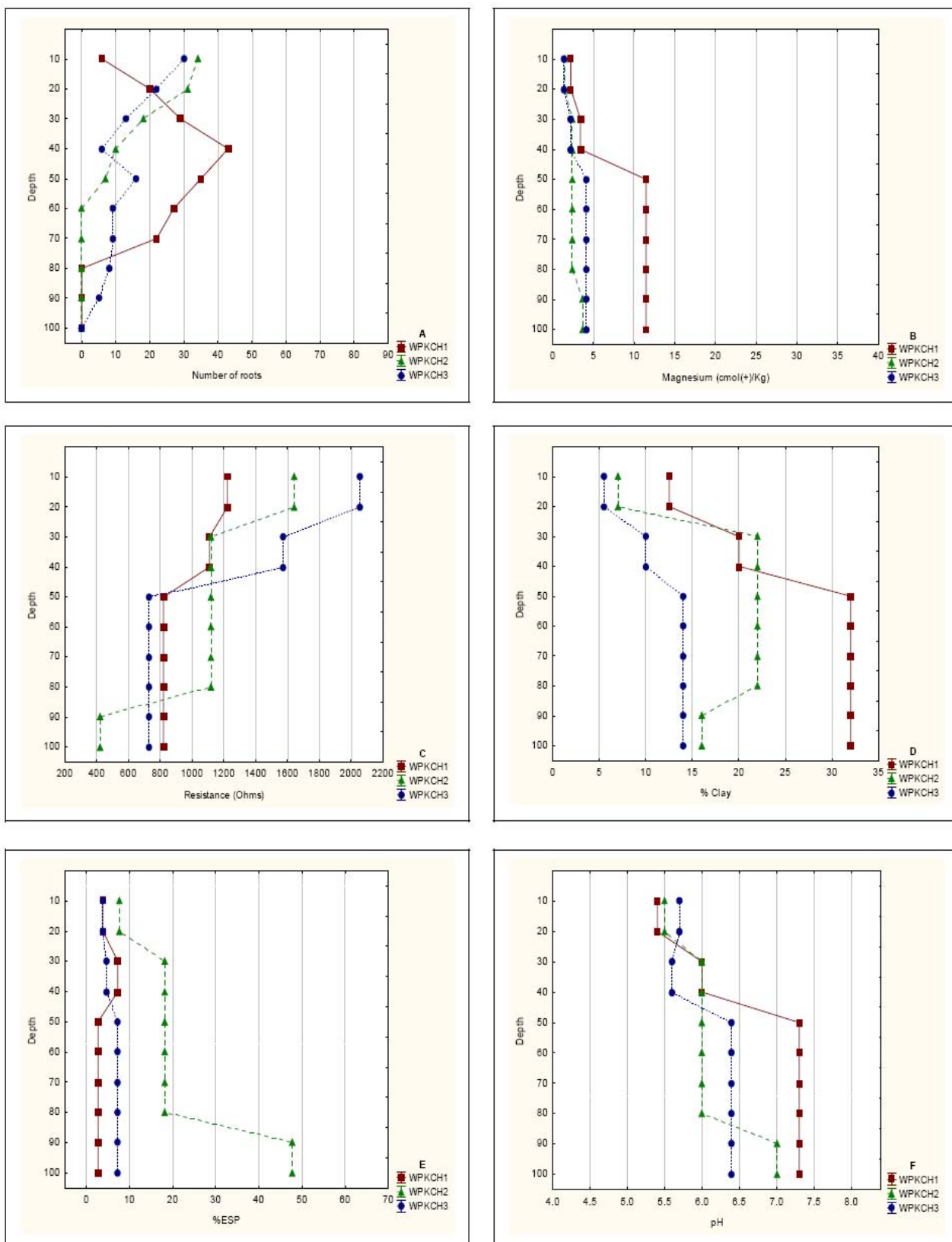
The observations here of a variety of soils conclude that pH, ESP, salinity, the concentration of magnesium compared with the concentration of calcium (Ca:Mg ratio), abrupt changes in texture and structure and the interaction between these restrictions delimit the “rooting soil volume” in the Robertson Valley.



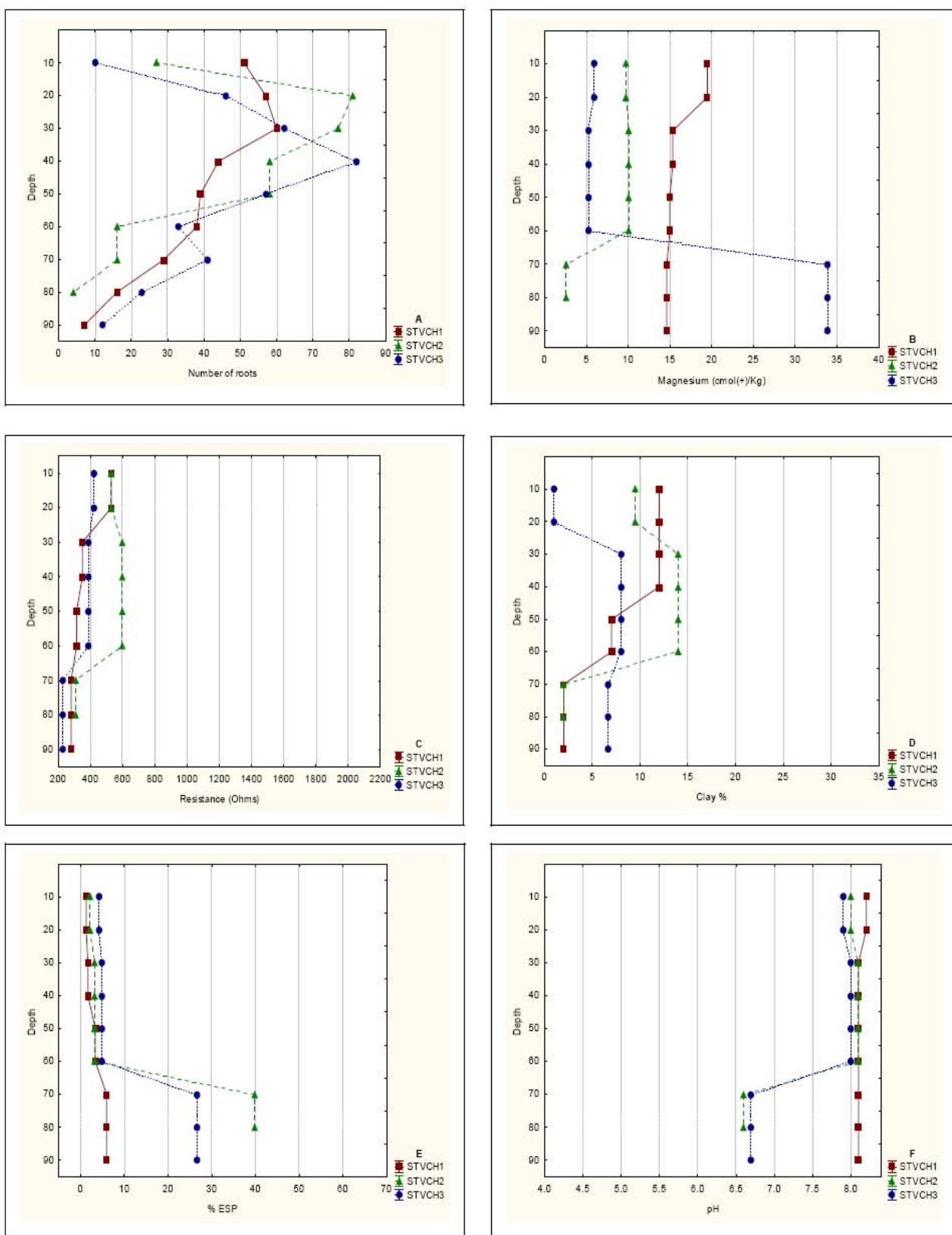
Figures 4.2 Comparison of WWSH mini plots with important soil properties and their distribution in depth. (A) root number. (B) magnesium content. (C) resistance. (D) Clay %. (E) ESP % (exchangeable sodium percentage). (F) pH.



Figures 4.3 Comparison of EXSH mini plots with important soil properties and their distribution in depth. (A) root number. (B) magnesium content. (C) resistance. (D) Clay %. (E) ESP % (exchangeable sodium percentage). (F) pH.



Figures 4.4 Comparison of WPKCH mini plots with important soil properties and their distribution in depth. (A) root number. (B) magnesium content. (C) resistance. (D) Clay %. (E) ESP % (exchangeable sodium percentage). (F) pH.



Figures 4.5 Comparison of STVCH mini plots with important soil properties and their distribution in depth. (A) root number. (B) magnesium content. (C) resistance. (D) Clay %. (E) ESP % (exchangeable sodium percentage). (F) pH.

Table 4.6 The twelve mini-plots studied for Chardonnay with their soil form and family, the number of contact points for thin and thick roots, the thin/thick root ratio and the total number of contact points for roots.

Chardonnay			Roots				Chardonnay			Roots			
Plot	Soil form	Depth cm	< 2 mm	≥ 2 mm	RATIO	TOTAL	Plot	Soil form	Depth cm	< 2 mm	≥ 2 mm	RATIO	TOTAL
STVCH1	Etosha Et 2220	A (0-20)	90	18	5	108	WBCH1	Glenrosa Gs 1112	A (0-20)	58	3	19	61
		B (20-40)	90	14	6	104			B (20-40)	106	4	27	110
		C (40-60)	66	11	6	77			C (40-60)	94	7	13	101
		D (60-80)	42	3	14	45			D (60-80)	32	3	11	35
		E (80-90)	7	0	7	7			*				
STVCH2	Oudtshoorn Ou 2211	A (0-20)	90	18	5	108	WBCH2	Augrabies	A (0-20)	75	5	15	80
		B (20-40)	91	44	2	135			B (20-40)	75	8	9	83
		C (40-60)	58	16	4	74			C (40-60)	61	2	31	63
		D (60-80)	20	0	20	20			D (60-80)	5	0	5	5
STVCH3	Augrabies Ag 2110	A (0-20)	55	1	55	56	WBCH3	Glenrosa Gs 1212	A (0-20)	124	7	18	131
		B (20-40)	126	18	7	144			B (20-40)	70	8	9	78
		C (40-60)	79	11	7	90			C (40-60)	68	5	14	73
		D (60-80)	60	4	15	64			D (60-80)	12	2	6	14
		E (80-90)	8	4	2	12			E (80-100)	0	0	0	0
KDCH1	Etosha Et 2221	A (0-20)	37	7	5	44	WPKCH1	Escourt Es 1100	A (0-20)	26	0	26	26
		B (20-40)	83	27	3	110			B (20-40)	67	5	13	72
		C (40-60)	61	16	4	77			C (40-60)	61	1	61	62
		D (60-80)	24	3	8	27			D (60-80)	22	0	22	22
		E (80-90)	0	0	0	0			E (80-100)	0	0	0	0
KDCH2	Tukulu Tu 2120	A (0-20)	50	4	13	54	WPKCH2	Sepane Se 2211	A (0-20)	58	7	8	65
		B (20-40)	40	18	2	58			B (20-40)	22	6	4	28
		C (40-60)	18	8	2	26			C (40-60)	6	1	6	7
		D (60-80)	6	4	2	10			D (60-80)	0	0	0	0
		E (80-90)	5	0	5	5			E (80-100)	0	0	0	0
KDCH3	Prieska Pr 2110	A (0-20)	46	8	6	54	WPKCH3	Escourt Es 1100	A (0-20)	52	0	52	52
		B (20-40)	61	15	4	76			B (20-40)	15	4	4	19
		C (40-60)	44	9	5	53			C (40-60)	20	5	4	25
		D (60-80)	9	1	9	10			D (60-80)	14	3	5	17
		E (80-90)	1	0	1	1			E (80-100)	4	1	4	5

Table 4.7 The twelve mini-plots studied for Shiraz with the soil form and family, the number of contact points for thin and thick roots, the thin/thick root ratio and the total number of contact points for roots.

SHIRAZ							SHIRAZ						
Plot	Soil form	Depth cm	Roots				Plot	Soil form	Depth cm	Roots			
			< 2 mm	≥ 2 mm	RATIO	TOTAL				< 2 mm	≥ 2 mm	RATIO	TOTAL
WTBRSH1	Glenrosa	A (0-20)	56	1	56	57	EXSH1	Etosha	A (0-20)	57	1	57	58
		Gs 2211	B (20-40)	64	2	32			66	Et 2221	B (20-40)	97	2
		C (40-60)	13	0	13	13			C (40-60)		85	0	85
	*								D (60-80)	55	2	28	57
WTBRSH2	Glenrosa	A (0-20)	23	0	23	23	EXSH2	Etosha	A (0-20)	55	1	55	56
		Gs 2211	B (20-40)	56	1	56			57	Et 2221	B (20-40)	81	3
		C (40-60)	31	2	16	33			C (40-60)		53	0	53
	*								D (60-80)	7	3	2	10
WTBRSH3	Glenrosa	A (0-20)	18	1	18	19	EXSH3	Etosha	A (0-20)	69	2	35	71
		Gs 2211	B (20-40)	50	1	50			51	Et 2211	B (20-40)	77	4
		C (40-60)	15	0	15	15			C (40-60)		88	5	18
	*								D (60-80)	71	3	24	74
WTRSSH1	Augrabies	A (0-20)	32	1	32	33	WVSH1	Swartland	A (0-20)	8	1	8	9
		Ag	B (20-40)	53	0	53			53	Gs 2211	B (20-40)	27	3
		C (40-60)	53	0	53	53			C (40-60)		10	0	10
		D (60-80)	16	3	5	19			D (60-80)	16	2	8	19
WTRSSH2	Augrabies	A (0-20)	20	0	20	20	WVSH2	Swartland	A (0-20)	9	0	9	9
		Ag	B (20-40)	53	3	18			56	Gs 12 12	B (20-40)	14	0
		C (40-60)	39	3	13	42			C (40-60)		15	1	15
		D (60-80)	15	4	4	19			D (60-80)	15	1	15	16
WTRSSH3	Augrabies	A (0-20)	44	0	44	44	WVSH3	Swartland	A (0-20)	60	1	60	61
		Ag	B (20-40)	60	8	8			68	Gs 2211	B (20-40)	60	2
		C (40-60)	23	0	23	23			C (40-60)		11	0	11
		D (60-80)	10	1	10	11			D (60-80)	11	0	11	11

In this study, if no soil restrictions were found within the “rooting zone”, a high number of thin roots were reported, together with high thin (< 2 mm) to thick (\geq 2 mm) root ratio values (Tables 4.6 and 4.7). The rooting ratio, together with the information of number of thin and thick roots allows a comparison between root systems (Van Zyl, 1984, cited by Southey, 1992). Thin roots play an important role in the absorption of water and nutrients, and in the maintenance of an hormonal balance as they produce cytokinins, and play an important role in the sensing of water deficit in the soils and the action of ABA in stomatal control (Loveys, 1984; Coombe, 2001). Total root number increases with moderate water deficit (50% plant available water - PAW), but decreases if the deficit increases (25% PAW) (Van Zyl, 1988). This increase in root number may be related with to an increase in root branching under moderate water deficits in order to increase the total absorbent surface as a strategy to overcome the deficit, however, when the deficit increases the plant probably cannot sustain the same growing rate.

Swanepoel and Southey (1989), in relation to a different rootstock but in an Oakleaf soil type (Soil Classification Working Group, 1991), also in Robertson, found root ratios (roots with a diameter \leq 2 mm: roots with a diameter \geq 2 mm) that ranked between 44.7 and 18.3, but with much higher numbers of total roots. On the other hand, ratios calculated from data of Serra-Stepke (2010) on Sauvignon blanc/R110 and R99 from six plots under irrigation in Stellenbosch (five plots under drip irrigation and one under micro-aspersion) ranked between 0.69 with 155 thin roots and 225 thick roots, and 3.52 with 225 thin roots and 64 thick roots. Archer and Hunter (2004), also in Stellenbosch, reported ratio values of 5.2 and 5.3 in high-quality vineyards, and ratios of 1.7 and 2.3 in low-quality vineyards. Other observations made in Chardonnay/101.14 Mgt at Robertson in this study (data presented in Chapter 5), show a root ratio two irrigated plots with no soil restrictions of 9.1 in Oa.DW3 (Chardonnay/101.14 Mgt) with 465 fine roots and 51 thick, and in and Oakleaf soil form a ratio of 26.3 in Et.WTRSS3 (Shiraz/101.14 Mgt) with 552 thin and 21 thick roots in a Etosha soil form. .

Archer and Hunter (2004) suggested that a ratio of 3 is the threshold. A ratio above 3 is a better-quality root system, and below is a low-quality one. However a low ratio does not necessarily mean a lower quality of root system. The differences in ratios (high in Robertson and low in Stellenbosch) are rather explained by the number of thick roots, with a higher number of thicker roots in the Stellenbosch region causing the ratio to be smaller.

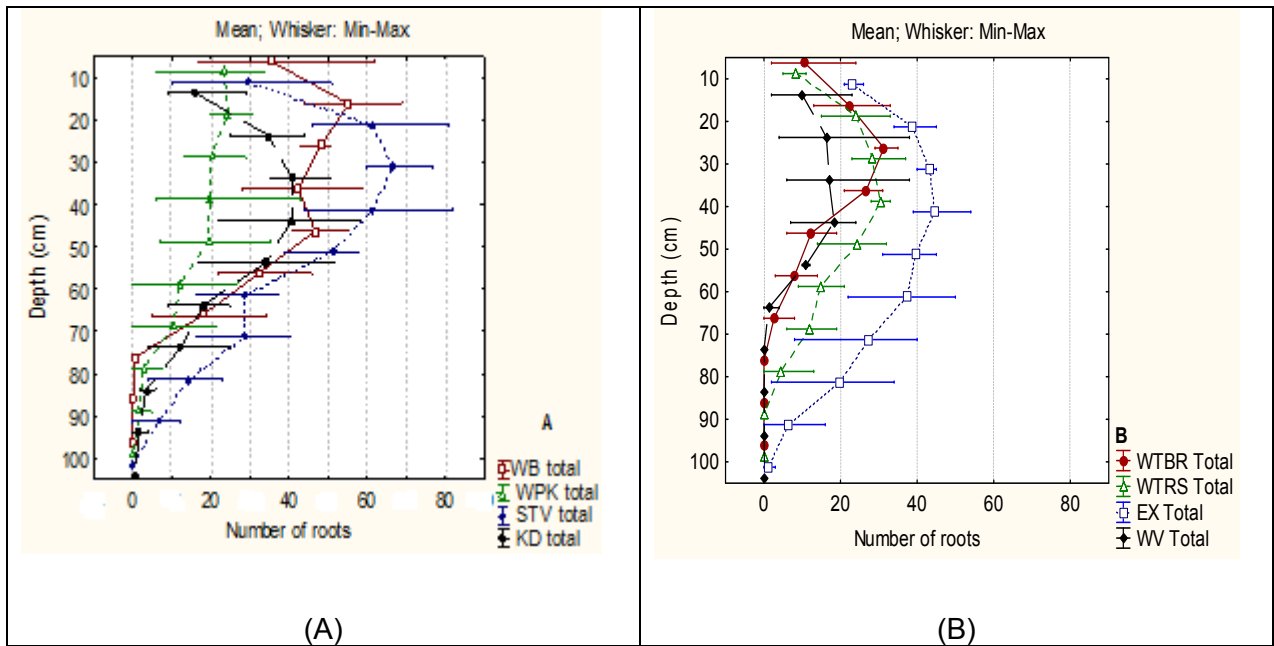


Figure 4.6 Mean plots of the total root distribution at different depths in the four plots of Chardonnay (A) and Shiraz (B).

4.5.2 The consequences of root development for canopy development and berry sugar loading

4.5.2.1 Canopy architectural differences between Chardonnay and Shiraz

Firstly, it is important to report the canopy architectural differences between Chardonnay and Shiraz found in this study.

Figures 4.7 and 4.8 are relevant for a comparison of canopy architectural differences. The differences in shoot length between Shiraz and Chardonnay are notable. Shiraz reached shoot lengths of up to 250 cm, with averages around 150 cm, while Chardonnay reached values of between 50 and 70 cm. In terms of leaf area (cm^2/shoot), Shiraz showed average values of between 2 500 and 3 000 cm^2 , which are similar to those reached by Chardonnay (Figures 4.6 B and 4.7 B). This means that Chardonnay accommodates a similar leaf area in shorter shoots. This architectural difference is caused by the length of the internodes, as the Chardonnay internode distance is shorter than that of Shiraz (data not shown). In terms of leaf size, the average size of the main and lateral leaves was also compared. The average size of an individual main leaf from all the plots of Shiraz was 110.4 cm^2 and the average size of a lateral leaf was 35.1 cm^2 . The average size of a main leaf in Chardonnay was 102.3 cm^2 and that of the lateral leaves was 30.4 cm^2 . The main Chardonnay leaves were 7.3% smaller than the Shiraz main leaves, and the lateral leaves were 13.3% smaller. The shorter internodes and the smaller area per leaf in Chardonnay for the similar total shoot leaf area can be interpreted as a more compact canopy in Chardonnay than in Shiraz. This could play an important role in facilitating the entrance of sun and wind within the canopy, thus affecting the canopy microclimate. These latter factors could influence the water management of these cultivars (which differs, as is shown in Chapter 3).

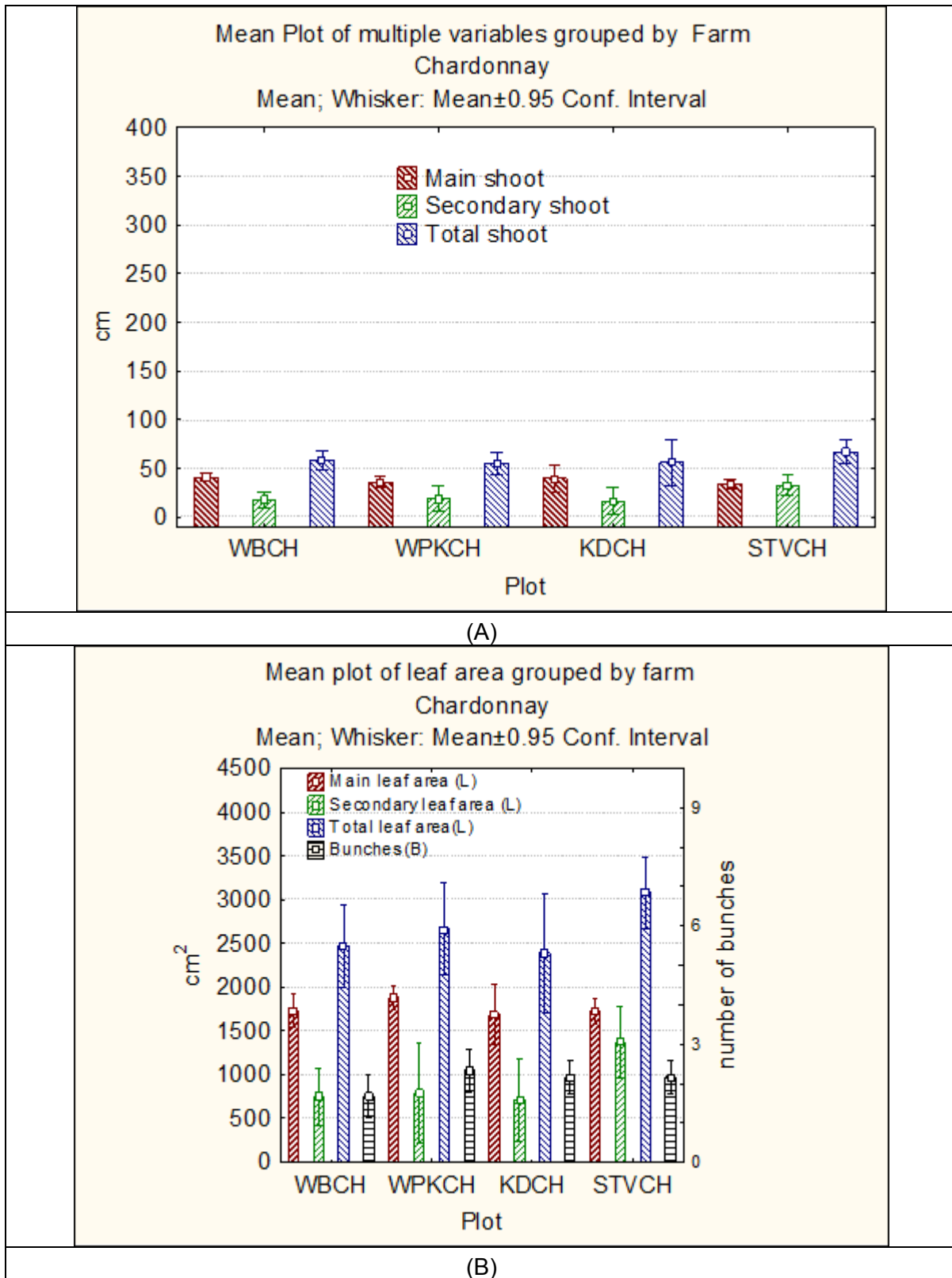


Figure 4.7 (A) Mean plot of shoot length for the four plots of Chardonnay. (B) Mean plot of leaf area per plot in Chardonnay.

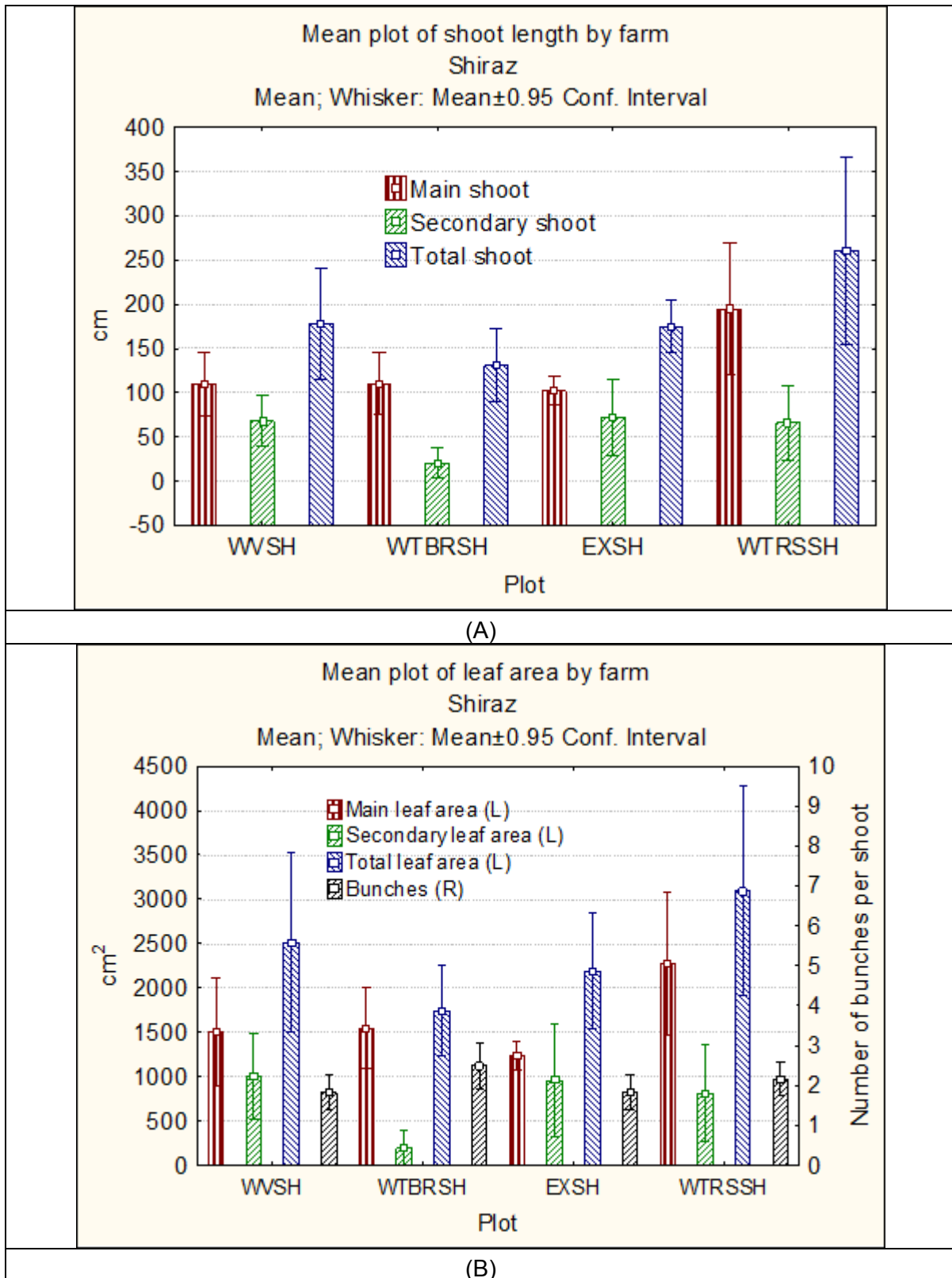


Figure 4.8 (A) Mean plot of shoot length for the four plots of Shiraz. (B) Mean plot of leaf area for the four plots in Shiraz.

4.5.2.2 Canopy growth

It has been widely reported that the subterranean growth of the grapevine is reflected in above-ground growth (Van Zyl & Van Huyssteen, 1980; Richards, 1983; Southey & Archer, 1988; Swanepoel & Southey, 1989; Wang *et al.*, 2001).

In order to discuss the implications of the root size for canopy development, two extreme plots for each cultivar were selected to better analyse this relationship and are discussed further.

Knowledge of the water status is essential in order to interpret the results. The importance of water status for canopy development and berry ripening was described previously. The water status measurements are thus used throughout the discussion of the following points.

The vigour of the two selected plots of Chardonnay and the two plots of Shiraz are compared in Table 4.8.

Smart *et al.* (1985) reported a leaf surface area for Shiraz of between 13 000 m²/ha to 29 000 m²/ha. Table 4.8 shows that, in this study, smaller values than those reported by Smart *et al.* (1985) were found in WTBRSH, which is also the plot with the lowest root density. In terms of shoot densities, Smart (1988) reported that low shoot densities (< 10 shoot/m) produced an open canopy with well-exposed leaves and fruits, in contrast to a high shoot density (> 30 shoots/m), which produced a canopy with the majority of fruit and leaves shaded. The highest number of shoots/m was found in WTRSSH, which was the more vigorous plot and also had the highest leaf surface. WPKCH shows the lowest density of shoots/m. In the case of WPKCH, this is also related to a small number of roots. Due the canopy size of WTRSSH it is suspected that not all the root system was exposed in the 1 m deep profile, that the root system was larger and that some roots had probably penetrated deeper.

Table 4.8 A comparison of the number of roots, pruning mass, shoots per meter and leaf area at véraison in six mini-plots of Chardonnay (CH) and six mini-plots of Shiraz (SH).

Code	Number of roots per m ²	Pruning mass kg/m cordon	Shoots/m	Leaf area m ² /ha at véraison
WPKCH1	121.33	0.339	10.8	12 424.9
WPKCH2	66.67	0.373	9.3	11 931.1
WPKCH3	78.67	0.382	10.6	16 454.3
KDCH1	172.00	0.379	15.4	16 468.9
KDCH2	102.00	0.308	15.3	14 760.1
KDCH3	129.33	0.341	13.3	16 307.9
WTBRSH1	90.67	0.407	16.83	12 093.9
WTBRSH2	80.67	0.308	23.33	8 053.3
WTBRSH3	56.67	0.264	21.83	9 605.5
WTRSSH1	105.33	0.866	14.58	25 728.9
WTRSSH2	91.33	0.978	13.42	21 539.8
WTRSSH3	97.33	0.841	12.83	27 421.6

Table 4.8 does not clearly corroborate that the number of roots is always coincidental with the pruning mass. This is probably because of water availability during the period of maximum shoot growth, and thus it may also be a link to the irrigation practices during this period. The amount of water available between anthesis and véraison can promote high shoot growth because the shoots are a strong sink during this period (Dokoozlian & Kliewer, 1995; Dry & Loveys 1999, 2000; Behboudian & Sing, 2001; Baeza *et al.*, 2007; Poni *et al.*, 2009). The hypothesis is that root systems of different sizes are able to promote a similar shoot growth when they receive the same amount of water before véraison (i.e. when the more active shoot growth takes place). In WPKCH, all the plots received the same water, but WPKCH2 had half of the roots found in WPKCH1 due to soil restrictions, with a slightly higher pruning mass (Table 4.8). After véraison, the increase in vapour pressure deficit of the atmosphere could not be fulfilled by the root system and water stress was manifested in the plant water status measurements (Table 4.10). Towards the end of the season, the water stress in the WPKCH2 plants was evident in the symptoms shown in the canopy, with yellowing and loss of leaves. The water stress probably affected the CO₂ uptake, which was reflected in the dynamic of sugar loading (Figure 4.9). The use of the wall method Böhm (1979), also has some limitations, which could have influenced, in this case, the accessibility to all the roots, since it assumes that the 2-dimensional plane is representative of the rooting volume, Also the rooting depth may not have been well described, especially in this soil of alluvial origin, for which other studies have reported that a high density of roots can grow deeper than 1 m (Southey & Archer, 1988).

In the WTBRSH and KDCH mini-plots, the number of roots corresponded with the pruning weight. A higher total root number was reflected in a higher pruning weight. WTRSSH had double the pruning weight of the WTBRSH, which is not reflected in the number of roots. The problem was in accessing the total root system in WTRSSH, as the soil pits were dug until a compaction layer was found. This compaction layer was between 40 and 80 cm deep, but it seemed that some roots had penetrated this layer. This idea is corroborated by the water status (Table 4.10), since almost no irrigation took place in this plot, but the water status did not show stress values, and the vines developed the largest canopy in this study. Thus it is possible that some roots penetrated the compacted layer and profited from deeper water reserves.

4.5.2.3 Plant water status and sugar loading

Water status plays an important role in the stomatal aperture and thus in CO₂ uptake. Photosynthesis is markedly reduced and the concentration of sucrose and starch decreases in water-stressed plants (Rodrigues *et al.*, 1993), which can influence the dynamic of sugar loading into the berry (Wang *et al.*, 2003).

In Table 4.9, values from Deloire *et al.* (2004) were used as references to interpret the results of the plant water potential at predawn.

Table 4.9 Scale for predawn values

Values of predawn leaf water potential (Mpa)	Degree of water constraint and stress (Deloire <i>et al.</i> , 2004)
0 to - 0.2	Absent to very mild
- 200 to - 0.4	Moderate and progressive
- 400 to - 0.6	Moderate to severe
-600 to - 0.8	Severe

The plant water status measurements of predawn leaf water potential and midday stem water potential are shown in Tables 4.10 and 4.11, along with the standard deviation of each measurement.

Table 4.10 Plant water measurements in each mini-plot of WPKCH and KDCH for three different dates, the mean of the measurement and the standard deviation.

Chardonnay			Ψ Predawn Mpa		Ψ Midday stem Mpa	
Plot	date	Miniplot	mean	Std. dev.	mean	Std. dev.
WPKCH	7/01/09	1	0.35	0.05	1.18	0.16
		2	0.33	0.03	1.33	0.06
		3	0.28	0.08	0.83	0.16
	23/01/09	1	0.67	0.12	1.99	0.16
		2	1.06	0.21	1.30	1.13
		3	0.22	0.05	1.09	0.19
	4/02/09	1	1.03	0.14	1.82	0.06
		2	0.87	0.25	1.88	0.17
		3	0.48	0.08	1.35	0.17
KDCH	7/01/09	1	0.32	0.06	0.82	0.26
		2	0.37	0.06	1.27	0.03
		3	0.32	0.08	0.83	0.13
	23/01/09	1	0.18	0.05	0.89	0.26
		2	0.22	0.06	1.24	0.21
		3	0.18	0.06	0.83	0.20
	4/02/09	1	0.27	0.12	1.05	0.11
		2	0.29	0.10	1.02	0.06
		3	0.25	0.05	0.90	0.09

Table 4.11 Plant water measurements in each mini-plot of WTBRSH and WTRSSH in five different dates, the mean of the measurement and the standard deviation.

Shiraz			Ψ Predawn Mpa		Ψ Midday stem Mpa		
Plot	date	Miniplot	mean	Std. dev	mean	Std. dev	
WTBRSH	15/01/09	1	0.30	0.10	0.57	0.06	
		2	0.20	0.09	0.60	0.05	
		3	0.37	0.08	0.63	0.06	
	29/01/09	1	0.21	0.01	0.75	0.09	
		2	0.16	0.02	0.82	0.13	
		3	0.26	0.12	0.87	0.08	
	7/02/09	1	0.27	0.06	0.65	0.13	
		2	0.47	0.18	0.71	0.08	
		3	0.49	0.05	0.63	0.04	
	17/02/09	1	0.72	0.03	1.38	0.06	
		2	0.75	0.09	1.35	0.06	
		3	0.67	0.16	1.47	0.09	
	15/03/09	1	0.29	0.10	1.10	0.05	
		2	0.22	0.16	1.12	0.06	
		3	0.18	0.04	1.12	0.28	
	20/03/09	1	*	*	0.90	0.13	
		2	*	*	1.10	0.05	
		3	*	*	1.26	0.08	
	WTRSSH	15/01/09	1	0.73	0.34	0.88	0.08
			2	0.53	0.03	0.63	0.13
			3	0.75	0.15	1.52	0.03
29/01/09		1	0.16	0.05	1.25	0.18	
		2	0.10	0.07	1.15	0.22	
		3	0.21	0.03	1.55	0.10	
7/02/09		1	0.13	0.06	0.65	0.14	
		2	0.30	0.09	0.57	0.13	
		3	0.13	0.06	0.65	0.06	
17/02/09		1	0.18	0.10	1.10	0.23	
		2	0.18	0.08	0.84	0.05	
		3	0.30	0.04	1.30	0.05	
15/03/09		1	0.38	0.06	1.47	0.08	
		2	0.37	0.03	1.32	0.36	
		3	0.53	0.08	1.57	0.15	
20/03/09		2	*	*	0.95	0.04	
		3	*	*	0.90	0.05	

The sugar loading corresponds to the amount of sugar loaded into the berry in relation to the berry volume (Brenon *et al.*, 2005). The results can be interpreted as a curve of loading and on a per-day basis. The sugar-loading curve shows when the zero sugar-loading point is reached, and the daily dynamic of sugar loading shows how much sugar has been loaded on a per-day

basis. The dynamic on a per-day basis seems to be correlated with grapevine functioning, since the water deficit inhibits the sugar unloading in the berry (Wang *et al.*, 2003).

The sugar loading measurements were taken from véraison, which for Chardonnay corresponded to 2009-01-7 and for Shiraz to 2009-01-16, and seem to be closely related to water status. The water status of the mini-plots and their dynamics of sugar loading are discussed below.

4.5.2.3.1 WPKCH

A large difference was found between the sugar-loading dynamics of the three different plots. It was reported above that the three WPKCH mini-plots had the smallest root systems in this study, but also a high variability in the total number of roots between the mini-plots (Table 4.10 & Addendum 4.1). A larger canopy is reported for WPKCH3 based on the pruning weight results (Table 4.8). The three mini-plots received the same amount of water, but the plant water status measurements were different, as was the dynamic of sugar loading (Table 4.10, Figures 4.9 & 4.10). WPKCH2 was the first to show stress symptoms in the canopy, followed by WPKCH1; WPKCH3 did not show any symptoms of water stress in the canopy, despite presenting a larger canopy. At véraison (i.e. 2009-01-07), the predawn water status (Ψ_{pd}) of all three mini-plots was around -0.3 MPa, which is considered a non-water-stress situation. Towards 2009-01-23 a marked difference took place between the plots, and values of -1.1 MPa Ψ_{pd} in WPKCH2 and -0.7 MPa Ψ_{pd} in WPKCH1 were registered, which are considered plant water stress (Deloire *et al.*, 2004). This is reflected in the curves of sugar loading from 2009-01-23 until 2009-01-30 (Figure 4.10). Water was given around 2009-01-29, which is shown in the recovery of mini-plots 1 and 3, but not in 2; this is probably due to problems with hydraulic conductivity, perhaps by embolism-induced cavitation of the xylem vessels (Flexas *et al.*, 2010), and probably enhanced by an unbalanced root:shoot proportion. The values were -1.0 MPa Ψ_{pd} in WPKCH1 and -0.87 MPa Ψ_{pd} in WPKCH2 on 2009-02-04, which is equivalent to water stress. WPKCH3 measured -0.48 MPa, representing a non-stress situation.

The variation in the total number of roots and root distribution related to canopy size are the most probable causes of these differences. WPKCH2 showed the earliest canopy stress symptoms, and was affected most in terms of sugar loading. The root system of WPKCH2 was the smallest of all the mini-plots, but it had a similar canopy size (i.e. pruning weight). WPKCH1 also showed canopy stress towards the end of the season, but it could recover from the stress situation, as reflected in the sugar loading. WPKCH1 showed double the number of total roots than WPKCH2, which may be responsible for its better recovery.

The more regular curve in terms of sugar loading was found for WPKCH3, with no stress signs in the canopy and plant water status measurements that proved a non-stress situation. Although WPKCH3 had the same number of roots as WPKCH2, but a larger canopy, the difference was probably in the root distribution (Addendum 4.1). In WPKCH3 a few roots managed to grow into the prismatic B horizon. These few roots probably helped the plant to profit from water held in this horizon. As was suggested by Van Huyssteen (1988a), sporadic deep roots could make a significant contribution to the water supply of the grapevine during periods of prolonged water stress, although without adding to the vine vigour.

4.5.2.3.2 KDCH

In the KDCH plots, the Ψ_{pd} readings showed no stress on the dates it was measured, with no great differences on each date between the mini-plots (Table 4.10). The values were always lower than -0.37 MPa, which was reported in the one plot at véraison (see Table 4.10). In terms of Ψ_{mds} , differences are reported between the mini-plots. The KDCH2 showed more negative values than the other two mini-plots, with -1.3 MPa on 2009-01-07 and -1.3 MPa on 2009-01-23. This plot had fewer total roots than the other two (Table 4.8).

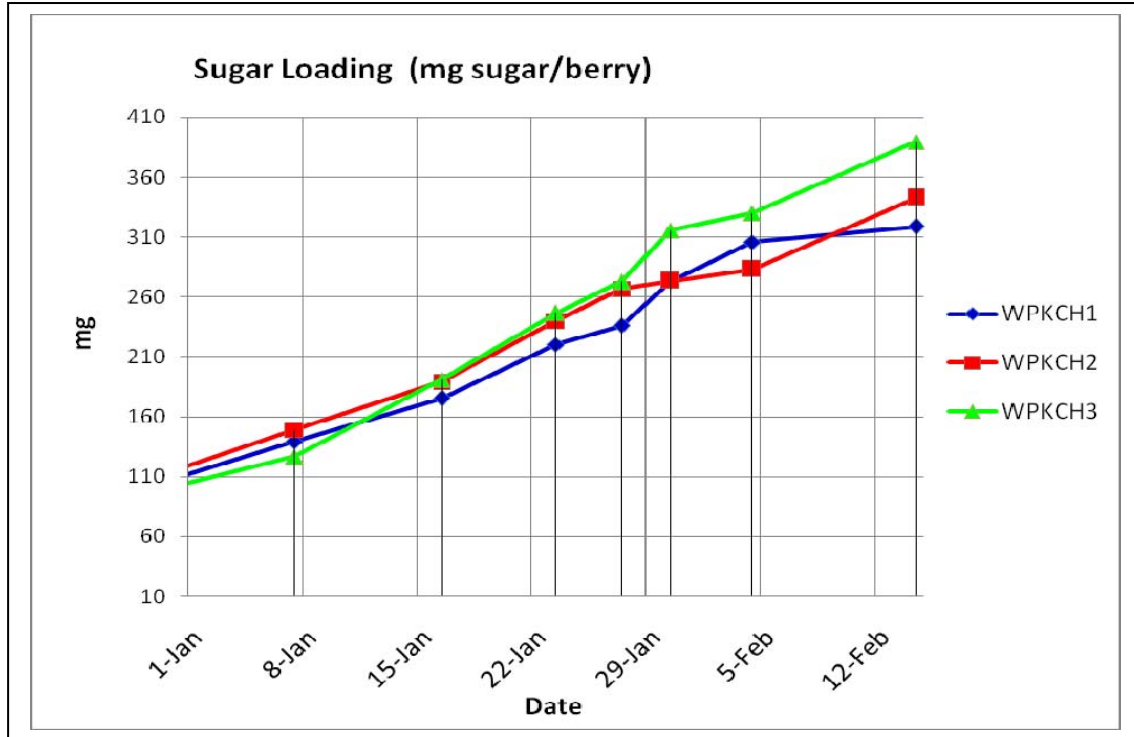


Figure 4.9 Curves of sugar loading for WPKCH mini-plots.

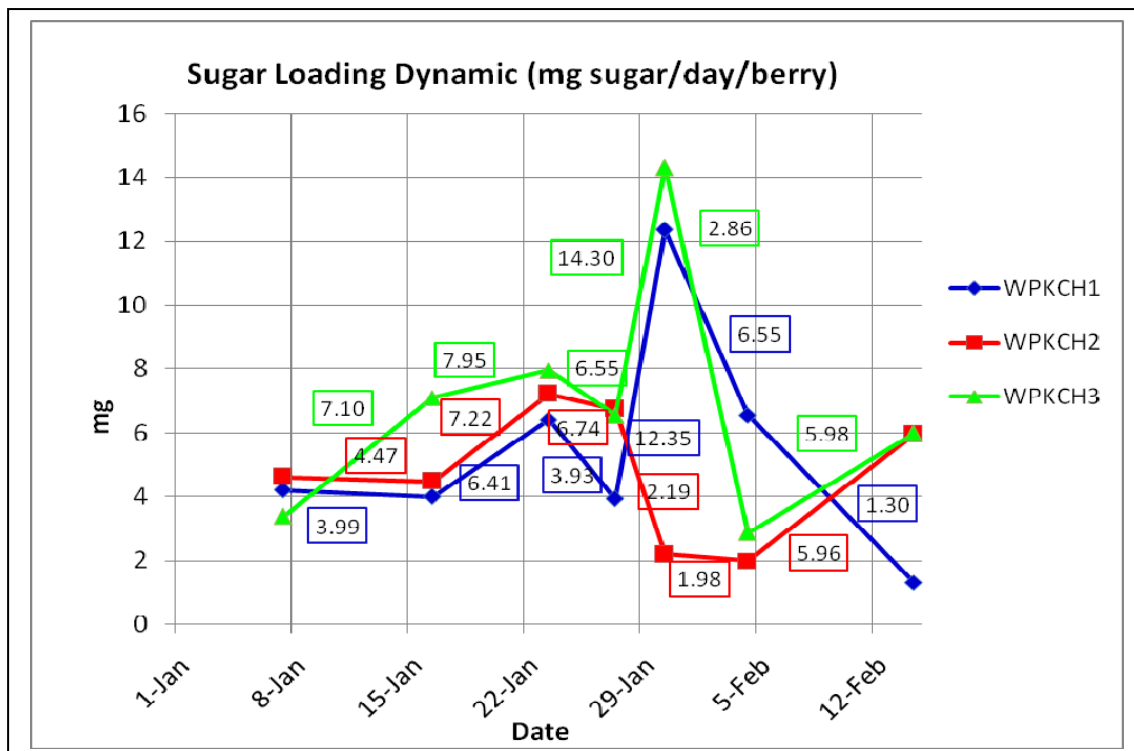


Figure 4.10 Curves of the daily dynamics of berry sugar loading for the WPKCH mini-plots.

In a dry region such as Robertson, where a high vapour pressure deficit (VPD) occurs at midday during January and February (i.e. ripening period), the total number of roots seems to play a fundamental role in maintaining the plant water status, and this is related to stomatal aperture. Regarding the sugar loading of KDCH2, there was a slow daily sugar loading before 2009-01-30, probably related to the smaller stomatal conductivity during midday, but followed by good recuperation from then on. The three plots showed a progressive curve of sugar-loading dynamics (to different degrees) until the zero sugar-loading point was reached. Consequently, the more negative values reached during midday in KDCH2 did not have severe consequences for sugar loading, and were only related to the capacity of this mini-plot to fulfil the water demand during midday due to the smaller number of roots in comparison to the other plots.

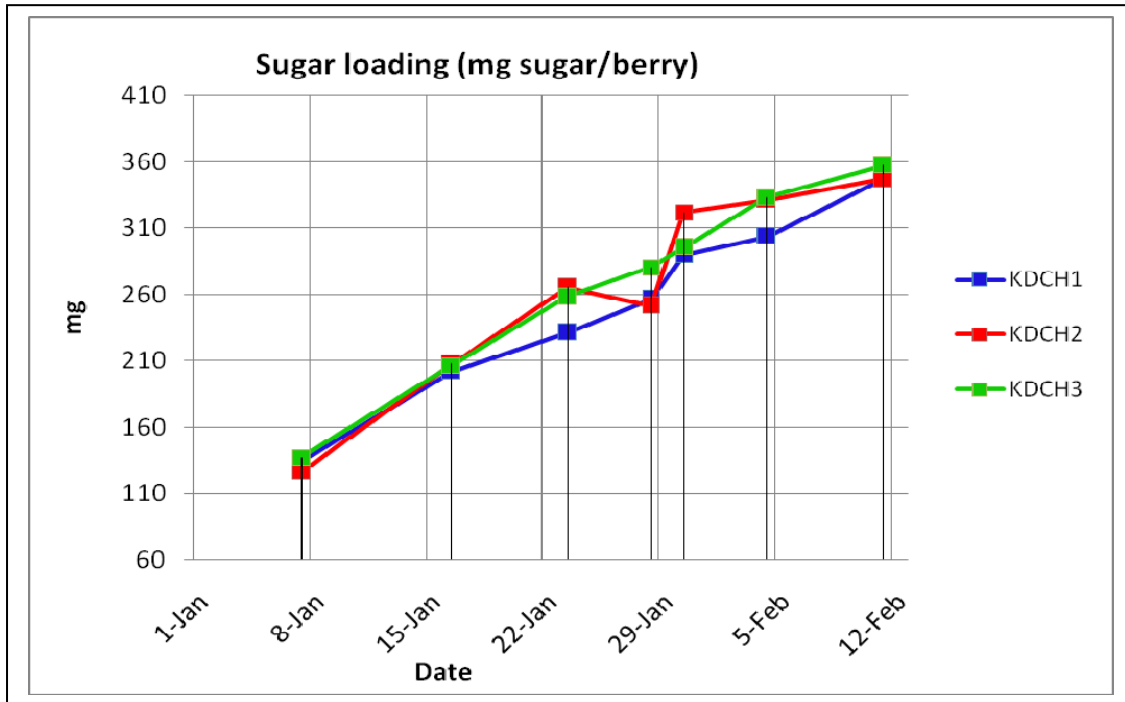


Figure 4.11 Curves of berry sugar loading for KDCH mini-plots.

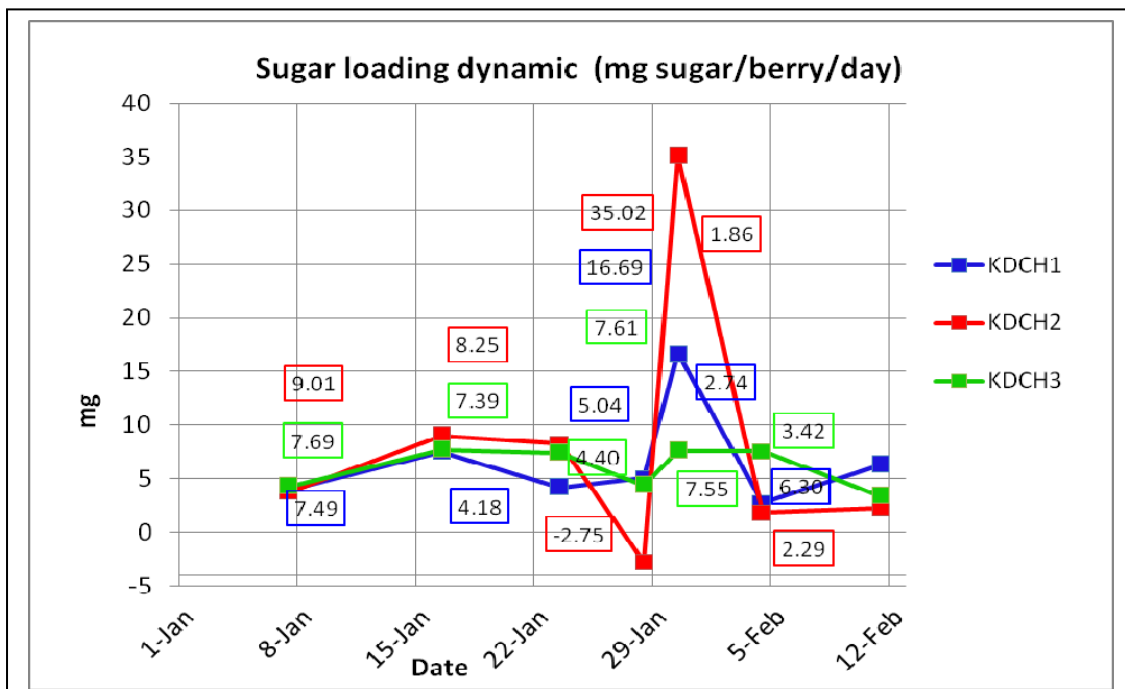


Figure 4.12 Curves of daily dynamics of berry sugar loading for the KDCH mini-plots

4.5.2.3.3 WTRSSH

The more negative Ψ_{pd} values at véraison in WTRSSH are reported in Table 4.11. All the Ψ_{pd} showed a non-stress water status from 2009-01-27 onwards. Regarding the Ψ_{mds} measurements, in most of the readings WTRSSH3 showed a more negative water status than the other two mini-plots. These lower Ψ_{mds} values are reflected in a slightly smaller curve of sugar loading (Figures 4.13 & 4.14), until the zero sugar-loading point was reached on 2009-02-17.

Considering that the Ψ_{pd} showed no stress at predawn, with similar values in all the readings from the three mini-plots, and that the difference only happened at Ψ_{mds} , it is believed to be related to the ability of that plot to cover the atmospheric water demand as a consequence of the slightly smaller root system or the accessibility to a water reservoir in the soil. Due to the position of this soil in landscape as an alluvial terrace of the Breede river, the latter seems to be more possible, although this is only speculative. In terms of irrigation, water was only applied near harvest 2 times (anecdotal data).

WTRSSH had the largest canopy in this study, with two and even three times larger pruning weight than that of WTBRSH, depending on the mini-plot (Table 4.8). It also showed big differences in berry weight evolution (Figure 4.17). A high level of berry shrivelling took place in WTRSSH, and it has been reported that this could be the result of phloem flow disruption together with berry transpiration (McCarthy & Coombe, 1999), or perhaps some back flow of water to the plant (Tyerman *et al.*, 2004). Considering that the plant water status does not show a stress situation, perhaps the discontinuity in the berry xylem, together with berry transpiration, may be the cause for the berry shrivelling in this case, the back flow to the plant should be considered as a possibility, since WTRSSH had a much larger canopy than WTBRSH.

4.5.2.3.4 WTBRSH

A relatively regular sugar-loading curve is reported between the three mini-plots, with relatively similar Ψ_{pd} and Ψ_{mds} water status reported for each date (Table 4.11). A high peak occurred in the sugar-loading curve for WTBRSH3 before 2009-01-27, followed by a decrease until 2009-02-07 (Figures 4.15 & 4.16). This could be related to the small total number of roots in WTBRSH3. The vines are relatively balanced in terms of total root number and pruning mass, with WTBRSH1 having almost double the total number of roots and pruning mass as WTBRSH3 (Table 4.8). The zero sugar-loading point was reached on 2009-02-17.

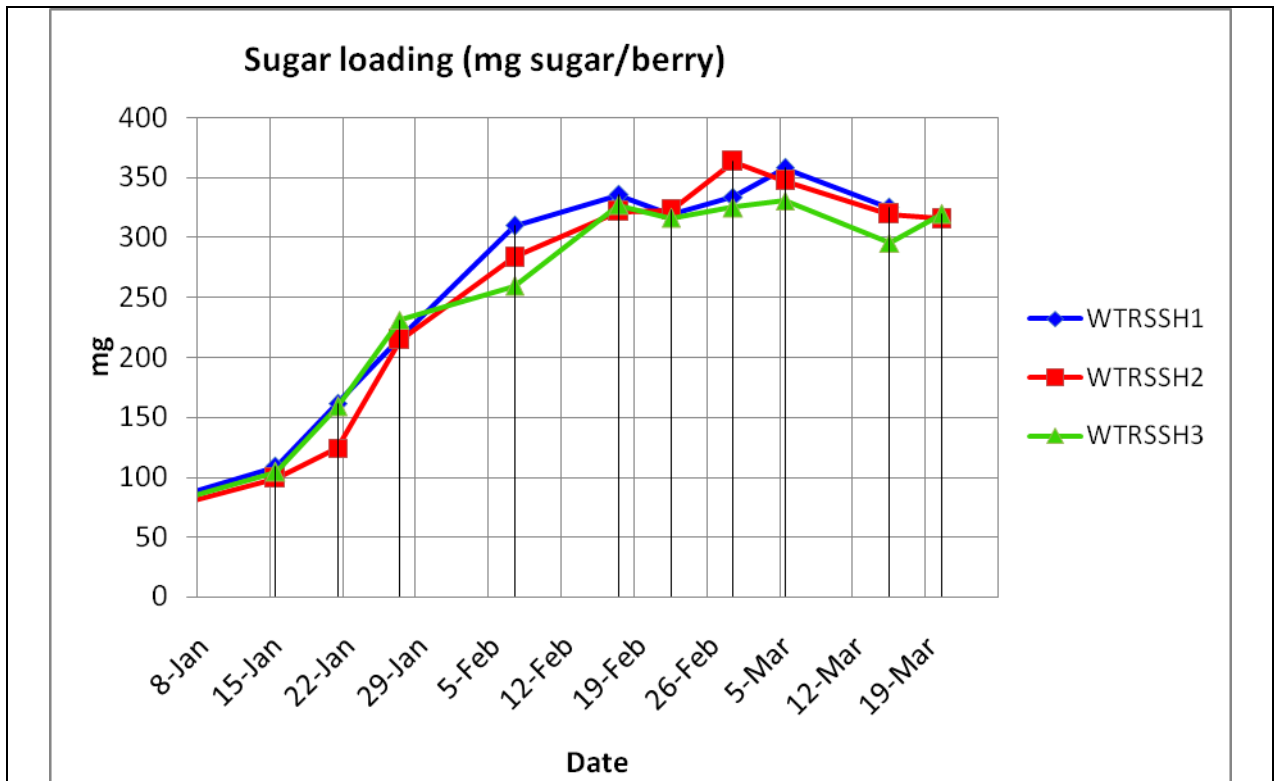


Figure 4.13 Curves of berry sugar loading for WTRSSH mini-plots.

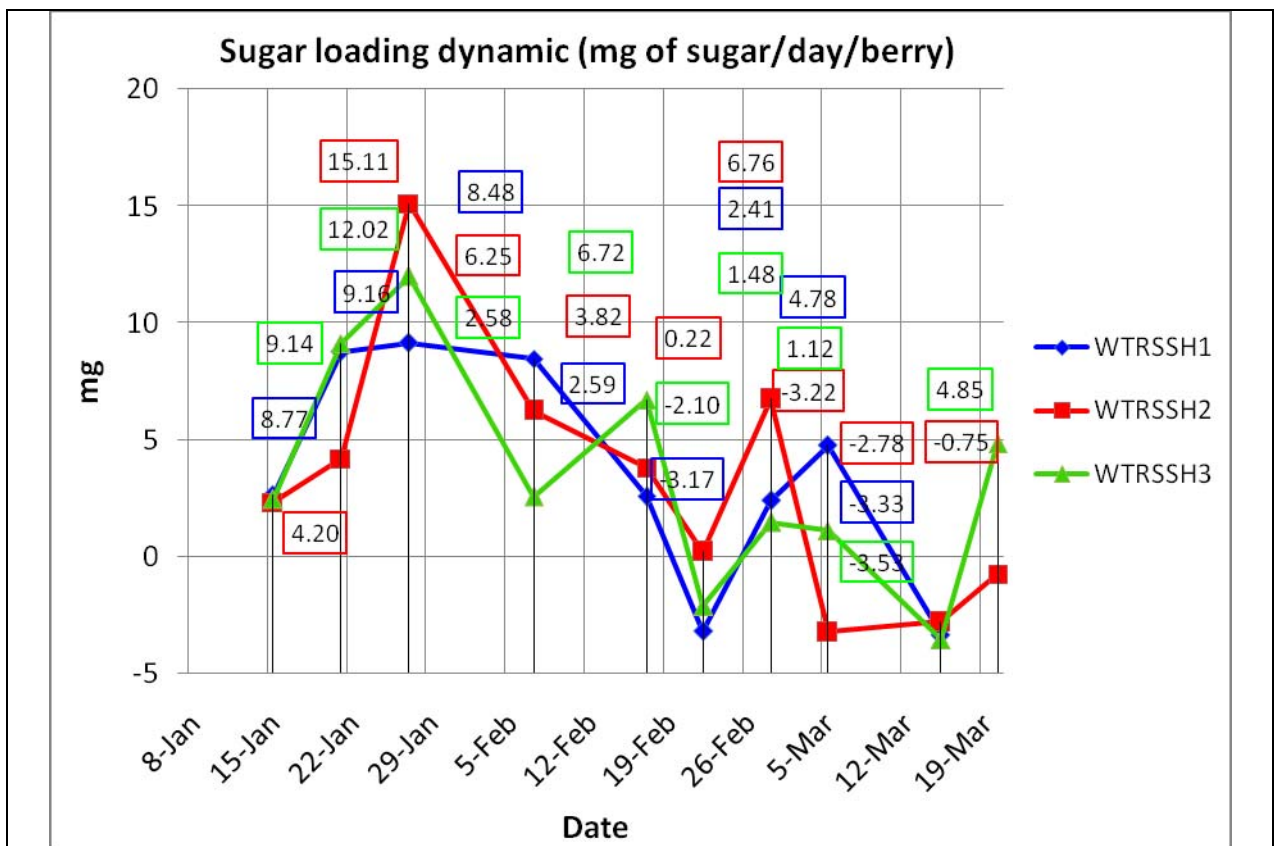


Figure 4.14 Curves of the daily dynamics of berry sugar loading for the WTRSSH mini-plots.

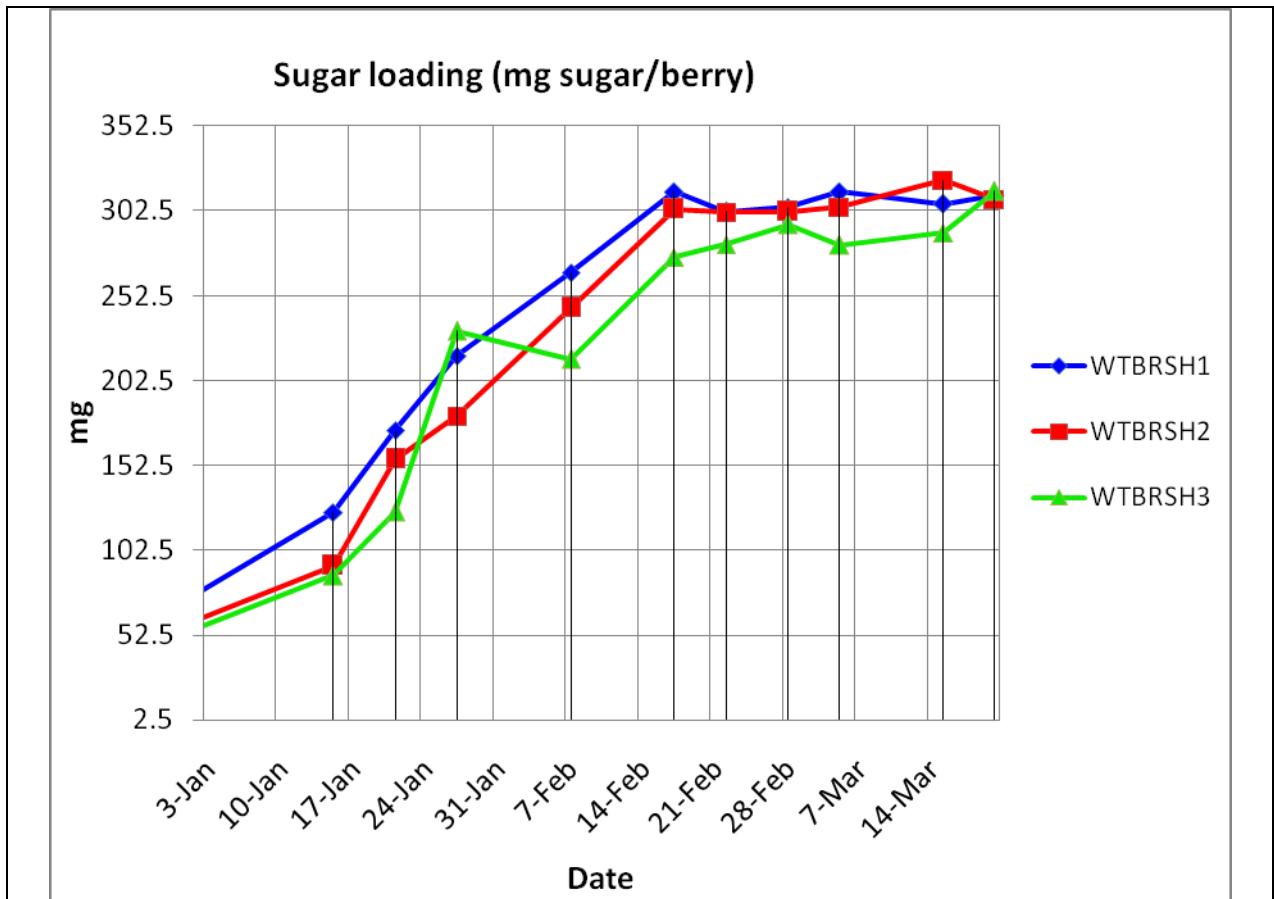


Figure 4.15 Curves of berry sugar loading for the WTBRSH mini-plots.

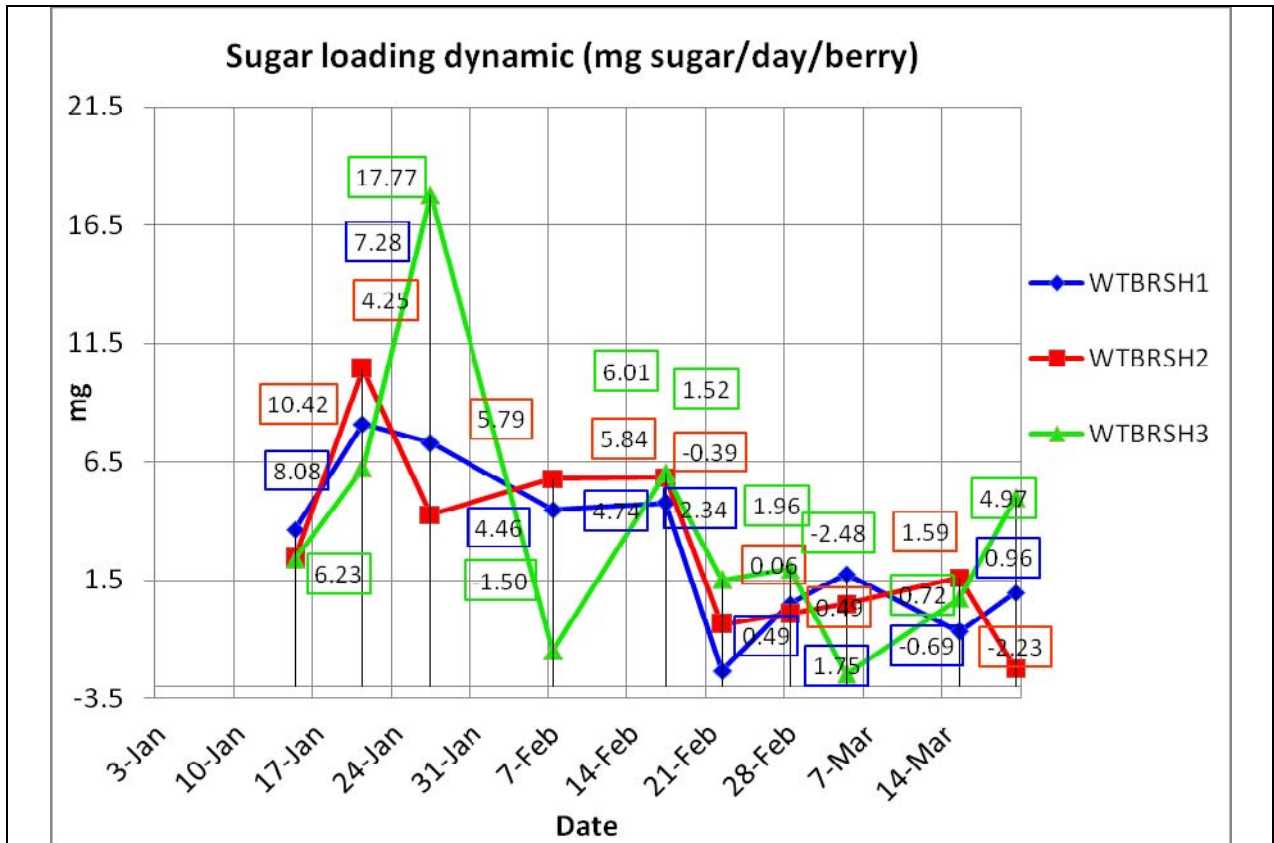


Figure 4.16 Curves of the daily dynamics of berry sugar loading for the WTBR mini-plots.

In terms of berry volume, it was observed that WTRSSH, the plot with the largest canopy, presented a higher berry weight than WTBRSH, the plot with the smallest canopy, during most of the ripening period (Figure 4.17). By the time of harvest, the weight of 100 berries sampled was very similar. A reduction of 40 g took place between 2009-02-17 and 2009-03-20 (i.e. harvest date). The average for the period is 12.5 mg/day, compared with the mass peak reached around 2009-02-07. Those 40 g represent a 23.5% loss in weight, which is a considerable amount. McCarthy and Coombe (1999) reported that berry weight loss takes place in Shiraz around 91 days post-flowering, irrespective of irrigation treatments, which suggests it may be a genetic characteristic of Shiraz. The date of flowering was not recorded in this study, although the two plots started losing weight from 2009-02-17 onwards. The difference in the magnitude of berry mass was evident.

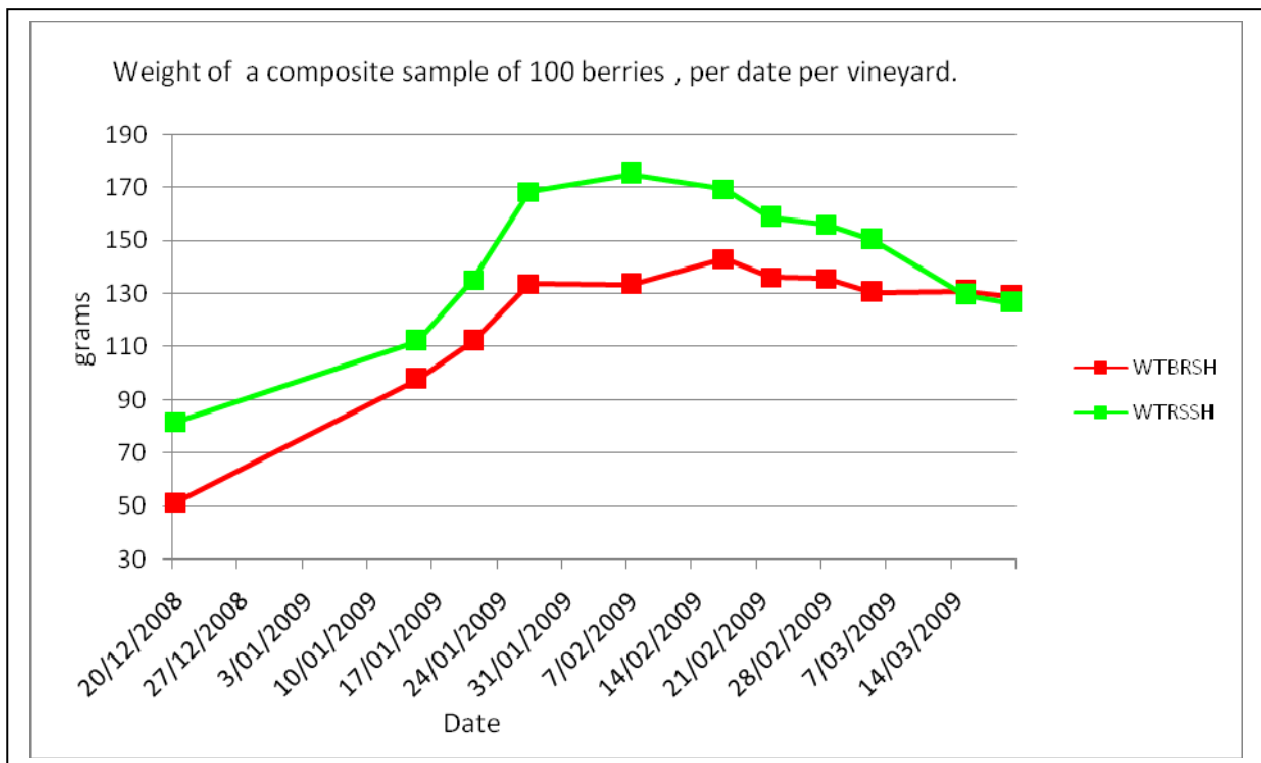


Figure 4.17 Comparison of berry weight development between the largest and the smallest canopies of Shiraz in a study in Robertson.

4.6 Conclusions

Root growth in the field was slowed by a combination of soil physical and chemical stresses and their intensity. In Robertson, the root system was limited by parent material (hard rock), hard pan carbonates, abrupt changes in structure and texture, the ESP (exchangeable sodium percentage), the soil salinity, the pH and the content of magnesium. The stresses operating may vary continually and differences in these soil properties were found within only metres. If none of these limitations were present, a larger number of roots could be found. The soil properties determine the rooting depth, the density and the extent of the root preference zone. The influence of irrigation is subject to the soil properties. The roots of 101.14 Mgt under an irrigation regime can grow without problems to a depth of 100 cm if the soil physical and chemical properties allow it. In some situations, it was found that some 101.14 Mgt roots were

able to penetrate the limitations or find cracks, and these deep roots would appear to contribute to water uptake.

A high average percentage of the total roots per profile (i.e. 91.26%) was found in the top 60 cm of the soil profile. This is related to soil properties limiting the roots' ability to penetrate deeper. In measurements done in the same area with the same rootstock under irrigation, but with no soil limitations in depth, the percentage of roots in the top 60 cm decreased to 66.23%.

In hydraulic fertility terms, the size and depth of the root system are also related to the reaching of different layers that can act as water sources, and this is linked intimately with the buffering capacity of the root system to deal with atmospheric changes, particularly during the day, in order to maintain the gas exchange at stomatal level without affecting the uptake of CO₂, but avoiding dehydration. The size and depth of the root system are also associated with the cultivar's capacity for stomatal control. In this study it was observed in WPKCH that a deep root system can have more buffering capacity than a larger but shallower one, in this particular case the deeper root system grew into a more clayey layer with different hydraulic properties, and the vines profited from the water storage there.

It is also reported in this study that, in several cases where a water constraint/water stress was observed, the dynamic of sugar loading into the berries was affected. This could hypothetically be associated with water status, as the latter is related to stomatal conductivity and thus to net CO₂ assimilation rate. This is interesting from a physiological point of view and could be used as an indicator of the grapevine functioning.

In Robertson, Chardonnay ripens in the middle of the hottest month (February), which means that a high atmospheric demand occurred in the last weeks of berry ripening, creating some environmental stress in the ripening berry. This also affected the Shiraz, and a vineyard with a large canopy was found in this study to lose 23.5% of berry mass due to dehydration during the last four weeks prior to harvest. The use of rootstocks that are more adapted to forage for water seems to be an alternative under dry conditions in order to ensure better grapevine functioning, especially during the hours of high atmospheric water demand.

This study concludes that each soil will have a restrictive potential, at which the interaction of all the possible stresses will be reflected by the size and distribution of the root system. The size of the root system is importantly related to the accessibility of water. Two important stages are recognised – canopy growth and canopy maintenance. In an arid zone, such as Robertson, these depend upon irrigation and are extremely important. They can perhaps be managed to a greater extent than in more wet areas. Firstly, the amount of water available prior to véraison has been reported to be related to the development of the canopy, and, secondly, in Robertson, the increase in atmospheric water deficit during the ripening period after véraison exerts an increased demand for water. In this regard, not all the soil properties-root system combinations performed satisfactorily in maintaining the canopy functioning, which affected the berry sugar loading and, in more extreme cases, the berry volume.

4.7 Literature cited

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Chapter 5

Research results

**An investigation into the relationship between
soil type and root system morphology in the
Robertson area**

An investigation into the relationship between soil type and root system morphology in the Robertson area

5.1 Abstract

Forty soil profiles were characterised in the Robertson valley. Each profile, for which root profiles were described, was associated with one of two scions, namely, Chardonnay or Shiraz. The results for each scion were analysed separately. The root density to a depth of 60 cm and to a depth of 100 cm was calculated. This data together with the total number of root contacts in the profile, the total number of root contacts with a diameter < 2 mm and > 2 mm, rooting depth and year of planting were analysed by means of Principal Component Analysis and 3 groups were identified, namely shallow rooting, and deep rooting with a higher density of roots and deep rooting with a lower density of roots. The extreme cases in each group are discussed in greater detail. The threshold at which the number of root contacts was found to considerably decrease for the shallow root system was found to be between 40 and 60 cm, while for the deep root system, a considerable percentage of the total root contacts was found between 80 and 100 cm depth. The spatial distribution of roots for the extreme cases in each group appeared to be predominantly a function of the soil properties rather than the genetic component or cultural practices. This does not, however, imply that root distribution is totally independent of these factors. The cultural practices, together with a combination of different chemical restrictions, appear to have a stronger effect in the intermediate group, namely the deep rooting low density (DRL) vineyards. The two groups of shallow rooting and deep rooting with high density could be associated with groupings of soil families (South African soil taxonomic system) that shared important soil properties. The shallow root systems were related to Glenrosa, Valsrivier, and Gamoep soils, and the deep rooting-high density group with the Oakleaf, Augrabies and Brandvlei soils. The shallow root systems of the first group are associated with solid restrictions to root growth as a result of the presence of parent rock or a hardpan carbonate layer or a very dense clay layer. The second group consisted of soils that originate from deposited material, without solid layers that limit depth penetration of roots.

Key words: Roots morphology, soil properties, soil type, Robertson.

5.2 Introduction

The grapevine needs to balance itself constantly between two changing environments – the rhizosphere and the troposphere. The soil-root-canopy system is extremely complex, and the role of the roots in this system is extremely important, since they are a fundamental link between the soil characteristics and the canopy. A direct correlation ($r= 0.97$) between the size of the root system and above-ground vine performance has been reported by Archer *et al.* (1988). A correlation between the size of the root system and the canopy has also been reported by Southey & Archer (1988), Van Huyssteen (1988a) and Swanepoel & Southey (1989).

Due to the important functions performed by the root, it significantly impacts on the performance of the grapevine (Southey & Archer, 1988; Morlat & Jacquet, 1993; Taiz & Zeiger, 2002). Root system morphology is reported to be modified, in different degrees, by the genetic material (Pongracz, 1983; Swanepoel & Southey, 1989; Southey, 1992; Morano & Kliwer, 1994),

although Smart *et al.* (2006) did not find evident genetically determined differences in root distribution in their comprehensive review.

The morphology of the root system has also been reported to be modified by planting distance (Archer *et al.* 1988, Hunter, 1998), trellis system (Van Zyl & Van Huyssteen, 1980; Archer *et al.*, 1988), irrigation system (Van Zyl, 1988; Araujo *et al.*, 1995; Bengough *et al.*, 2006; Soar & Loveys, 2007), plant age (Van Zyl, 1988), and canopy management practices such as partial defoliation (Hunter & Le Roux, 1992; Hunter *et al.*, 1995).

Soil physical and chemical properties also play an important role modifying the root system morphology (Van Huyssteen & Weber, 1980; Conradie, 1988; Smart *et al.*, 2006). The soil agronomic potential has been defined as the soil aptitude to ensure the plant's vegetative growth, provided that soil can fulfil the need for water, minerals and oxygen at the root level (Champagnol, 1997). The three components of soil fertility (physical, chemical and hydraulic fertility) are explained by three soil parameters, namely texture, structure and chemical composition. These play an important role in determining the soil porosity and the "rooting soil depth", defined as the volume of soil available in which roots can grow and in the extent of the roots' preferred zone (Champagnol, 1984).

A clear tendency for better grapevine performance with increasing soil depth has been also established (Van Huyssteen, 1988a). The soil physical characteristics will influence the balance between water/air and the supply of minerals to the grapevine's roots (Saayman & Van Huyssteen, 1980; Van Huyssteen, 1988b). Soil properties will greatly influence a specific rootstock genotype (this study, Chapter 4). They will play an important role defining the rooting depth and the extension of the so-called rooting zone (Champagnol, 1984).

The rooting depth is extremely important. Improvements in grapevine performance have been reported by means of extending soil availability with soil preparation before planting (Van Huyssteen, 1988a). The rooting depth is related to water storage capacity (Myburgh *et al.*, 1996). The rooting depth has been also associated with the buffer capacity, especially in hot climatic conditions. A rooting system that better colonises the profile has a better buffer capacity when it is confronted with heat events such as heat waves, and better recovery thereafter (Archer & Hunter, 2005). Because of the importance of the rooting depth in grapevine performance, it has been used as a criterion to characterise viticultural terroirs (Bodin & Morlat, 2006).

This study comprises descriptive research on the soils in the Robertson area and their relationship with the root system morphology of two cultivars on various rootstocks. The soil was considered to restrict root growth *per se*, and the restrictive properties for each profile were interpreted in relation to the response in the development of the root system. From this point of view it is possible to say that a soil has a "rooting restriction potential" that can vary according to many of the soil properties, and that the root system is highly affected in depth and density by the magnitude of these restrictions. Forty soil profiles were investigated and the root system in each was mapped. The results of this research are presented below.

5.3 Materials and methods

5.3.1 Plot selection

The plots form part of a research network in commercial vineyards in Robertson. There were two scions, namely Chardonnay and Shiraz. The observation points were well distributed throughout the Robertson Valley. Additional information concerning the plots is presented in Tables 5.1 and 5.2.

Table 5.1 Vineyard characteristics for reference Chardonnay plots in the Robertson Valley

Chardonnay Plot	Rootstock	Planting date	Vine Spacing	Trellis System	Irrigation type	Frequency in peak time
KB2	R110	1998	2.4 x 1.2	4-wire ext P	micro	265m ³ xweek
BSR2	R110	2004	2.4 x 1	3 strand Hedge	micro	6hxweek
E4	Ramsey	1998	2.5 x 1.2	4-wire ext P	micro	7hxweek
EX3	101-14Mgt	1995	2.5 x 1.5	5-wire Double ext P	drip	1xweek
G5	-	1996	2.75 x 1.2	5-wire ext double P	drip	40m ³ /ha/day
GB2	R110	1987	2.4 x 1.2	4-wire ext P	drip	2xweek
WV2	R110	2004	2.4 x 1	4-wire ext P	micro	6hxweek
KD3	101-14Mgt	1996	2.5 x 1.2	4-wire ext P	drip	2xweek
KK2	R110	2002	2.4 x 1.2	5wire ext P	micro	4hxweek
L2	R110	1998	2.5 x 1	4-wire ext P	drip	2xweek
RB3	101-14Mgt/ R110	1996	2.4 x 1.5	5-wire Double ext P	micro	6hxweek
SBV3	101-14Mgt	1994	2 x 1.5	5-wire ext P	drip	12hxweek
WB3	101-14Mgt	1996	2.5 x 1.4	4-wire ext P	drip	18hxweek
DW3	101-14Mgt	1995	2.2 x 1.2	2 strand hedge	micro	6hxweek
WTPR1	R99	1988	2.6 x 1	5-wire ext P	micro	2xweek
WTRS1	R99	1988	2.5 x 1	5-wire ext P	drip	2xmonth
GL1	R99	1999	2.5 x 1.2	3-wire P	drip	6hx3xseason

Table 5.2 Vineyard characteristics for reference Shiraz plots in the Robertson Valley

Shiraz Plot	Rootstock	Planting date	Vine Spacing	Trellis System	Irrigation type	Frequency in peak time
KB2	R110	2001	2.4 x 1.2	4-wire ext P	drip	265m ³ xweek
BSR2	R110	2002	2.44 x 2	3 strand Hedge	micro	6hxweek
DW5	-	-	2.5 x 1.2	3-wire P	drip	16hxweek
E2	R110	2000	2.5 x 1.2	4-wire ext P	micro	3x6hxweek
EX3	101-14Mgt	2000	2.5x1.5x1.25*	5-wire double ext P	drip	1xweek
G2	R110	1999	2.75 x 1.2	5-wire ext double P	drip	40m ³ /ha/day
GB2	R110	1995	2.4 x 1.2	5-wire double ext P	drip	2xweek
GL1	R99	2000	2.5 x 1.2	2-strand hedge	micro	3hxweek
WV3	101-14Mgt	1998	2.4 x 1	4-wire ext P	micro	6hxweek
KD6	Paulsen 1103	2000	2.5 x 1.2	3-wire P	drip	2xweek
KK1	R99	1999	2.4 x 1.2	5-wire ext P	micro	4hxweek
L 2	R110	2001	2.5 x 1.5	5-wire double ext P	drip	2xweek
SBV2	R110	2000	2 x 1.5	5-wire ext P	drip	12hxweek
RB3	101-14Mgt	1992	2.4 x 1.2	5-wire double ext P	micro	6hxweek
WB2	R110	2000	2.75 x 1.22	2 strand hedge	drip	16hxweek
WTBR3	101-14Mgt	2000	2.4 x 1.2	5-wire ext P	drip	-
WTRS3	101-14Mgt	1999	2.5 x 1.2	5-wire ext P	micro	1x2months
WPK5	-	-	2.7 x 2	4-wire ext P	drip	1xweek

* The inter-row distance changes every second row

- data unknown

5.3.2 Soil profiles

Soil pits were dug in each miniplot parallel to the vineyard row at 30 cm from the grapevine trunk, with the grapevine trunk centred. The pits were 1.5 m in length and 1 m in depth, if no soil restriction was found beforehand.

5.3.3 Soil descriptions

The soil description and classification were done according to the South African soil taxonomic system (Soil Classification Working Group, 1991) by an experienced soil scientist, Braham Oberholzer from VinPro.

5.3.4 Soil chemical analyses

A composite sample of each horizon was taken from the different faces of the soil pit, and analysed according to standard methods by an independent Laboratory.

5.3.5 Root profiles

The root profiles were analyzed following the method described by Böhm (1979), utilising a grid composed of 150 squares of ten cm² each. Roots were counted and classified according to their diameter, into five categories (≤ 0.5 mm, 0.5-2 mm, 2-5 mm, 5-7 mm and ≥ 7 mm). Fine roots were considered to be roots between ≤ 0.5 mm and 2 mm, and thick roots were from 2 mm to ≥ 7 mm.

5.3.6 Statistical analysis

Principal component analyses were performed separately on the data from the Chardonnay and Shiraz plots using The Unscrambler® software. In each case the variables of root density to a depth of 60 cm and to the profile depth of 100 cm, the total rooting depth, the vineyard age, the total number of root contacts in the profile and the number of contacts for roots that had a diameter less than or greater than 2 mm were included. A one-way ANOVA was performed on the groups identified using the PCA. The Statistica® software was used.

5.4 Results and discussion

The importance of soil depth is evident in grapevine performance, especially in association with the volume of soil that acts as a water “reservoir” (Bodin & Morlat, 2006). There is a tendency for canopy growth to increase with increasing soil volume (Myburgh *et al.* 1996; Wang *et al.*, 2001, Wheaton *et al.*, 2008). Canopy growth is favourable up to certain point, and the detrimental effect of excessive vegetative growth has been well documented, as it affects canopy and bunch microclimate. It was reported by Wang *et al.* (2001) that in Kyoho grapevines favourable berry characteristics are achieved at 20 cm soil depth and when the rooting soil volume was adjusted to about 0.025 m³ per square meter of leaf area in a buried bed. The smaller the rooting volume, the faster the soil water potential decreased (Wang *et al.*, 2001). This concept coincides with that of Myburgh *et al.* (1996), although the figures differ. Myburgh *et al.* (1996) reported an optimum vegetative growth in the fourth year of between 60 cm and 100 cm soil depth for non-irrigated treatments and 40 cm and 80 cm for irrigated treatments.

An approach from product to source was used in this study. The product is the root system morphology. Thus, the starting point of the analyses is the rooting pattern. The response was analysed and grouped based on the importance of rooting depth and rooting density for grapevine performance. The possible causes in each group are discussed and the common points are reported.

A principal component analysis (PCA) was performed to investigate grouping of the plots based on characteristics of the rooting profile. Grouping was found for the Chardonnay and Shiraz plots (Fig. 5.1 & 5.2).

For the Chardonnay plots (Fig 5.1), PC1 describes the total size of the root system, while PC2 describes the density of roots up to 60 cm. PC1 would therefore seem to separate the plots based on root density while PC2 seems to separate the plots based on root depth. Using the results of this PCA and visual interpretation of the rooting profiles, three groups could be identified, namely, shallow rooting (SR), deep rooting-high density (DRH) and deep rooting-low density (DRL). SR is separated from the groups DRH and DRL along PC2. DRH and DRL are

clearly separated along PC1. This is determined by the total number of root contacts in the profile, which is very closely related to the number of thin roots. A high percentage of the total roots in most of the plots have a diameter of less than 2 mm. The number of thick roots and the year of planting seem to play a smaller role in separating these groups. Some plots that have a high density of roots up to 60 cm and that also have roots that penetrate to the depth of the profile fall close to the centre of PC2 but to the right of PC1 (e.g. Oa G5, OaDW3). Gs.WB3 falls towards the upper end of PC1 and to the middle of PC2. This is due to the high root density of this plot in the top 60 cm of the profile. However no roots were observed in Gs.WB3 at a depth below 60 cm. As was observed by Van Zyl (1988), rooting density can be affected by plant age. For the three plots that are on a Glenrosa soil form, Gs.WB3 is the oldest (planted in 1996), which may be the reason for the higher root number per m² of soil. However this is not related to the rooting depth, as has been pointed out by the same author. A grapevine root system can populate the full soil depth of 1 m during the second year after planting (Van Zyl, 1988).

A similar separation of the different groups was observed for Shiraz. The group SR falls predominantly in quadrant I, being separated from DRH in terms of rooting depth density and the total number of roots. DRH is found to the far right of PC1, as it is characterised by a higher density of roots as well as a deeper rooting system. DRL is separated from SR along PC2 due to the deeper root penetration in the first group, but separated also from DRH, along PC1 due to the lower number of total roots. Ag.L2 has a slightly higher number of roots than the other DRL plots, and is thus located just over the PC2 towards the DRH group. Van Zyl and Van Huysteen (1980) and Archer *et al.* (1988) reported that under homogeneous soil conditions the number of roots can be increased if the trellis system size is increased. In the study of Archer *et al.* (1988), the soil form is not mentioned, although the slanting trellis system promoted root growth to a depth of 1.2 m, which implies that the experiment was carried out in a deep soil. In the study of Van Zyl and Van Huysteen (1980) they worked with an Oakleaf soil form (Soil Classification Working Group, 1991) underlain at 700 mm by a hard pan, impenetrable to roots. They found that the slanting trellis had significantly more roots than the other three trellising systems. The tendency for the number of roots in the other three systems was: Lengthened Perold > Perold > bush vines. These differences were, however, not statistically significant. This suggests that the soil with less restrictive potential would maybe express more differences in root number regarding trellising system, but when soil limitations are present, these differences decrease. Van Zyl and Van Huysteen (1980) also pointed out in their experiment that the soil properties were dominant in determining the root distribution pattern. Thus the differences between trellis systems (table 5.2.) may have some influence in the separation between DRH and DRL, but not into the classification of DR or SR. This is confirmed in the groupings found by means of PCA

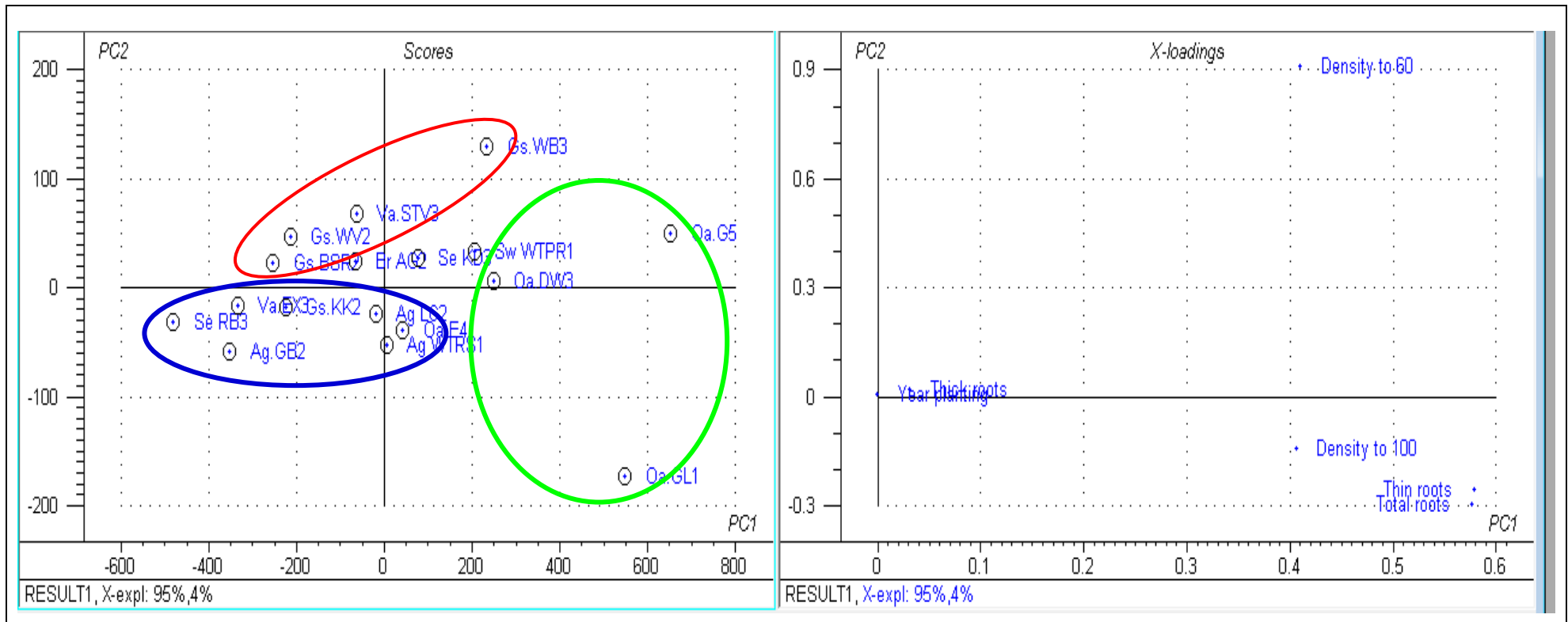


Figure 5.1. Principal component analyses (PCA) of the Chardonnay plots investigated. The graph on the right shows the variables analysed and their contributions to the first 2 principal components. In the graph on the left, the plots are indicated in relation to the first 2 principal components.

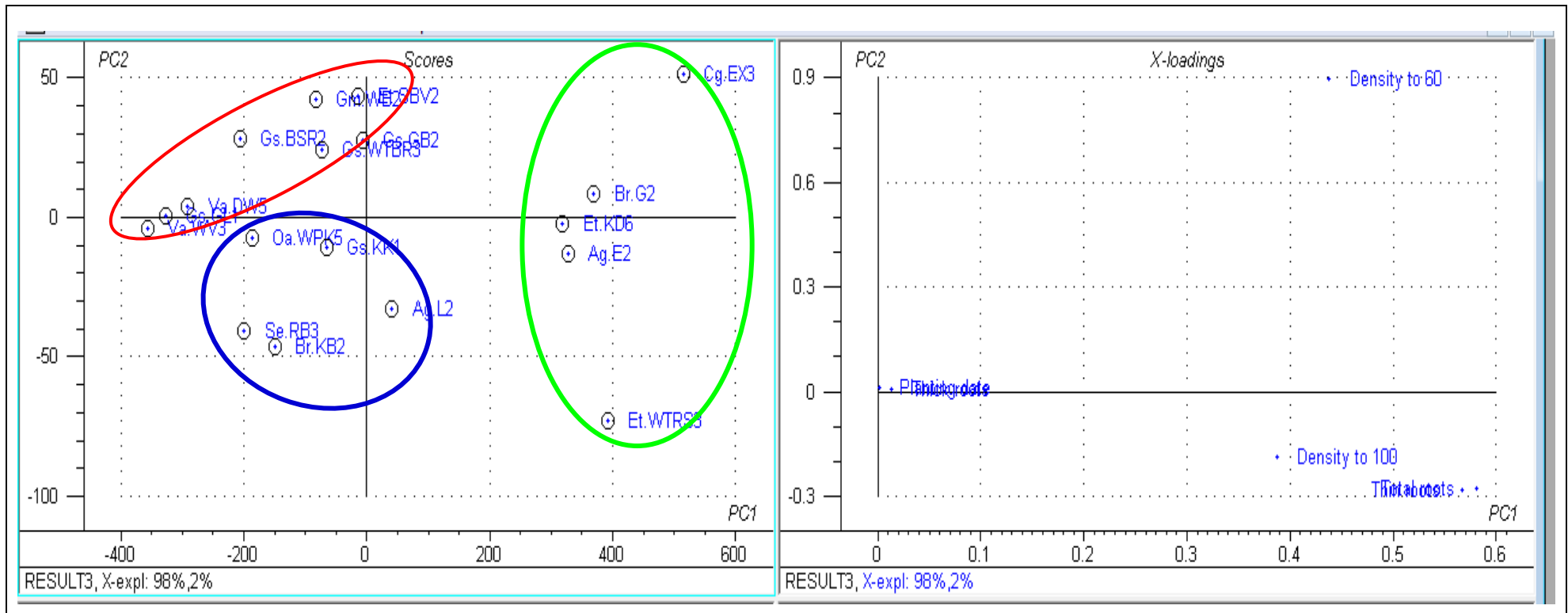


Figure 5.2 Principal component analyses (PCA) of the Shiraz plots investigated. The graph on the right shows the variables analysed and their contributions to the first 2 principal components. In the graph on the left, the plots are indicated in relation to the first 2 principal components.

A one-way ANOVA was performed to identify differences between the groupings (DRH; DRL, SR) for each cultivar. The comparison was made using the root density between 60 and 100 cm depth called D40. For Chardonnay (Fig. 5.3), DRH differed significantly from SR and DRL. The fact that DRL did not differ significantly from SR would appear to be due to fact that the amount of root of the high density plots was much higher, than the differences between the SR and DRL in the D40.

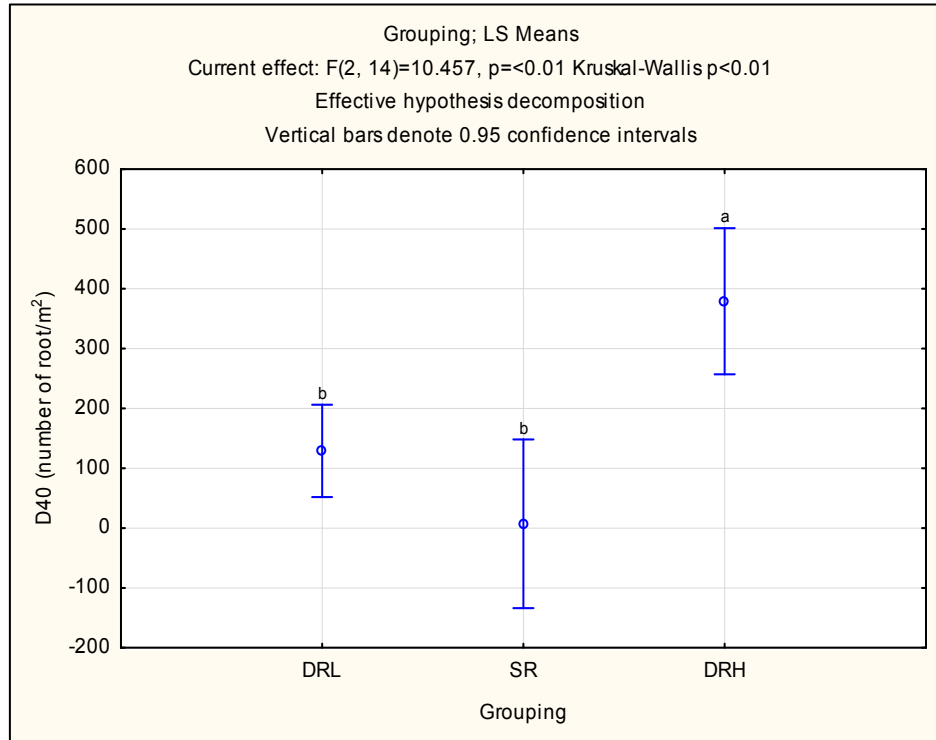


Figure 5.3 The comparison of the different groups of Chardonnay (DRL = deep rooting low density; SR = Shallow rooting, DRH = Deep rooting high density). Different letters denote significant differences at $p\leq 0.05$.

In Shiraz (Fig. 5.4) the three groups were differed significantly from each other. The clearer division observed in the PCA is corroborated with the one way ANOVA.

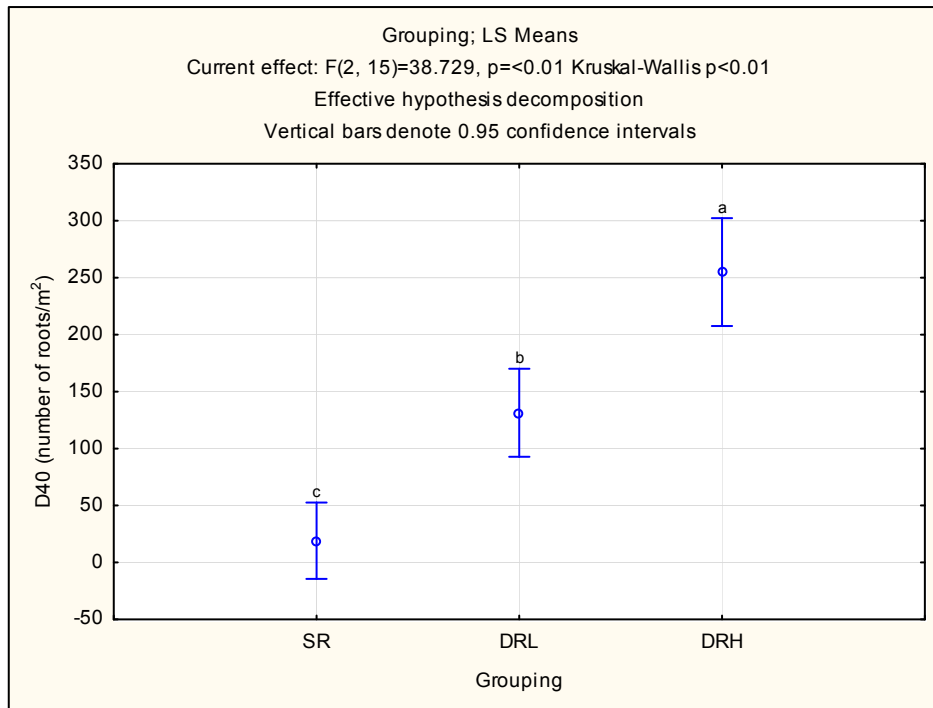


Figure 5.4 The comparison of the different groups of Shiraz (DRL = deep rooting low density; SR = Shallow rooting, DRH = Deep rooting high density).

Planting distance has also been shown to have an effect on root density and on the rooting angle (which is associated with depth of the rooting system) (Archer & Strauss, 1985; Hunter 1998). These authors have shown that closer plant spacing increases the number of roots/m². The possible effect of the planting distance could be masked in this study by the different soil properties between the plots, and in particular soil volume. The soil volume available for the root growth is a function of the soil depth. A planting distance of 2.4 m x 1.2 m in a soil with 0.6 m depth will induce a different response than in a soil with 1 m depth. Soil depth will greatly influence the total amount of roots. Other soil properties can also be involved in affecting the soil volume (e.g. soil origin, degree of weathering).

In terms of irrigation, the type and frequency have been reported to affect root distribution in different ways. Bengough *et al.* (2006) and Soar and Loveys (2007) showed that root distribution is altered by the type of irrigation, which affects of the distribution of water and nutrients in the soil. According to Araujo *et al.* (1995), root growth and branching proliferated in the wetted zone under the dripper point. Van Zyl (1988), in an experiment in Robertson in a Hutton soil form (Soil Classification Working Group, 1991), also found a major concentration of roots under the dripper point compared to a micro-sprinkler, although he found that the total amount of roots was the same in both cases. For drip irrigation, more roots were concentrated in the wetted soil sphere, while for the micro-sprinkler irrigation, roots were more uniformly distributed. As it was pointed out by Southey and Archer (1988), the water distribution pattern is a function of the physical conditions of the soil, and thus it can be considered as secondary to soil type. In this study, drip and micro-sprinkler irrigation were used but no clear separation occurred between them in terms of root distribution through the soil profile, which does not directly imply that there is no an irrigation effect but probably as discussed above the effect may be secondary when confronted with soil properties.

Regarding the genetic influence, the effect of the rootstock over the root distribution has not been widely studied in the literature and the results seem to be inconclusive. Southey and Archer (1988) reported that the spatial root distribution of a particular graft combination is dominated by the soil properties, but that the root density appears to be a function of the rootstock. Swanepoel and Southey (1989), in a soil with minimal restrictions to root penetration, reported that root density and penetration were affected by rootstock. The results of Swanepoel & Southey (1989) in an Oakleaf in the Breede River valley under sprinkle irrigation showed that 1103 Paulsen was in the high density group and 140 Ruggeri in the low density group. Exactly the opposite was reported earlier by Archer & Southey (1988) in Stellenbosch in a Clovelly soil, where 140 Ruggeri had the highest density, and 1103 Paulsen was one of the lowest. The reasons for these disparate results are not clear and soil pH was discarded as a possible reason by Swanepoel & Southey (1989). Smart *et al.* (2006) reviewed more than 200 trenches that have been reported in the literature and they could not find any consistent differences between rootstocks. In this study, no relationship was found between rootstock and rooting depth, roots density, or thin to thick root ratio (root number and ratio per rootstock are presented in Addendum 5.8 & 5.9). The same rootstocks were found in each of the three different rooting groups (SR, DRH, DRL) (Fig. 5.1 & 5.2) and so no rootstock could be associated with differences in rooting depth or rooting density. As was suggested by Southey & Archer (1988) and Smart *et al.* (2006), the differences in rooting depth are predominantly a function of the soil properties. The observations in this study concur with these authors, but from this study it also seems that root density can be strongly determined by soil properties, as well as potentially by cultural practices such as irrigation, planting density and plant age, making it extremely difficult to associate rooting density with a determined rootstock type.

The grouping of the extremes in the rooting system (SR and DRH) can be explained by important soil properties that seem to exert a stronger influence than the genetic component and the viticultural practices.

5.4.1 The differences in parent material between shallow and deep soils

5.4.1.1 The shallow root systems

The division of the plots by rooting depth enabled the grouping of soil according to the presence or absence of determined restrictions at ca. 60 cm soil depth. This depth is 10 cm deeper than the depth reported in the study of Bodin & Morlat (2006) for weakly weathered rock plots (i.e. 50 cm) but is that used by Smart *et al.* (2006) as a threshold in their study.

Selected Chardonnay plots with low root depth are represented in the Figure 5.5 (a), and the Shiraz plots with low root depth are represented in Figure 5.5 (b).

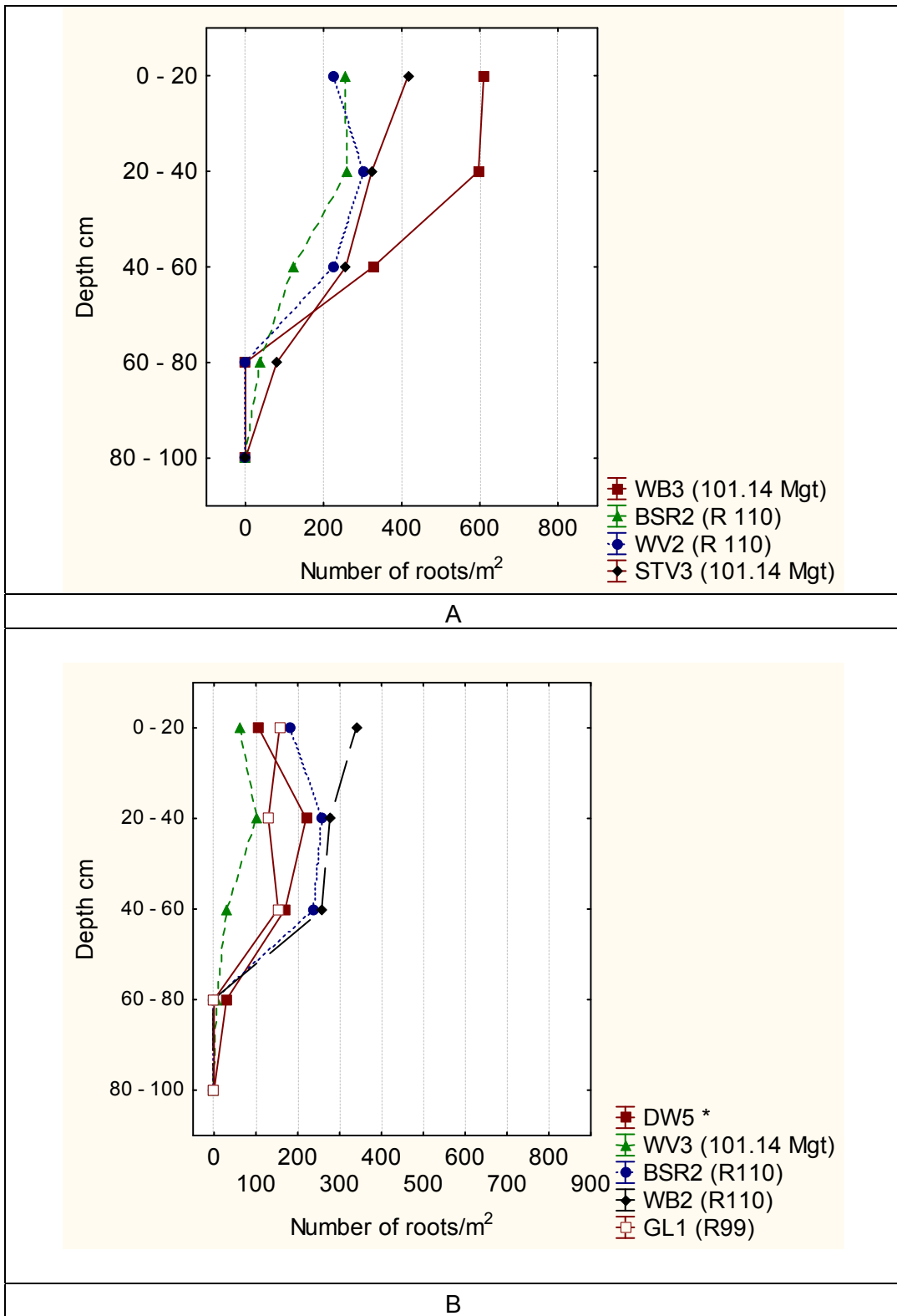


Figure 5.5. Number of roots per 20 cm depth for selected plots with shallow root systems (SR) for Chardonnay (a) and Shiraz (b). * information not available

The chemical properties reported in the literature that affect root growth directly or indirectly were analysed and the results were compared to the thresholds reported in different publications (for a more detailed description of the restrictive factors and the way they affect root system development, see Chapter 4). In the Chardonnay soil profiles, low values of resistance were found in two plots. The presence of sodic horizons was reported in WBCH and BSRCH from 20 cm downwards and in STVCH there was a highly sodic horizon from 20 cm downwards (according to thresholds from Nicholas, 2004). A low ratio of Ca:Mg related to a low content of Ca, was also found in the three plots (i.e. BSRCH, WVCH and STVCH).

There were no recognisable chemical coincidences that could be associated in all the four plots. However, they differed in the physical aspect. The four plots were classified in the field to have a hard consistency from 20 cm downwards. The four plots had a gradual transition between the first two horizons. Three of the plots corresponded to the Glenrosa soil form (a Lithic soil) and one to Valsrivier (a Duplex soil) (Soil Classification Working Group, 1991; Fey, 2010). The Glenrosa soil type comprises an orthic A horizon and a lithocutanic B. The lithocutanic B has been characterised by the Soil Classification Working Group (1991) as “one of minimal development of an illuvial B horizon in weathering rock. In situ weathering of rock under a topsoil has produced a heterogeneous and, typically, highly variegated zone consisting of soil material (relatively homogenised without traces of weathering rock) interspersed with saprolite or weathering rock in various stages of breakdown. Furthermore, this zone grades into relatively unaffected and, eventually, fresh rock, sometimes at fairly shallow depth”. In this case the Lithocutanic B consists of weathering shale. The three plots with Glenrosa soil grade into fresh rock at depths of 60 cm. The soil depth is thus limited by the presence of parent rock and the thickness of the lithocutanic horizon. For STVCH, classified as Valsrivier soil form (Oberholzer, B; VinPro; Personal communication, 2008), root growth was limited by the presence of a pedocutanic B horizon, enriched with sodium and with a hard consistency, underlain by a horizon of unconsolidated material, also with a hard consistency. A pedocutanic horizon is defined by the Soil Classification Working Group (1991) as having “a moderately to strongly developed subangular or angular blocky structure in the moist state. It has clearly expressed cutanic character resulting from illuviation of the fine materials manifested as prominent cutans on most ped surfaces. The concept embraces B horizons that have become enriched in clay, presumably by illuviation and that have developed moderate or strong blocky structure”. The increases in clay percentage are shown in Addendum 5.1. This definition indicates possible restrictions to growth due to the strong structure. The clay enrichment can cause problems in water movement, and the situation is aggravated by the accumulation of sodium, which also influences the soil structure (Wheaton *et al.*, 2008). The limited drainage can promote the accumulation of other salts (i.e. related to the quality of the irrigation water) and a resulting increase in soil consistency, which represents a rooting restriction factor (Van Huyssteen, 1988a; Wheaton *et al.*, 2008). In weathering terms, a pedocutanic horizon has a more strongly developed structure than a neocutanic or a lithocutanic horizon, and can represent a restriction to root growth, but is not as restrictive as prisma-cutanic horizon. STVH could also represent a deep rooting pattern with low density roots and can thus be considered transitional between the two classes. The limitations imposed by the Glenrosa and Valsrivier soils have a different origin, but have the same effect over root growth.

In the Shiraz plots with shallow root systems, the soils were classified according to the South African soil taxonomy into WVSH (Valsrivier), DWSH (Valsrivier), BSRSH (Glenrosa), GLSH (Glenrosa) and WBSH (Gamoep, a Calcic soil; Fey, 2010) (Oberholzer, B; VinPro; Personal

communication, 2008). Chemically speaking, a low resistance value was found in DWSH from 80 to 100 cm (Table 5.3). Slightly low values for the Ca:Mg ratio were found in WVSH from 80 to 100 cm, and in BSRSH from 20 cm downwards. In terms of the sodium concentrations in WVSH, the concentration was classified as sodic from 40 cm down, and in DWSH from 80 to 100 cm.

The clay content showed an increase in depth in WVSH, from 9.6% to 21.6% at 50 cm, together with an increase in consistency from firm to very firm, coinciding with the decrease in the root number (see root wall profile in Figure 5.8). The clay content in DWSH also increased from 80 cm to 100 cm, from 5.8% in the top horizon to 27% in the last (i.e. 80 to 100 cm). In GLSH it increased from 10.2% to 18.2% from 40 cm down. The clay increases were accompanied by increases in the consistency perceived in the field, which probably affected the root exploration into those layers, by influencing the porosity, and thus the water drainage and the ratio of CO_2/O_2 .

The limitation in depth in the Shiraz plots was determined by the presence of a Lithocutanic horizon in the Glenrosa soil forms found in BSRSH and GLSH at 60 cm depth, and by the consistency of the pedocutanic horizon and the accumulation of sodium in the Valsrivier soil forms found at DWSH at 60 cm and at WVSH at 50 cm, and by a hard pan carbonate layer at WBSH (i.e. Gamoep), found at 50 cm depth.

Glenrosa and Valsrivier were reported to limit the root depth in the shallow profiles of Chardonnay and Shiraz, and Gamoep also presents limitations to root growth for Shiraz. Thus, root exploration was found to be limited by the distance from the soil surface to either the weathering rock or the high-consistency layers of unconsolidated materials with or without signs of wetness underlying a pedocutanic B horizon, or to a hard pan carbonate. These represent a limit to depth penetration of roots. The degree of limitation for the rooting depth depends of the proximity of these layers to the soil surface.

An example of the soil descriptions Valsrivier and Glenrosa are shown in Figures 5.6 and 5.7. The corresponding root wall profiles of these soils are presented in Figures 5.8 and 5.9.


Depth mm	PROFILE 39 : Shiraz Soil form: Valsrivier Soil family: Va2212	Horizon	Colour	Texture	Fragments	Structure	Consistency	Permeability	Transition
0-300		Ortic A	Brown	Medium loamy sand	20% coarse	Weak apedal poreus	Slightly hard	Rapid	Gradual
200-800		Pedocutanic B1	Yellow Red	Medium loamy sand	>50 % coarse & >20 % bolders	Fine angular block	Hard	Moderate	Gradual
>800		Unconsolidated material without signs of wetness B2	Pale brown	Medium sandy clay loam	Lime in fragments	Apedal to fine crumbled	Hard	Moderate	No transition up to 900

Figure 5.6 Soil description of a Valsrivier soil at Robertson (DWSH) (Oberholzer, B; VinPro: Personal communication, 2008).

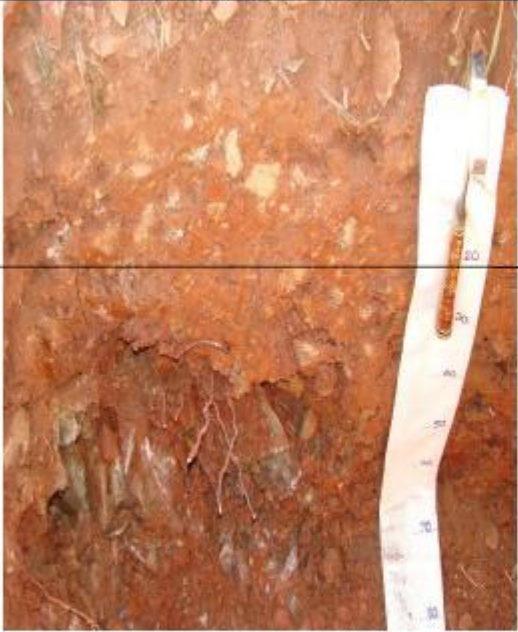
Depth mm	PROFILE 25: Chardonnay Soil form: Glenrosa Soil family: Gs 2211	Horizon	Colour	Texture	Fragments	Structure	Consistency	Permeability	Transition
0-200		Ortic A	Light red	Fine Sandyloam	40% fine & 10% coarse	Weak apedal poreus	Slightly hard	Rapid	Gradual
200-600		Litocutanic B1	Yellow Red	Fine sandy clay loam	>80 % coarse	Weak crumble	Hard	Moderate	Gradual
>600		Litocutanic B2	Pale brown	Fine Sandy clay loam	No lime in fragments	Apedal to fine crumbled	Hard	Moderate	No transition up to 900

Figure 5.7 Soil description of a Glenrosa soil at Robertson (BSRCH) (Oberholzer, B; VinPro: Personal communication, 2008).

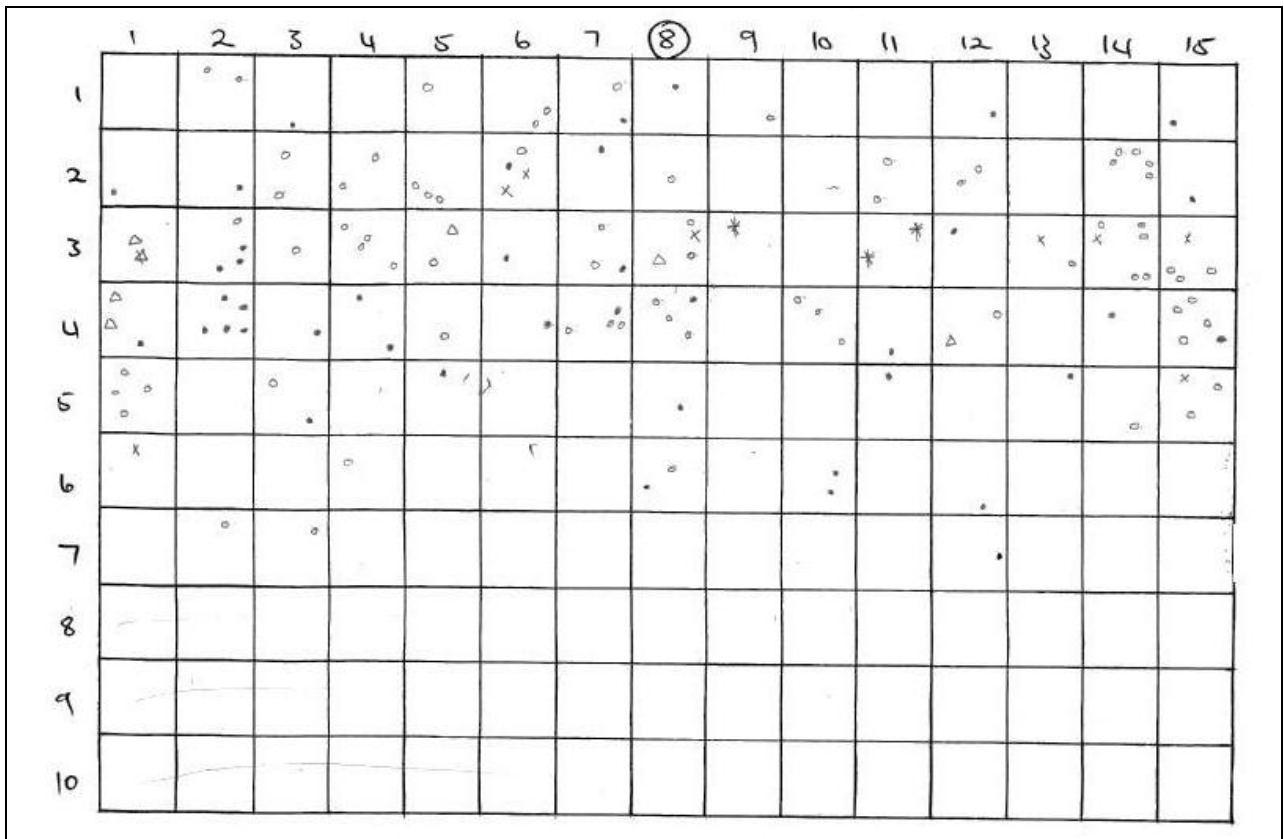


Figure 5.8 Root wall profile in a Valsrivier soil form (WVSH) in Robertson. Number associated with depth and horizontal distance represent decimetres. The root diameter in mm is represented for the following symbols ● = < 0.5; ○ = 0.5 – 2; × = 2 – 5; △ = 5 – 7; * = > 7.

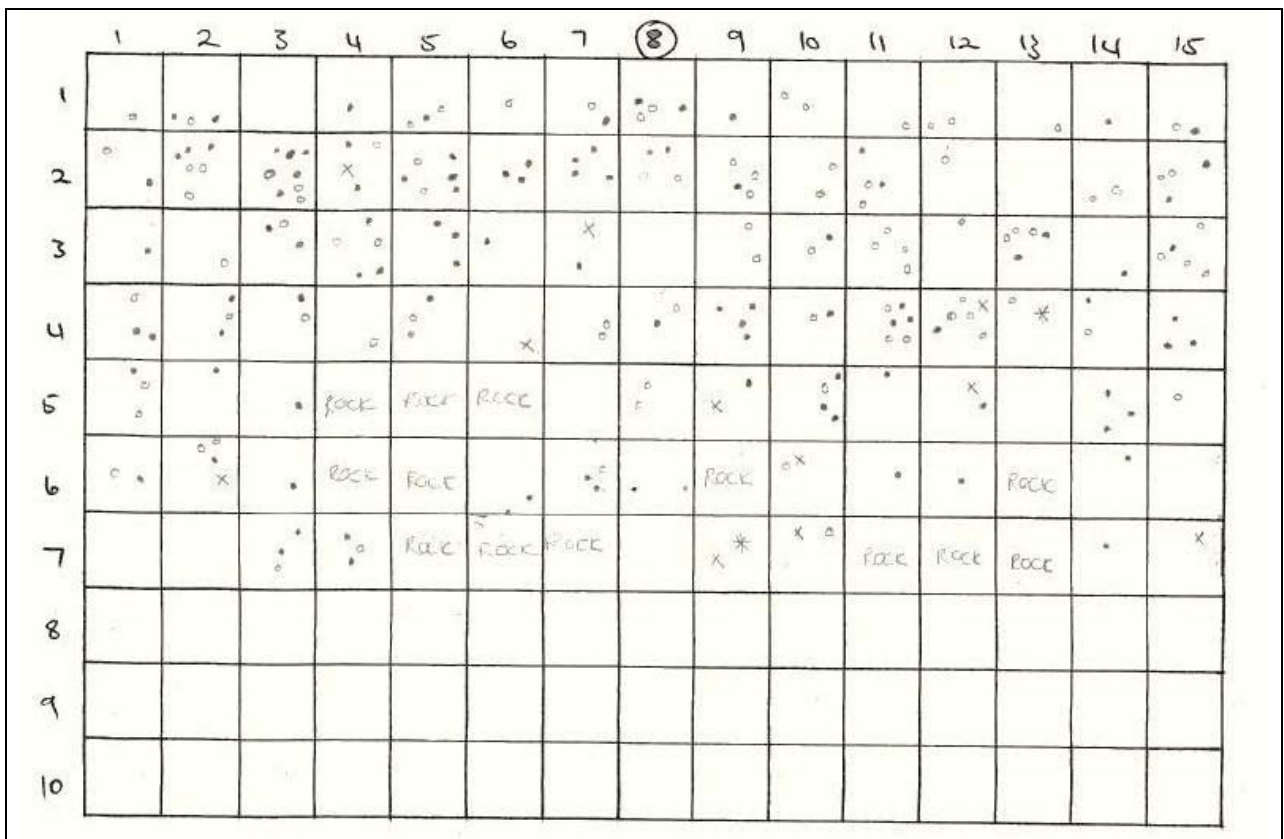


Figure 5.9 Root wall profile in a Glenrosa soil form (BSRCH) in Robertson. Number associated with depth and horizontal distance represent decimetres. The root diameter in mm is represented for the following symbols ● = < 0.5; ○ = 0.5 – 2; × = 2 – 5; △ = 5 – 7; * = > 7.

5.4.1.2 The deep root systems

The group with deep rooting systems could be further divided according to root number. Two groups with extremes were analysed for each cultivar, one group containing the three plots with the lowest number of roots (Fig 5.10 (a)), and the other group containing three plots with the most roots (Fig. 5.10 (b)).

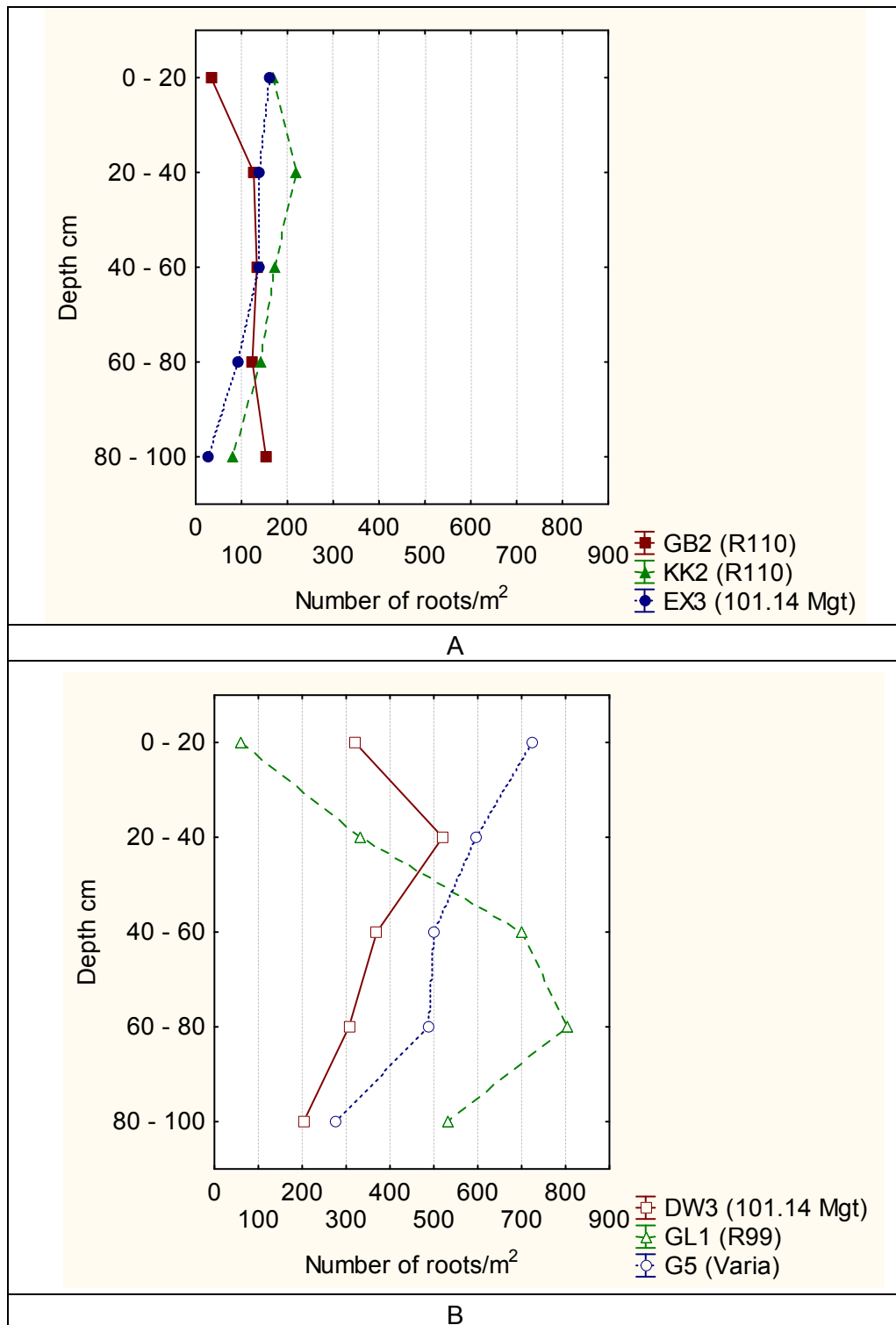


Figure 5.10 Number of roots per 20 cm depth for selected plots of Chardonnay where (a) has a deep low density root system and (b) has a deep high density root system

5.4.1.2.1 Deep root system with high root density

The threshold between the groups containing the high and low root density was 250 roots/m² in each of the 20 cm depth layers, where at least four of the five delimited layers in each profile were below the threshold in the case of low density, and above this threshold in the case of the high density.

For Chardonnay, low pH values were found in the three plots from 20 cm down, with ranges between 5.3 and 4.3 (Addendum 5.1). For DWCH the soil pH was 5.3 from 40 cm down, for GLCH the pH was 5.0 from 60 cm down, and for GCH the soil pH was 4.3 from 30 cm down. We would expect a restriction for root growth at GCH as a result of this low pH, but one of the highest root densities was measured throughout its profile. A low soil pH restricts root growth through nutrient availability and the increase of exchangeable aluminium, and the positive effects of liming have been related to improvements of the soil physical properties as low soil acidity can be associated with massive and dense subsoils (Conradie, 1988; Nicholas, 2004; Wooldridge *et al.*, 2010). At GCH, the soil structure was favourable for root growth. Aluminium toxicity was described by Nicholas (2004) to cause weak root growth, with short and stubby roots and little branching. These symptoms were not observed here. Therefore, although exchangeable aluminium was not directly measured in the soil chemical analyses, the concentration present in this profile may have been insufficient to cause toxicity symptoms on root growth. In terms of nutrient availability, no deficiencies were noted (values compared to Conradie, 1994). These results suggest that where there is no limiting soil property other than soil pH, a low soil pH (e.g. 4.3 KCl) is not enough to substantially restrict root growth. Furthermore, some research suggests that older roots may be able to resist aluminium toxicity through the formation of multiple periderm layers (Swanepoel & De Villiers, 1988). DWCH presented also a highly sodic horizon from 40 cm downwards, which seemed to slightly affect the number of roots. The presence of sodium has been reported to affect the soil structure by dispersion (i.e. breakdown of micro-aggregates into individual constituents of sand, silt and clay). However, the total content of different salts reflected in the soil resistance might protect the soil structure, as the resistance value is not low (i.e. is far from being considered to be limiting factor), but indicates the presence of some salt in the profile that could protect the soil structure from the dispersive effect of sodium (Nicholas, 2004).

In this group of Chardonnay vineyards, the common point between the plots would appear once again to encompass the soil physical properties. The three soils corresponded to an Oakleaf soil form (orthic A/neocutanic B) (Soil Classification Working Group, 1991), a Cumulic soil (Fey, 2010). All three had a gradual transition between horizons. The homogeneity and extent of the neocutanic horizon would seem to be key to understanding the high root number and rooting depth of these vineyards. Normally, the changes between one horizon and the next are characterised by changes in the horizons' structure. These changes seem to influence root penetration. The extent of the depth of the B horizon in the three soil profiles presents a homogeneous structure and soil properties, which seem to be more important than the limiting chemical properties.

The neocutanic horizon has been described by the South African Soil Classification Working Group (1991) as "to occur in unconsolidated material, usually transported, which has undergone pedogenesis to a certain extent. Recent sediments and other unconsolidated materials provide the parent material of many soils. Neocutanic character is recognized when soil formation in

unconsolidated material has not progressed sufficiently far to produce one or other distinctive diagnostic horizon, but has brought about a certain amount of re-organization of the material”.

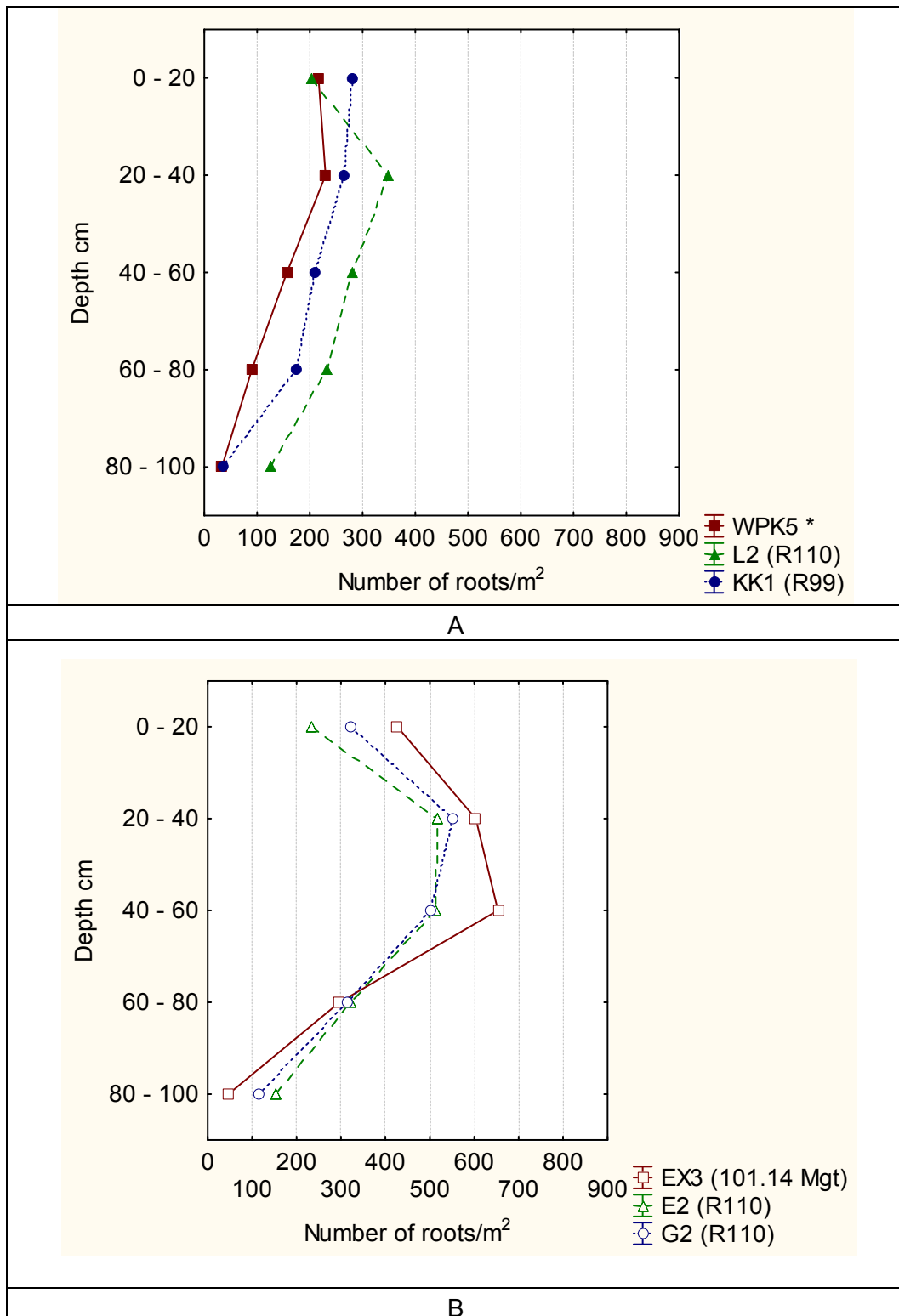


Figure 5.11 Number of roots per 20 cm depth for selected plots of Shiraz where (a) has a deep low density root system and (b) has a deep high density root system

In the deep-rooting plots of Shiraz (Fig. 5.11 (b)), no physical or chemical limitations of any kind were found. The three plots corresponded to different soil types, namely Coega (orthic A/soft carbonate B/hard pan carbonate B2 – a Calcic soil), Augrabies (orthic A/neocarbonate B – a Cumulic soil) and Brandvlei (orthic A/soft carbonate B – a Calcic soil).

The Coega form described here and the Gamoep form described under the shallow rooting soils are both contained within the colloquial soil group known as “hard Karoo” soils in South Africa. This is due to the fact that these soil forms present a hard pan carbonate layer. In both soils the hard pan carbonate was found at 50 cm depth. The soil structure for both hard pan horizons was described as platy (Oberholzer, B; VinPro; Personal communication, 2008). However, these two soils have been classified in this study in different extremes, one being a DRH the other a SR. The difference in root penetration lies in the quality of breakage of the hard pan by the soil preparation and the condition of the hard pan observed 8 years after the soil preparation took place. The DRH profile (i.e. Coega) was prepared to a depth of 1.6 m and the SR (i.e. Gamoep) was prepared to a depth of 1 m (anecdotal data). Although these depths are given for soil preparation, the actual depth will be shallower due to soil settlement post-preparation. However it is clear that the Coega soil was prepared to a greater depth than the Gamoep soil. In fact, it was not possible to prepare the trench for the Gamoep soil to a depth greater than 60 cm (Fig. 5.10), while the trench for the Coega soil could be prepared to the full 1 m of study depth.



	(a)	(b)
Scion	Shiraz	Shiraz
Rootstock	101.14 Mgt	R 110
Planting date	2000	2000
Soil preparation	Cross rip 1.6 m	Cross rip 1 m
Soil form	Coega	Gamoep
Diagnostic properties	Orthic A/ soft carbonate/ hard pan carbonate	Orthic A/ Neocutanic/ hard pan carbonate
Root system	DRH	SR
Depth to hard carbonate	50 cm	50 cm

Figure 5.12 A comparison between two soil forms (i.e. Coega and Gamoep) with a hard pan carbonate layer at 50 cm depth having different rooting depth and number due to the effect of soil preparation on the rooting zone (DRH = deep rooting high density; SR= shallow rooting)

The effective soil depth loosened by soil preparation is thus reflected in the size and depth of the root system. Thus, correct soil preparation can play an extremely important role in determining conditions and extending the rooting zone in the presence of hard pan carbonates and other restrictions, as has been reported by Van Huyssteen (1988a). Figure 5.12 shows how the roots have colonized the hard pan carbonate in the Coega form (a), and how the layers have been broken up into smaller pieces, while for the Gamoep (b), the hardpan layer impeded the digging of the trench and has impeded the root penetration in terms of depth.

These three examples of vineyards in the DRH class for Shiraz are related to the presence of carbonates. The consistency of the profiles varies between soft and slightly hard. Changes from the first to the second horizon are gradual and the permeability was described as moderate to rapid in the three plots. The presence of carbonates and their nature have been related to their distribution in the profile, depending on whether they are forming a pan or if they are fragments (Nicholas, 2004). In these cases, they are distributed as fragments in horizon B as well as being present as a pan. The fragments are expected to have a positive effect on the physical and hydraulic properties of the soil. The neocarbonate horizon is described by the Soil Classification Working Group (1991) as a horizon that occurs “in unconsolidated material usually transported, which has undergone a pedogenesis to an extent which excludes the horizon from a diagnostic stratified alluvium. The general discussion of the neocutanic B is applicable to the neocarbonate B. They differ in that neocarbonate is a horizon of accumulation of calcium and/or magnesium”. The soft carbonate has a morphology that is largely that of the calcium carbonates, the difference with the neocarbonate is that the morphology of the soft carbonate is dominated by the carbonates. The deep rooting plots with a high number of roots that were noted for Chardonnay and Shiraz contain horizons that have evolved from recent sediment depositions with a certain degree of pedogenesis. Although the origin of these depositions is not specified, they could have evolved from aeolian sands or alluvial valley-fills (Soil Classification Working Group, 1991), with the difference lying in the presence of carbonates. The consistency, homogeneity and extent of these horizons impose fewer restrictions on the rooting exploration in depth and the development of root numbers.

An example of the Oakleaf soil description and one of Augrabies are shown in Figures 5.13 and 5.14. The corresponding root wall profiles of these soils are presented in Figures 5.15 and 5.16.



Depth mm	PROFILE 40 : Chardonnay Soil form: Oakleaf Soil family: Oa 2211	Horizon	Colour	Texture	Fragments	Structure	Consistency	Permeability	Transition
0-400		Ortic A	Yellow brown	Medium to coarse sandy	>10% fine	Weak apedal poreus	Slightly hard	Rapid	Gradual to prominant
400- 1500		Neocutanic B1	Yellow Red	Medium coarse sandy loam	>10 % fine	Apedal to fine crumbled	Slightly hard	Rapid	

Figure 5.13 Soil description of an Oakleaf soil at Robertson (DWCH) (Oberholzer, B; VinPro; Personal communication, 2008)


Depth mm	PROFILE 14: Shiraz Soil form: Augrabies Soil family: Ag 2120	Horizon	Colour	Texture	Fragments	Structure	Consistency	Permeability	Transition
0-100		Ortic A	Light yellow brown	Fine loamy sand	>10% coarse tillite surface fragments	Apedal poreus	Slightly hard	Moderate to good	Gradual
100-700		Neocarbonate B1	Yellow red	Fine sandy clay loam	>15 % lime nodules & 40% fine fragments	Apedal poreus	Loose	Good	Gradual
>700		Neocarbonate B2/C	Pale brown	Fine Sandy loam	>70 % coarse fragmenst with lime nodules	Apedal to fine crumbled	Slightly firm to firm	Moderate	Gradual

Figure 5.14 Soil description of an Augrabies soil at Robertson (Oberholzer, B; VinPro; Personal communication, 2008)

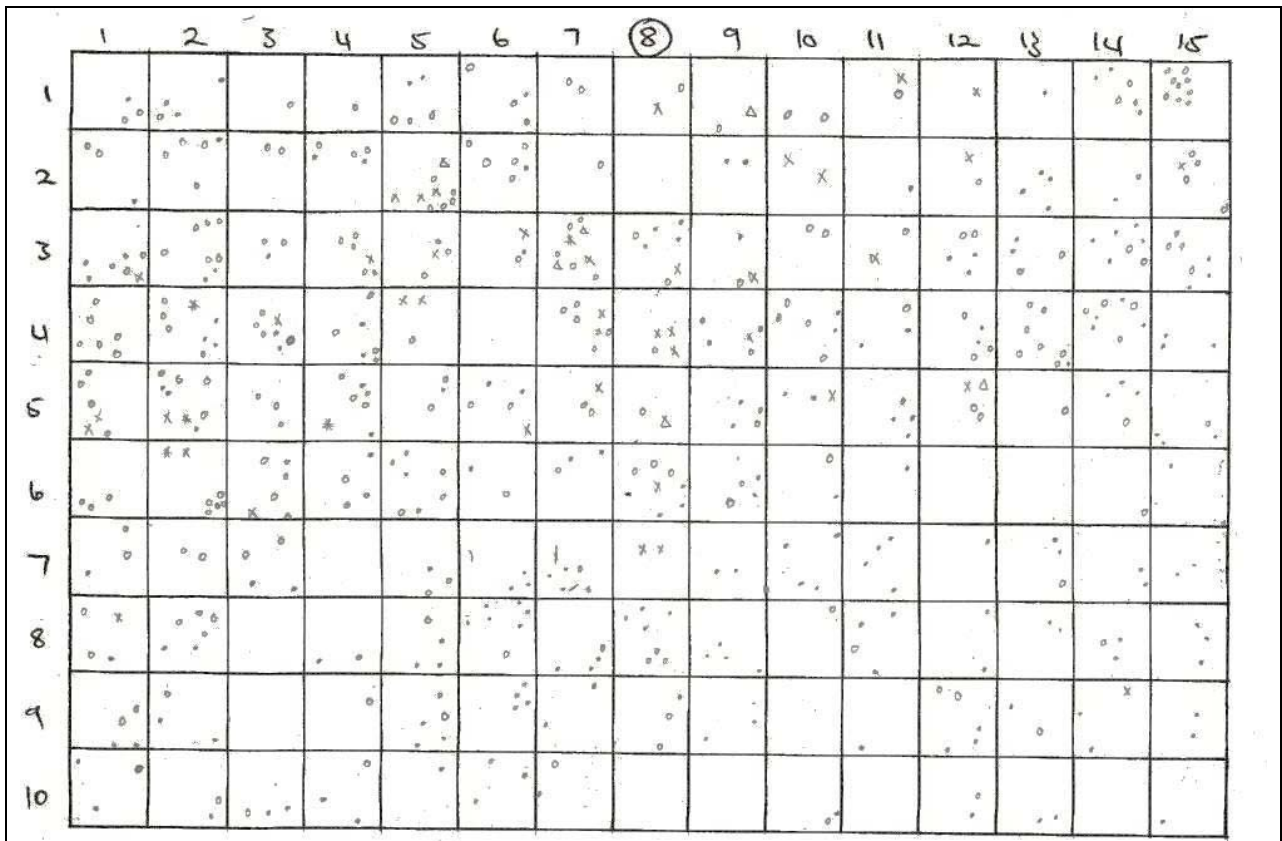


Figure 5.15 Root wall profile in a Oakleaf soil form (DWCH) in Robertson. Number associated with depth and horizontal distance represent decimetres. The root diameter in mm is represented for the following symbols ● = < 0.5; ○ = 0.5 – 2; × = 2 – 5; △ = 5 – 7; * = > 7.

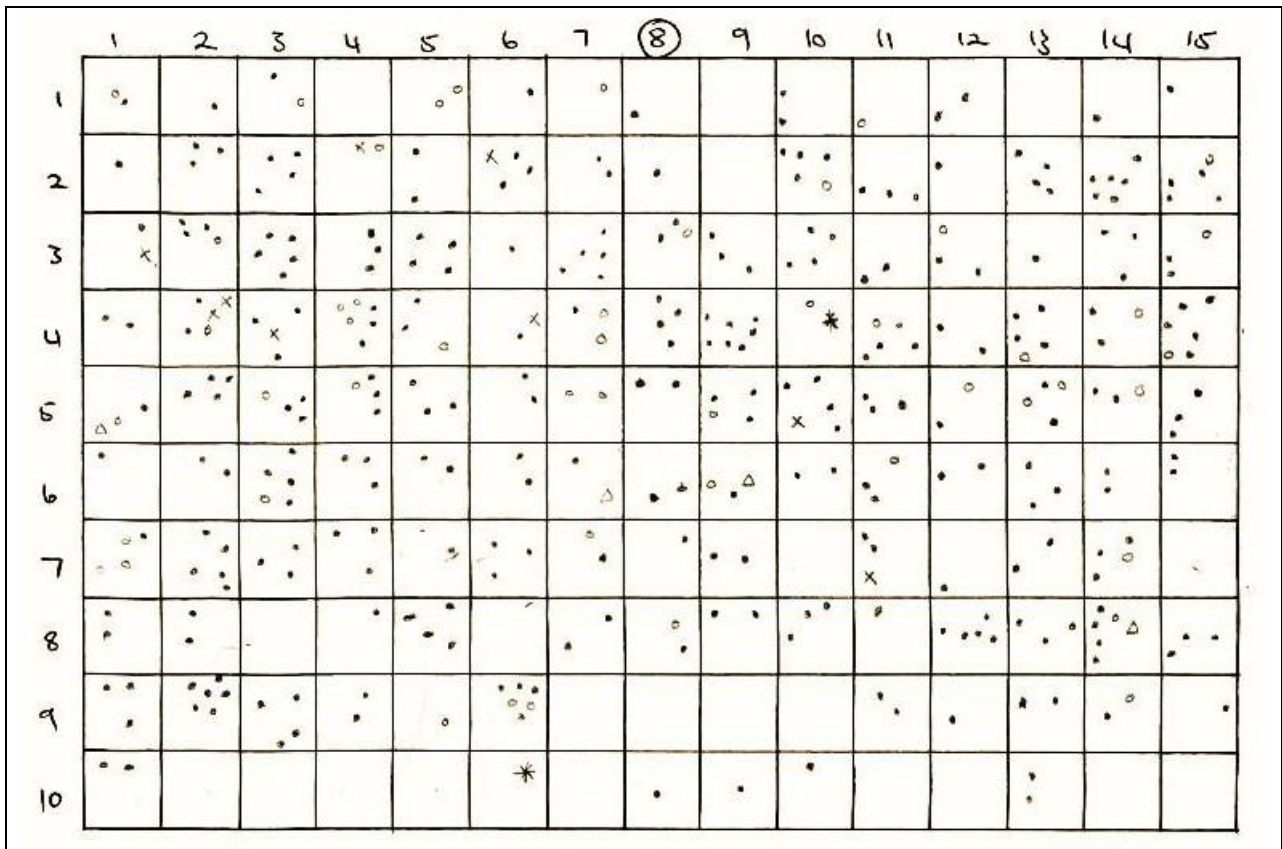


Figure 5.16 Root wall profile in a Augrabies soil form (LSH) in Robertson. Number associated with depth and horizontal distance represent decimetres. The root diameter in mm is represented for the following symbols ● = < 0.5; ○ = 0.5 – 2; × = 2 – 5; △ = 5 – 7; * = > 7.

5.4.1.2.2 Deep root systems with low root density

For the profiles analysed in this group, no physical limitation in soil depth was observed above 100 cm, but restrictions to root density seemed to occur. These were of a different nature for the various plots. The soil forms reported are Glenrosa, Valsrivier, Oakleaf and Augrabies. The first two soil forms were described in the shallow rooting group, and the last two were described in the deep rooting high density group. This is related to changes in the restrictive soil properties, which could be ascribed either to the soil nature or perhaps to the influence of some cultural practices, which are case-dependant. For the Glenrosa and Valsrivier soils, the thickness of the lithocutanic and pedocutanic horizons offered more volume for root exploration, thus relieving the degree of the restriction to a certain extent. The extension of the lithocutanic horizon until 100 cm allowed the root penetration in the Glenrosa form present at KKCH and KKSCH. For the Valsrivier form present at EXCH, the pedocutanic horizon was from 20 to 90 cm depth, also allowing more roots in depth. However, the properties of the B horizons were still restrictive for rooting density. Some of the soil properties that can be suggested as restrictive for root density in these plots are discussed below. For KKCH, a lower pH of 4.9 and 5 was measured from 20 cm down and a hard consistency noted in addition to the restrictions imposed by the lithocutanic horizon on the soil volume. For GBCH, low resistances values of 350 ohms measured in the first 20 cm and of 320 ohms downwards indicated some salt accumulation. For EXCH, a low Ca:Mg ratio was found from 20 cm down, together with a sodic horizon, and highly sodic values from 80 cm to 100 cm. For the Shiraz plots, KKSCH had a very low pH, ranging from 4.7 in the top 20 cm to 4.0 between 80 and 100 cm.

Although Glenrosa and Valsrivier soil forms were reported for the shallow soil class, here they form part of the deep rooting group, but they were still restrictive in terms of root density (number of roots/m²). On the other hand, although Augrabies and Oakleaf soil forms were reported as being associated with the class of deep rooting with a high root density, here they have also been shown to present restrictive properties for root density, apparently in relation to soil chemical properties. The situation in this class would appear to vary from case to case, suggesting that different soil properties can be combined in various ways and/or interact with some cultural practices to result in a determined root system development.

The depth rooting pattern for the extreme classes (i.e. shallow and deep high density) can be related to determined soil morphological characteristics. These characteristics can be associated with the parent material in Robertson (i.e. weathering rock or deposits), and they are represented by specific families of the South African soil taxonomy. These relations are supported by important characteristics, described by the diagnostic horizons. However, care must be taken since the South African soil taxonomy does not include the thickness of the horizons, which plays an extremely important role in the available soil volume. Merely knowing the form, therefore, will not provide sufficient information.

A model in terms of which the degree of weathering of the parent rock can be described was proposed by Morlat (1989), cited by Bodin & Morlat (2006). This method uses a field soil model based on the type of parent rock, the depth and the clay richness of the soil, as they are related to the weathering level of the parent rock. They recognise three types of soil, namely weakly weathered rock (WWR), moderately weathered rock (MWR) and strongly weathered rock (SWR). This model assumes that depth and clay content increase from WWR < MWR < SWR (Bodin & Morlat, 2006). Bodin and Morlat (2006) measured physical and chemical soil

properties, water supply conditions, phenology of the grapevine and vine vigour. In most of the measurements they reported differences between the weakly weathered plots and the strongly weathered rock, but for the different measurements and for different years, the moderately weathered rock sometimes was closer to SWR, sometimes closer to WWR. This is probably the result of various combinations of properties that characterize the extremes. The same would appear to be true in this study, where the extremes are well differentiated by distinct soil properties, but the group of deep rooting low density (DRL) shares properties with both extremes, resulting in an intermediate situation. Morlat's model is not applicable in the Robertson region because the degree of weathering of the parent material is not the point of contrast between the SR and DR. The arid characteristics of Robertson have kept considerable areas of soil in the young stages. Important horizons identified in this study that drastically influence the rooting system are the lithocutanic and the neocutanic B horizons. Both of these represent soils in a young stage of genesis but from different parent material (i.e. rock and deposited material respectively). The contrast points found in this study are the restrictive properties of each profile, determined to a great extent by the B horizon.

Table 5.3 Possible restrictive characteristics associated with different horizons (Hoffman, E.; Personal communication 2010).

Subsoil horizons and materials			Equivalence to WRB
Diagnostic horizon or material	Probable limitation	Limitation class	
Lithocutanic B	Weathering rock Density Alkalinity	Moderate-serious Moderate-serious Variable	Glossic qualifier
Neocarbonate B	Alkalinity High density Salinity	Moderate-serious Low-moderate Variable	Calcic
Neocutanic B	High acidity High density	Variable Low-moderate	Cambic
Pedocutanic B	Strongly developed structure Density Salinity High sodium	Moderate Moderate-serious Low-moderate Moderate	Argic
Soft carbonate horizon	Alkalinity Density Salinity	Moderate-serious Low Variable	(Hypo) Calcic
Hard pan carbonate	Cementation Alkalinity Salinity	Moderate-serious Moderate-serious Variable	Petrocalcic

WRB= World Reference Base for Soil Resources. (IUSS Working Group WRB, 2006)

In Table 5.3, the horizons that have been described in this study and the possible limitation they can present to root growth according to Hoffman (2010, personal communication) and the equivalent of those horizons to the WRB system (IUSS Working Group WRB, 2006) are provided.

A more suitable model for the Robertson situation, which could perhaps be valuable to other arid areas, could be an index of restriction to assess each of the soil restrictive properties in a specific situation and to calculate a restriction index for that soil. Figure 5.17 contains a proposal with regards to the effect of the restrictive properties over the number of roots (i.e. represented by the brown arrow, where the thickness relates to root number). This could be an interesting way of ranking soils, since it allows for the sum of different restrictive properties as they occur in the field, but more work needs to be done in adapting corresponding values for each property and in defining thresholds for the categories described in this study.

Of interest would be the development of a rooting restrictive index. The least restrictive soil profile would present a high number of roots in depth and in density.

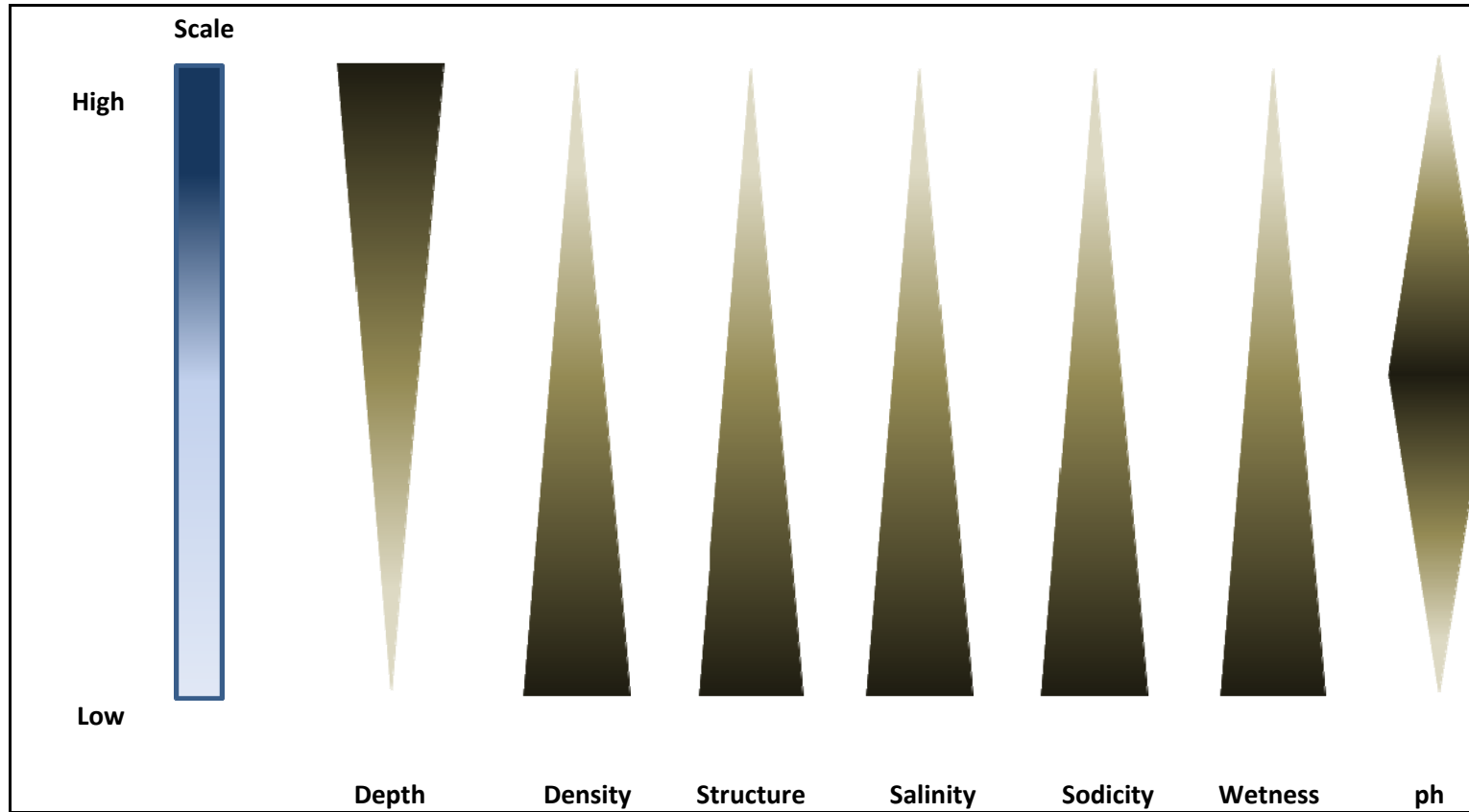


Figure 5.17 A proposed model based on data of this study to represent soil restrictive properties and their influence over the root system. The blue bar is an indication of the intensity of each of the mentioned restrictions. The brown arrows represent the influence of these restrictions on the number of roots.

Regardless of the differences in rootstocks, irrigation system, planting distance and plant age, it seems from this study that the soil influence is mainly due to the properties derived from the soil origin and pedogenetic processes, which affect the effective rooting depth and the presence of limiting factors, which in turn can be expected to influence the grapevine performance, such as root depth and rooting density.

5.5 Conclusions

The complexity of the soil system and its influence on the root system morphology is evident. Soil physical and chemical properties, plus cultural practices are difficult to evaluate separately, since they interact to varying degrees.

Important characteristics of the root system, namely rooting depth and rooting density, were chosen for their importance in the grapevine development. In Chardonnay four plots were found to present the shallowest root system of all, and fourteen were chosen as deep root systems. A second grouping was made in the deep root group, with one group including four farms with a high number of roots, and ten farms with deep but a small number of roots. In Shiraz eight plots were the shallowest, in the deep rooting plots five represented high rooting density, and five low rooting densities. The heterogeneity of the plots in terms of irrigation type, planting distance, rootstock material, plant age, and soil type, is an important characteristic of this study.

In this study it was found that root distribution (depth and density) was highly determined by the soil properties, which does not imply that it is totally independent of cultural practices and genetic expression. It is also shown that cultural practices that modify important soil properties, such as pre-planting soil preparation can have a high impact in the posterior morphology of the root system. Other cultural practices that have been shown in the literature to have an effect over the root system, such as irrigation, trellis system and planting distance, seem to be subjected in varying degrees to soil properties.

The extreme cases of shallow roots and deep roots with high root density could be grouped according to certain soil characteristics. These characteristics are associated with the origin of the soil and, very importantly, with the thickness of these horizons and the homogeneity in the depth and nature of the transition between horizons. These aspects determine the soil volume available for, and the ease of root growth. Glenrosa, Valsrivier and Gamoep soils in the Robertson area presented clear physical limitations to rooting depth, and the available soil volume was determined by the thickness of the B horizon. At the other extreme, soils developed from deposited materials, namely Oakleaf, Augrabies and Brandvlei, represented the lower level of restrictions to root growth, mainly due to an extensive available soil volume. The grouping in terms of soil families that occurred when putting together similar root systems was interesting, but it also showed that the more restrictive group (i.e. the shallow root system) could develop deep root systems, although with limitations in root density. In contrast, the less restrictive group could also produce some low-density root systems when other restrictions were present, for example chemical limitations.

The diagnostic horizons of the South African soil taxonomy can represent important soil characteristics that determine root morphology despite the differences in rootstock and irrigation system.

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Chapter 6

General discussion and conclusions

GENERAL DISCUSSION AND CONCLUSIONS

6.1 General discussion

Grapevines thrive by continuously accommodating both their structure and function to the two changing environments in which they grow. This adaptation is extremely complex and the response must be integrative in nature. Changes in the troposphere occur on a diurnal and seasonal basis, but changes in the rhizosphere are comparatively slower and related more to seasonal changes.

In a dry and arid area, an important aspect is the increasing temperature and the increasing water pressure deficit in the troposphere (Chaves *et al.*, 2007; Costa *et al.*, 2007). Thus the grapevines are subjected to high evaporative demands, coinciding with the last stages of berry ripening towards harvest time. The canopy size represents the grapevine's evaporative surface. It reflects the size of the root system and the water availability, especially in the stage of active shoot growth (i.e. before véraison).

In an area like Robertson, the temperature and evaporative demands reach a maximum at the time when the berries are close to harvest. The control of the plant water status is thus, at this stage, extremely important in order to actively maintain the photosynthetic process to ensure normal berry ripening and sugar loading (Loveys, 1984; Wang *et al.*, 2003), while avoiding an extreme loss of water and the consequent risk of dehydration. These factors pose a big challenge to the balance of the soil-root-canopy system in terms of water status. In this regard, differences have been also reported between cultivars (Schultz, 1996, 2003; Rogiers *et al.*, 2009; Vandeleur *et al.*, 2009).

In this study it is reported that the two cultivars studied, namely Chardonnay and Shiraz, have different ways of managing their water status. The water status and stomatal conductivity at the end of the season were compared in a daily cycle, and the canopy status was assessed visually. This comparison was performed with four cultivars (i.e. Shiraz, Grenache noir, Chardonnay and Pinot noir) at the end of the 2009 season, with no irrigation, in a spatially homogeneous soil. The results in terms of water status and in stomatal conductivity placed cultivars into two groups. One group was constituted by Grenache, Chardonnay and Pinot noir, and the other by Shiraz. Shiraz has been previously described as having an "optimistic" behaviour (Schultz 1996, 2003). In this study, Shiraz was evidently under stress throughout the day, as shown by a very negative stem water potential and very low stomatal conductivity measurements. The plant water status was probably so depleted that the amount that was available for transpiration was held extremely tightly by the tissues. The canopy also showed extreme symptoms of stress, and advanced berry shrivelling was observed. Although the three cultivars in the other group, namely Grenache, Chardonnay and Pinot noir, were in a stress situation, it was milder than that of the Shiraz. The better situation compared to Shiraz was reflected in less negative stem water potential measurements throughout the day, slightly higher stomatal conductance, and recovery of the initial water status towards the end of the day. The canopy was in a better condition, the bunches were protected and no sign of berry shrivelling was observed. Grenache has been described in the literature as pessimistic. It is thus suggested that the cultivars Chardonnay and Pinot noir show near-pessimistic behaviour, but a more detailed study is recommended in order to achieve more conclusive results. The four

cultivars were grafted onto Richter 99. This implies that the differences in water-use management were dependent on a certain degree of control by the aerial parts.

The size of the root system plays a key role in arid areas. Firstly, the size of the root system determines the size of the canopy to a certain extent, and thus the transpiration surface. Secondly, the size of the root system determines the buffer capacity during seasonal and diurnal events with high evaporative demands. According to a number of sources, the root system is also involved in many mechanisms of the root-to-shoot signalling control of the stomata aperture (Loveys, 1984; Dry & Loveys, 1999; Stoll *et al.*, 2000; Davies *et al.*, 2002), and the rootstock genotype and scion cultivars play a role in water uptake through the expression of aquaporins at the root and canopy level (Galmés *et al.*, 2007; Vandeleur *et al.*, 2009).

In this study it has been shown that the size of the root system in regions that depend on irrigation is strongly influenced by soil properties. The morphology of the root system in a two-dimensional plane (i.e. the root-wall method) was studied for 101.14 Mgt in four different soil types, each with Chardonnay or Shiraz as scion. The rooting depth was related to the effective soil depth. The restriction factors determining soil depth were of a physical (i.e. hard pan carbonate, high consistency layers and freshly weathered rock) and/or chemical nature (i.e. salinity, sodicity and pH).

Depending on the soil volume available for growth, the size of the root system in an arid region will play a fundamental role in the canopy development before véraison, and in sustaining the canopy after véraison. It is suggested that irrigation (which represents an extremely important management tool under these conditions) should be used with this in mind. It was shown that a small root system could promote the same canopy size as others with the same water applied before véraison, but that the small root system struggles to supply enough water when the evaporative demand of the troposphere increases after véraison, resulting in a stress situation. The plant water status is responsible for the plant functioning and, importantly, influences transpiration and photosynthetic activity. The shortage of water is therefore related to the sugar loading into the berries. The results were thus interpreted using the berry sugar loading as reference for a constraint/stress plant situation. In this study it was also observed that 23.5% loss of berry mass took place in four weeks in the Shiraz plot with the largest canopy area, probably due to berry dehydration.

As a consequence of these conditions it was found that a root system with fewer roots but growing with some depth into clayey layers can maintain a better functioning canopy than one with higher numbers of roots but shallower growth, which depleted the soil water content much faster. The function of these deep occasional roots deserves more study, as do the management techniques of soil preparation that can create favourable conditions for them to develop.

Soil properties affect the root morphology. Every soil will thus have a restrictive potential. A soil with a low restrictive potential will allow the root system to develop in depth and in density. On the other hand, different degrees of restriction can be found. The more evident are due to the great importance of effective soil depth for grapevine functioning. The soil depth represents a large restriction in the soil available for root growth, as well as a restriction on water storage. In this study, 40 plots of two scions cultivars on various rootstocks were studied. The root systems

were grouped by depth into two groups: shallow rooting (SR) and deep rooting (DR). The latter group was divided further into DR high root density (DRH) and DR low root density (DRL). In the two extreme groups (i.e. SR and DRH), it was found that each group shared similar soil properties, and that those properties differed when comparing the groups to each other. The root system grouped as DRL combines characteristics of the two extreme groups. It is also suggested that the influence of cultural practices is probably more strongly manifested in this last mentioned group, alleviating or increasing determined restrictive properties under particular conditions. The presence and combination of these soil physical and chemical properties determine the restrictive rooting potential of the soil.

The different characteristics that separate the extremes were associated with determined diagnostic horizons described in the South African Soil Classification (Soil Classification Group, 1991), which determined that certain soil families corresponded to one group and others to another group. Extremely important were: the parent material, the properties that classify the B diagnostic horizons, and the thickness of this B horizon. The homogeneity in depth and the nature of the transition between horizons also play an important role in determining the soil volume available and the easiness of root growth. Soil families associated with the shallow root system were Glenrosa, Valsrivier and Gamoep. Soil families associated with the deep and high-density root system were Oakleaf, Augrabies and Brandvlei. The diagnostic horizons of the South African soil taxonomy can represent important soil characteristics that determine the root morphology despite the influence of many other properties and the differences in rootstock and irrigation system. The soil properties must be assessed in every single case to determine the thickness of the horizons and the presence of any limiting factors in the horizons.

6.2 General perspectives

The generation of knowledge in respect to differences in the dynamics of transpiration in different cultivars is an exciting field of research. The revealing of the different strategies and metabolic routes participating or interacting in the plant's water use (in transpiration control, and in water uptake), the further development of the concepts of isohydric and anisohydric, and the more detailed classification of cultivars (i.e. scions and rootstocks) will generate new knowledge that will challenge the ways of thinking about irrigation, dry-land cultivation, site-cultivar selection and the scion-rootstock combination. This represents valuable knowledge in the new scenario of increasing temperatures and water scarcity. Metabolic knowledge must be paired with the understanding of agronomical management aspects that have an impact at the physiological and biochemical level.

This study showed the hydraulic importance of deep roots, especially in a duplex soil situation. These occasional deep, thick roots seem to play an important role in terms of water uptake and maintaining the canopy without promoting excessively vigorous growth. Their importance in water uptake, and possibly also techniques of soil preparation that could ameliorate certain parts of the limiting factors in the soil to favour their growth, represent an interesting field of research. These thick roots could be related to slower water uptake that does not promote excessive vigour during the shoot growth stage, but that maintains a hydrated canopy during berry ripening.

The data gathered in forty soil profiles in the Robertson area showed the importance of root properties in relation to root development. In this area, similar soil properties were shown to be

restrictive to root growth to varying degrees. The combination of these characteristics in a determined soil can be related to the restrictive potential of that individual combination of properties. In this regard, further research could entail the creation of a restrictive rooting index that makes it possible to rank and compare individual soils according to interacting soil properties.

6.3 General conclusions

The root system plays a determining role in grapevine performance. The morphology of the root system is intimately related to soil properties. The soil system represents a set of restrictions to root growth. The soil properties exert an influence over the root growth of different genotypes.

In terms of scion influence on root growth, it seems as if the differences in water use between Chardonnay and Shiraz could play a role, but this needs to be studied in more detail. Chardonnay and Shiraz differ in their water-use strategy. Chardonnay seems to be closer to Grenache (isohydric cultivar) in terms of water use. The more pessimistic use of water could signify that more water is available over the season for use by the plant.

In an arid zone, the low water pressure in the atmosphere and the high temperature exert a big influence on the plant water status. The ability of the root system to supply the plant with water during periods of high demand (i.e. on a daily basis and during the ripening period) is related to canopy functioning and berry ripening. During berry ripening, the functioning of the plant seems to be closely related to berry sugar loading. The grapevine balance determined by the combination of the soil-root-canopy complex and the influence of management techniques is extremely important in order to achieve a good ratio in the canopy:root system, a functional canopy and solid berry ripening.

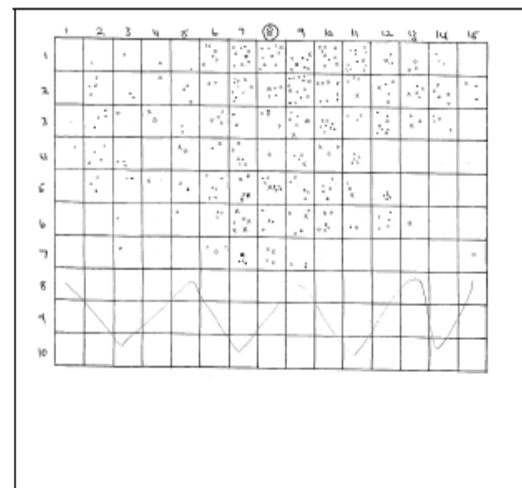
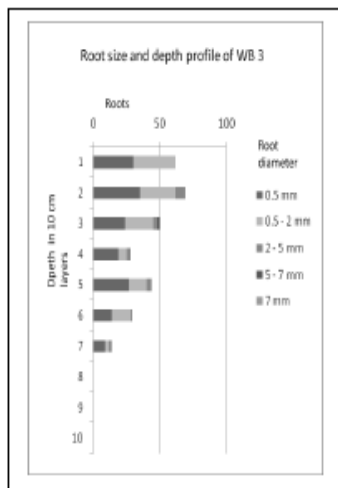
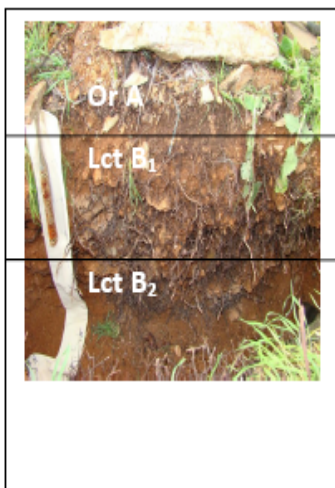
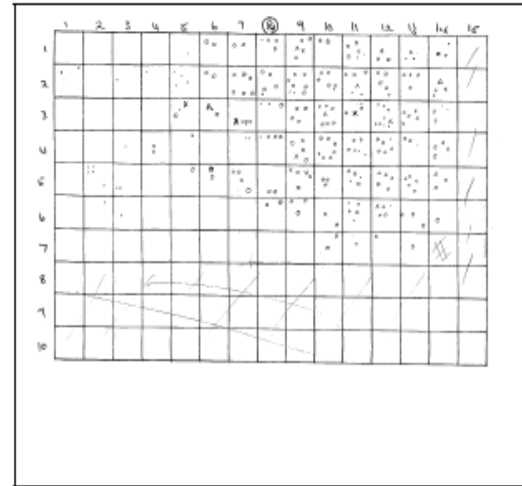
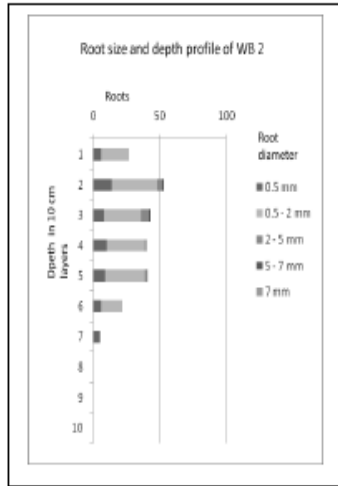
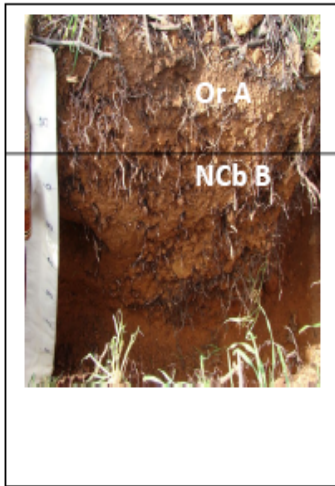
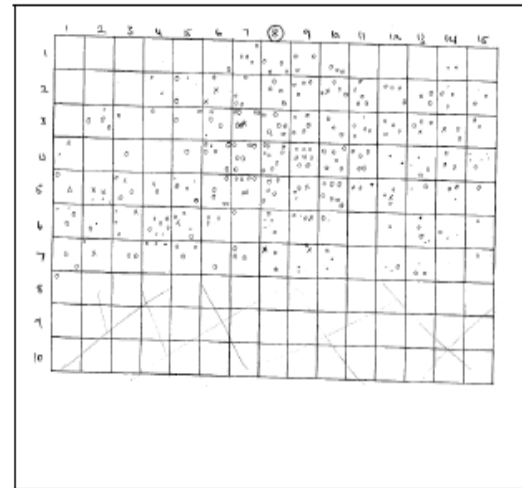
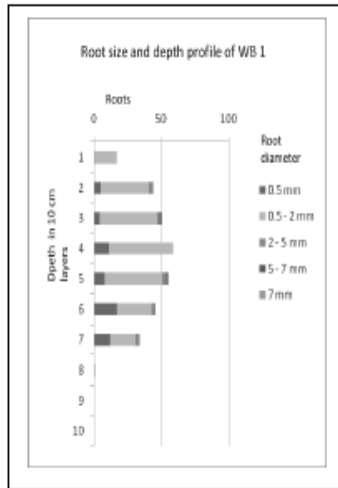
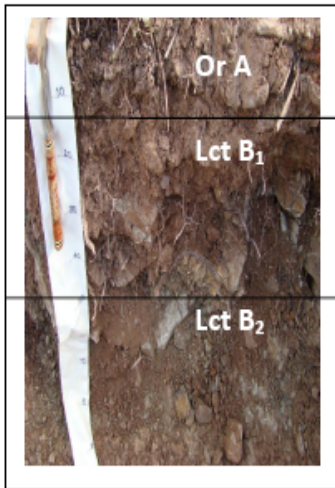
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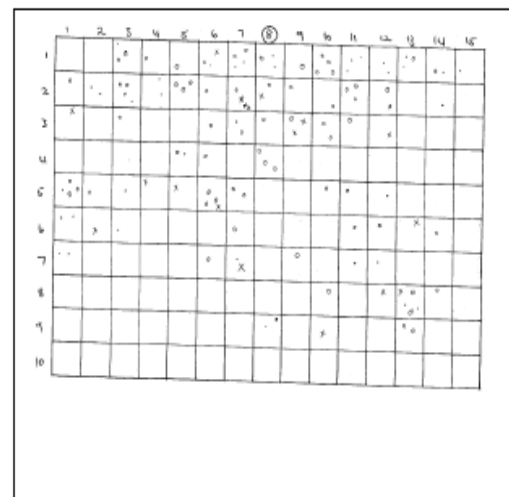
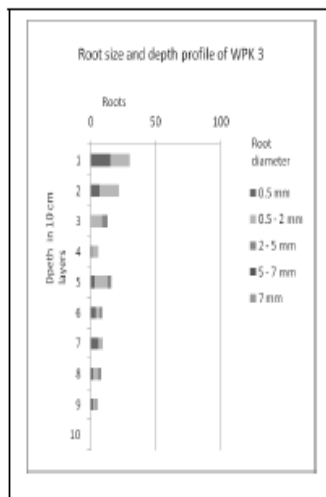
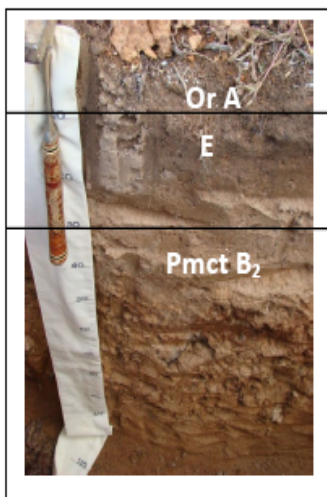
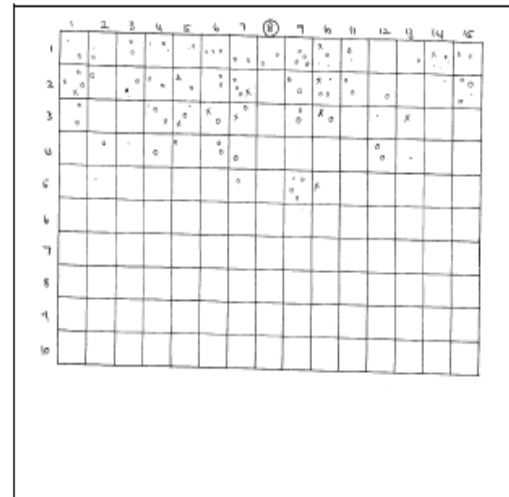
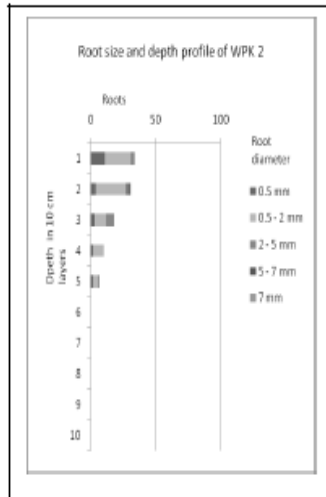
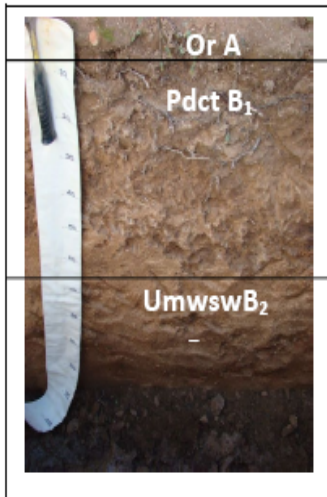
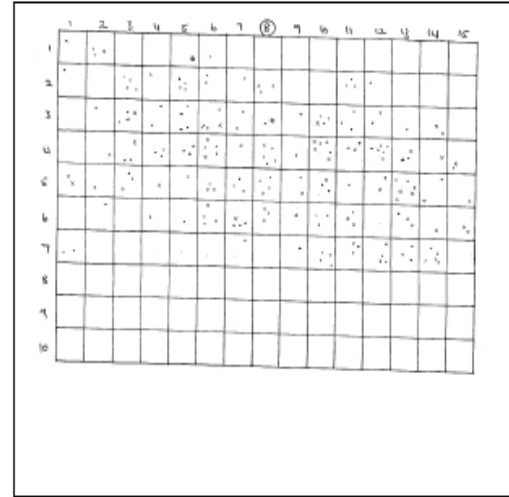
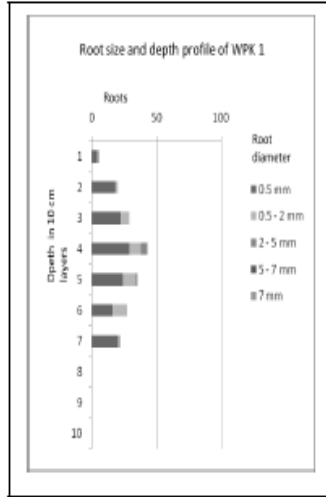
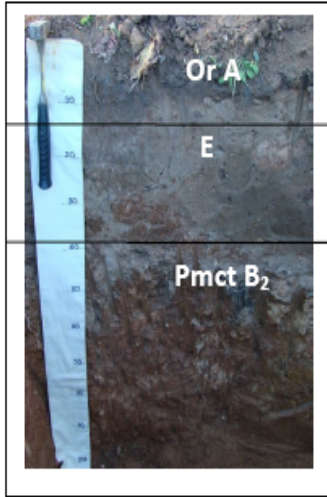
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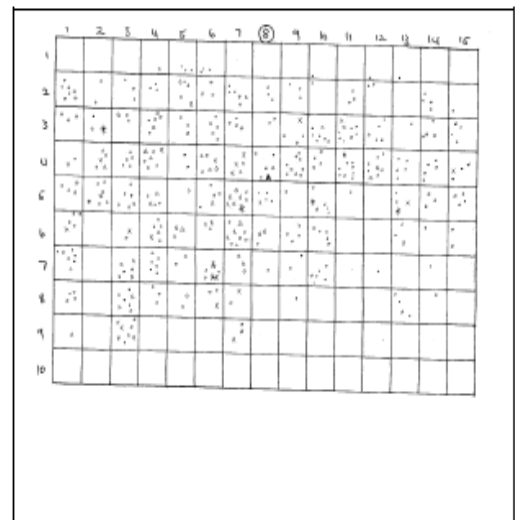
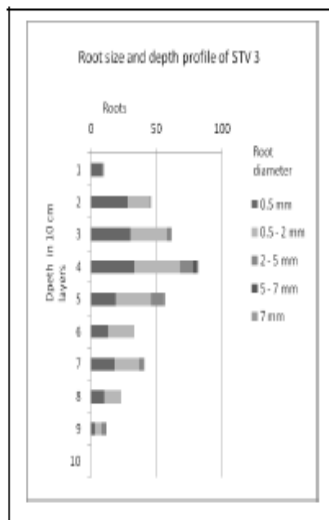
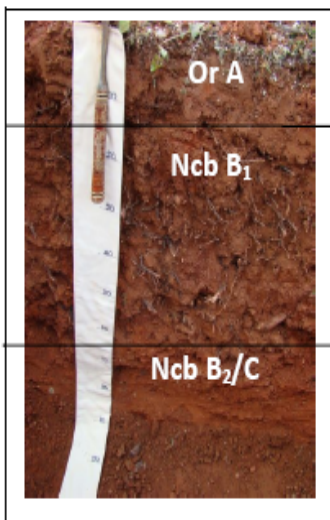
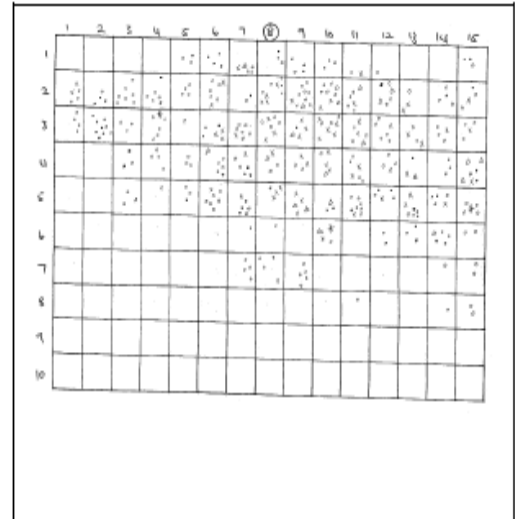
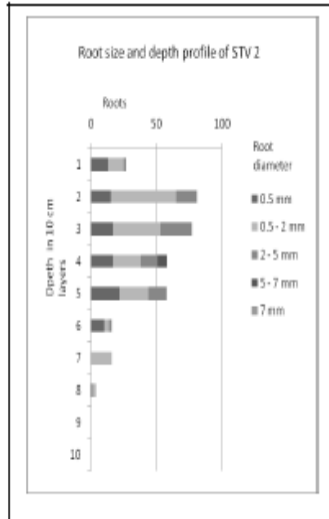
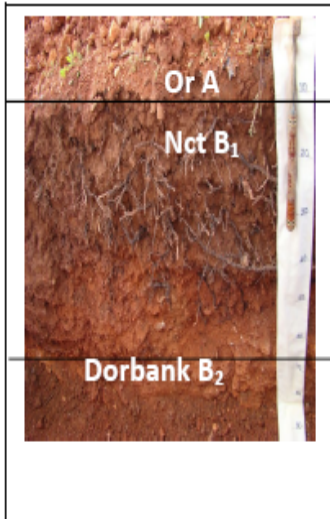
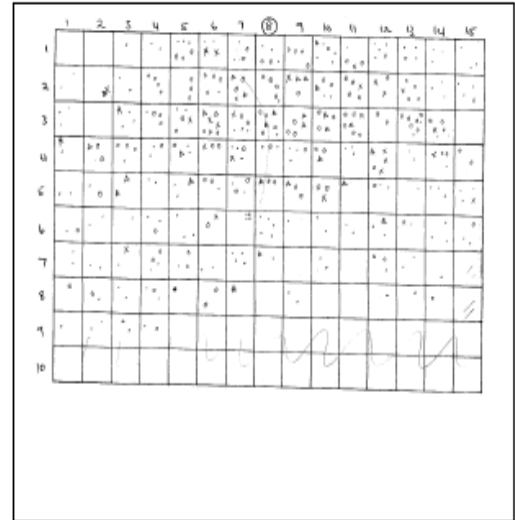
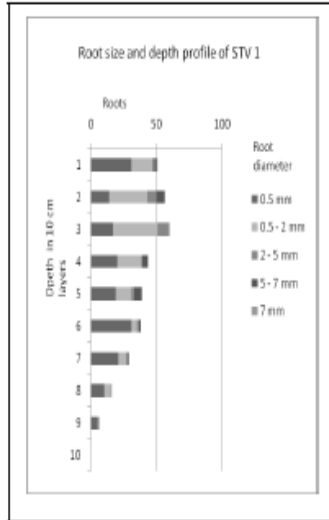
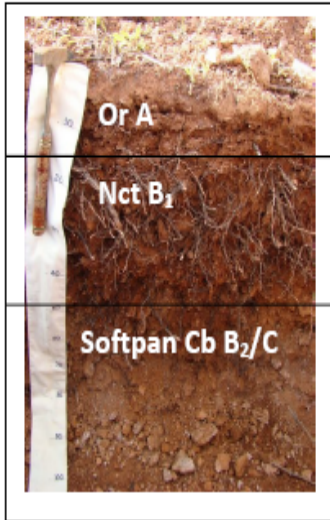
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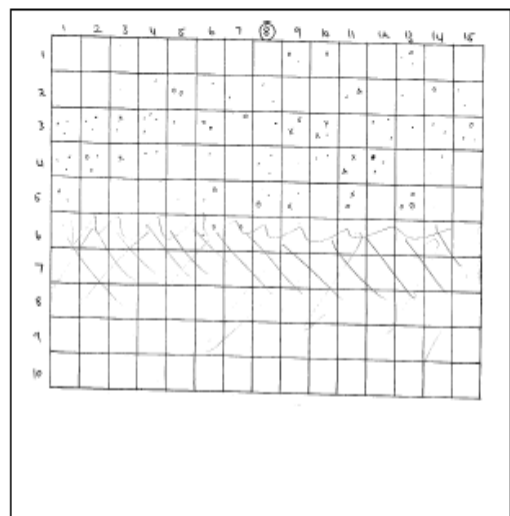
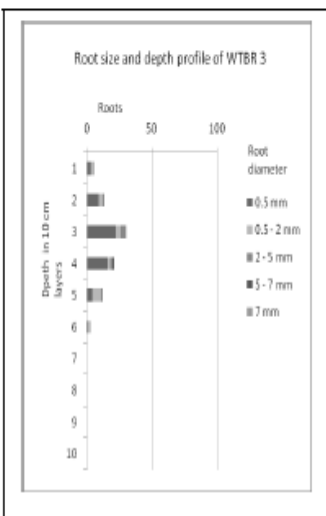
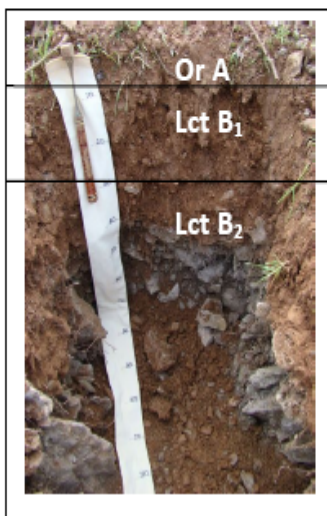
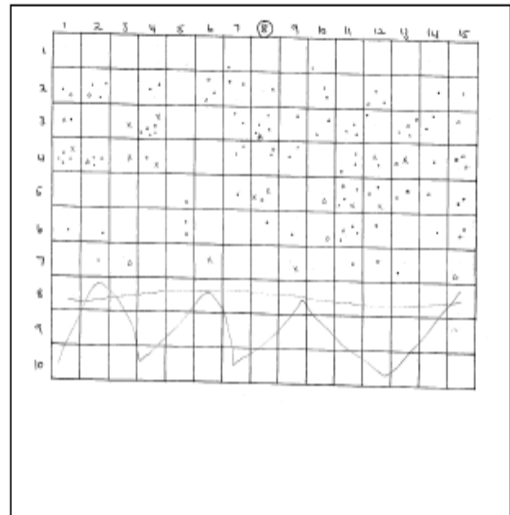
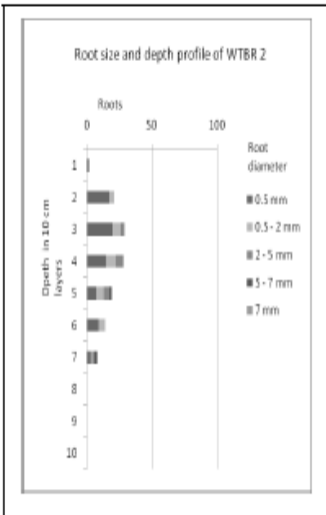
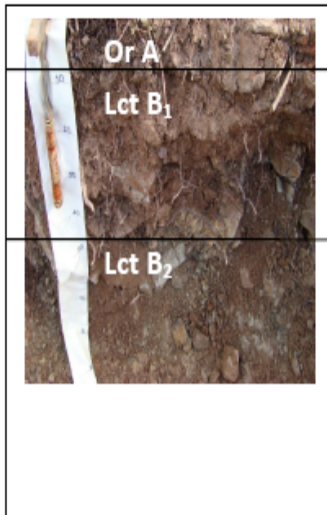
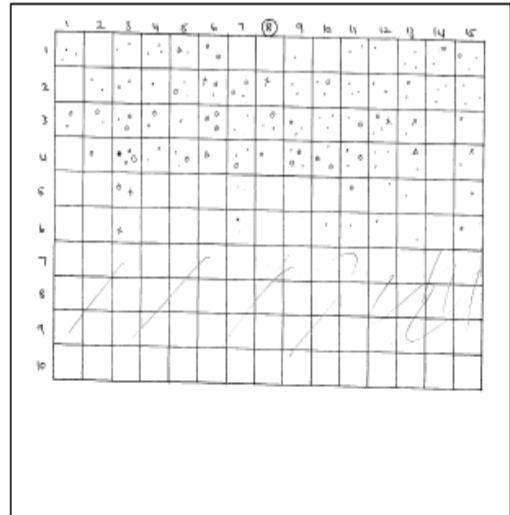
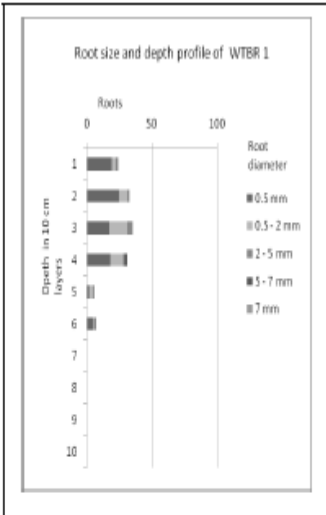
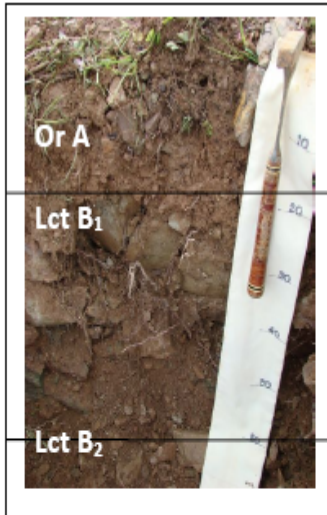
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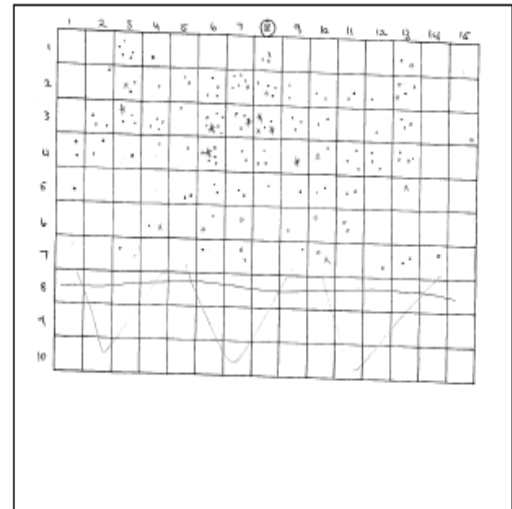
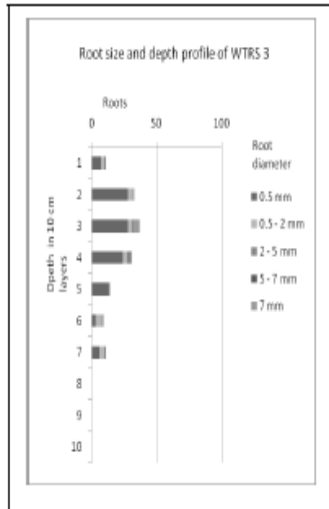
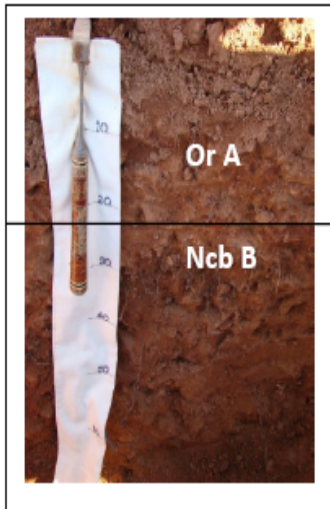
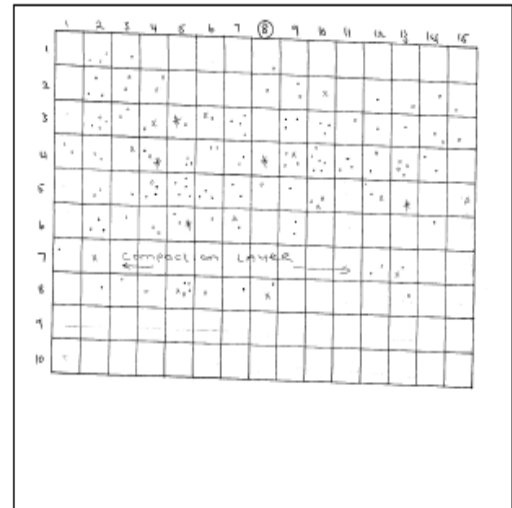
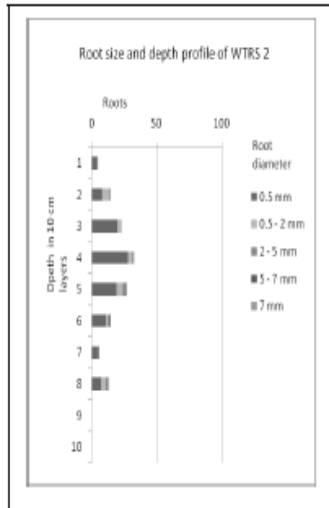
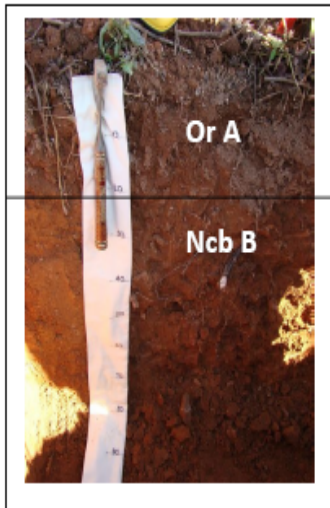
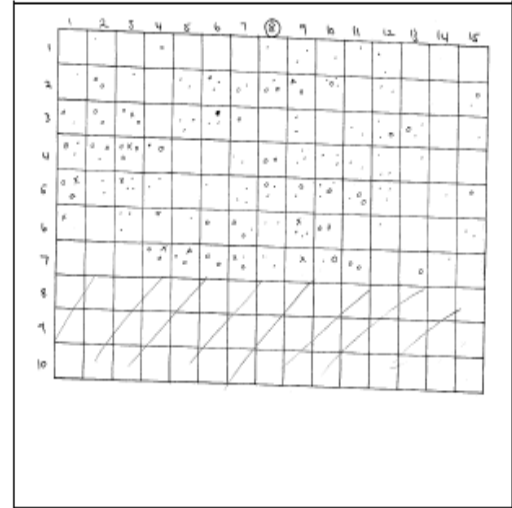
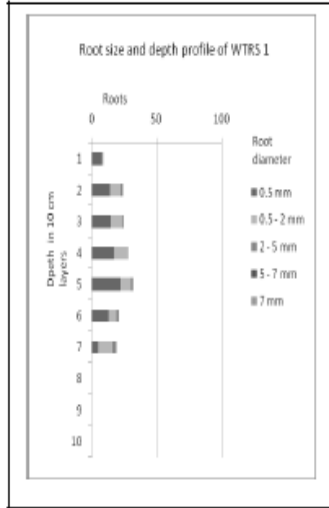
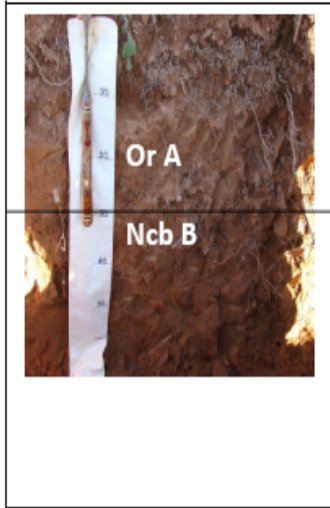
Addendum 4.1 Soil profile pits with its roots counting and root profiling

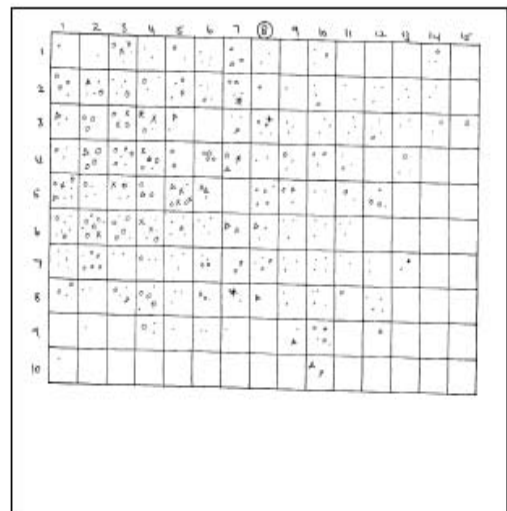
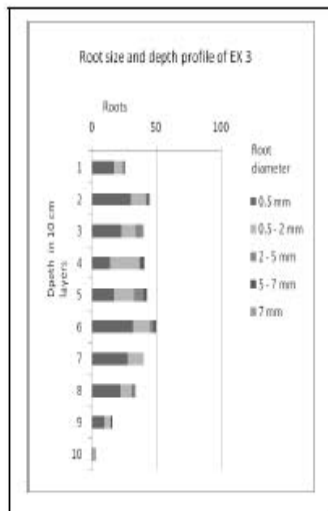
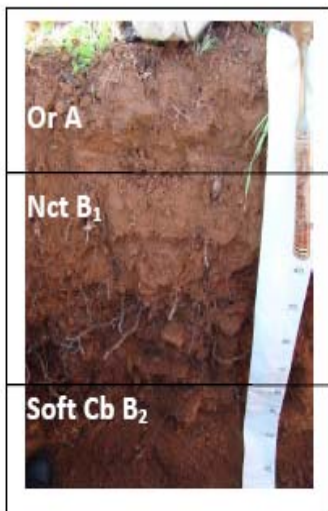
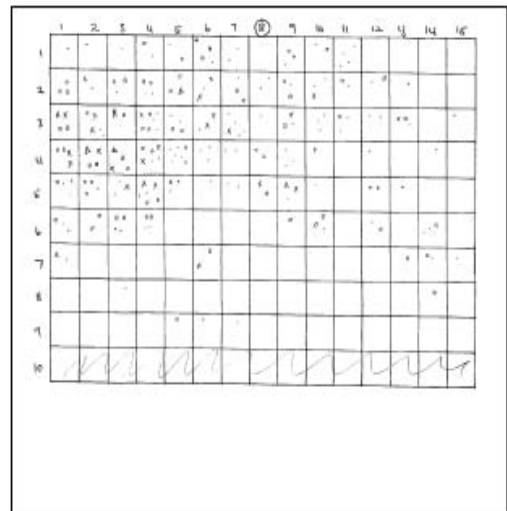
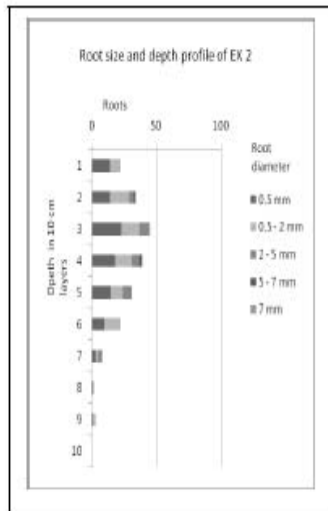
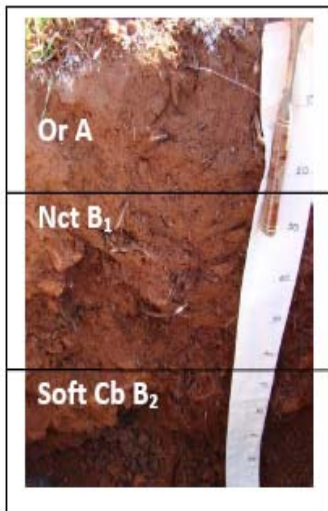
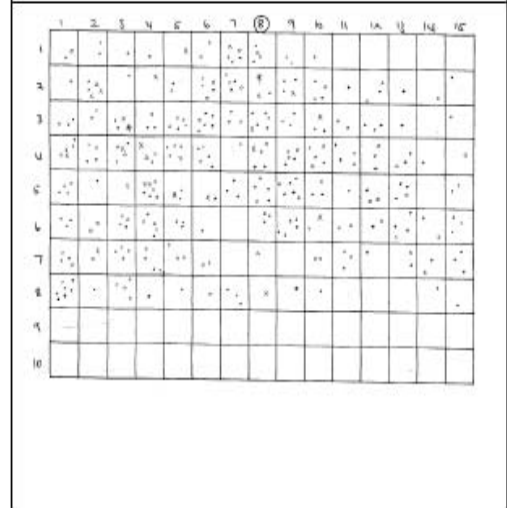
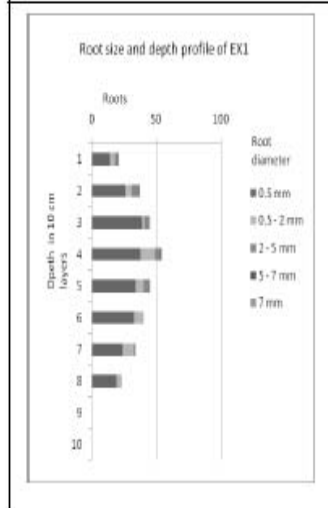
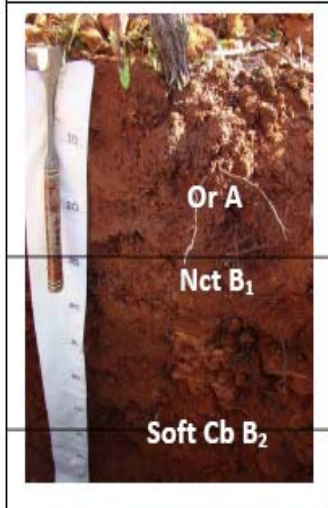


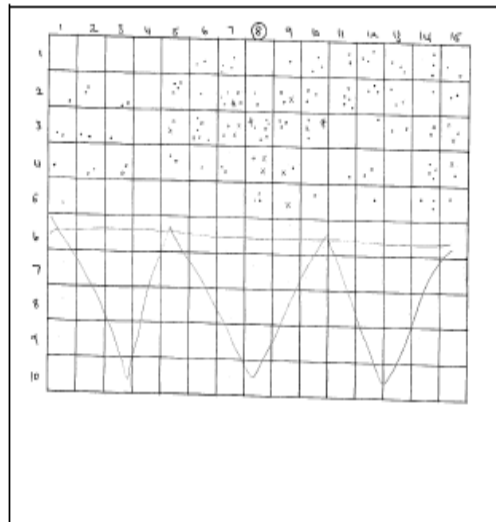
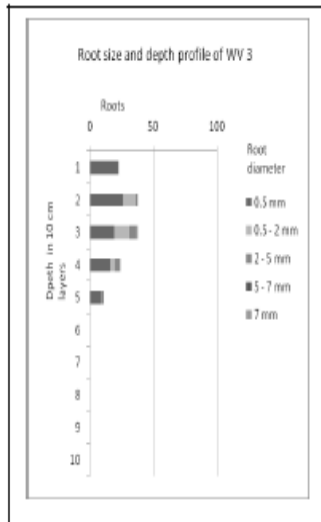
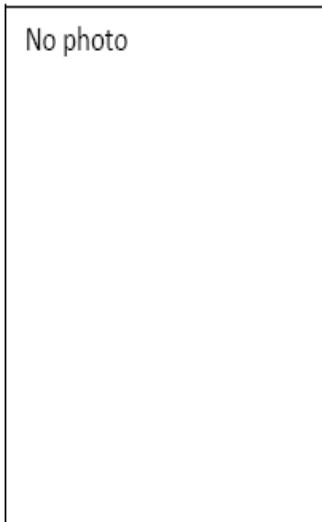
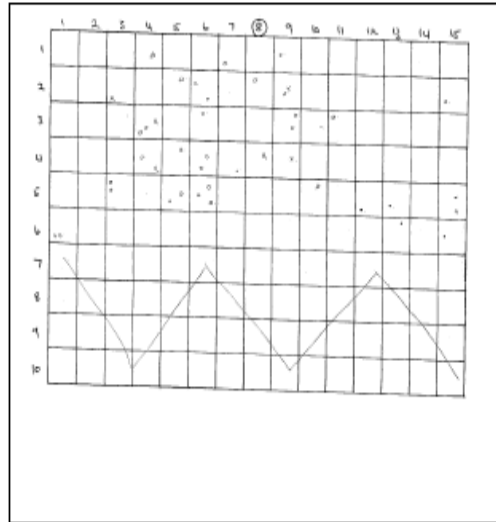
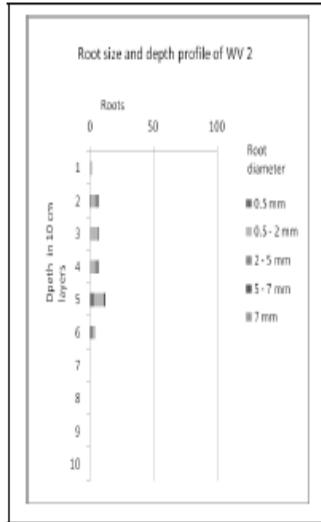
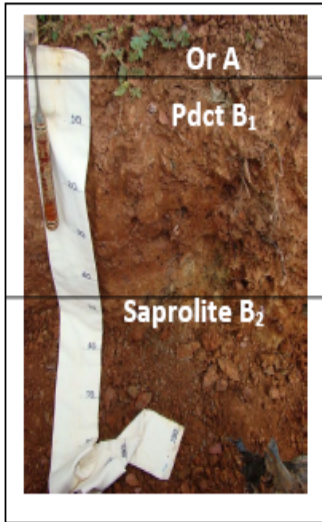
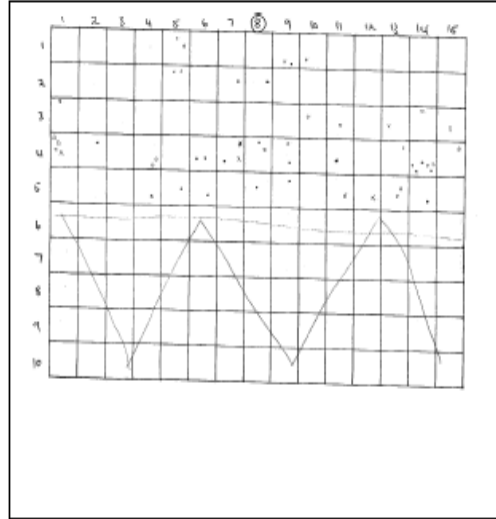
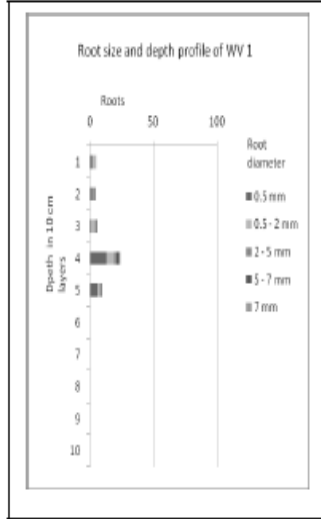
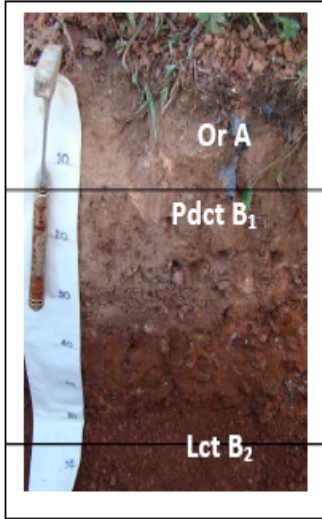












Addendum 4.2 Abbreviations in addendum 4.1

Abbreviations	
Or	Orthic
Lct	Litocutanic
NCb	Neocarbonate
Pmct	Prismacutanic
Pdct	Pedocutanic
Umwsw	Unconsolidated material with sign of wetness
Nct	Neocutanic
Softpan Cb	Softpan carbonate
Hardpan Cb	Hardpan carbonate

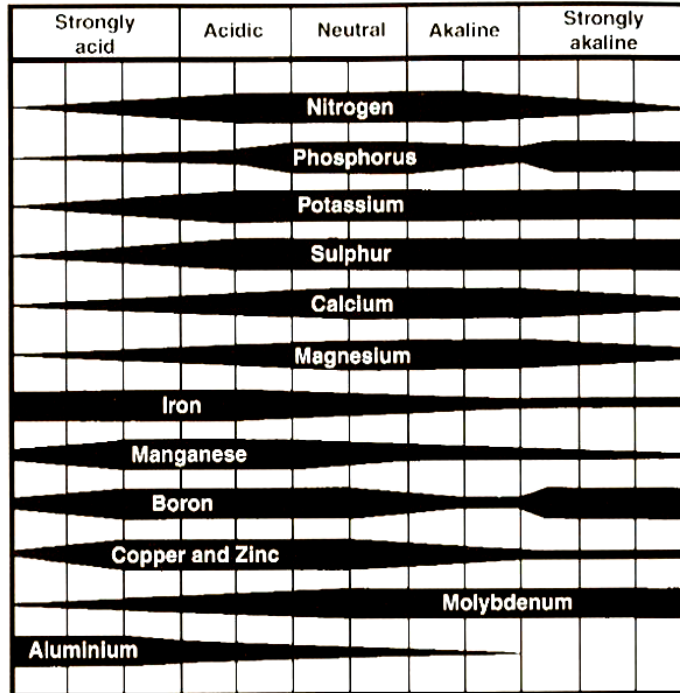
Addendum 4.3 Rating for the soil chemical measurements from Nicholas (2004)

Rating for exchangeable cations (Nicholas, 2004)			
Analysis	Rating		
CEC (cmol(+)/Kg)	Low	Medium	High
measured	<input type="checkbox"/> 5	5 - 15	<input type="checkbox"/> 15
by sum of bases	<input type="checkbox"/> 3	3 - 10	<input type="checkbox"/> 10
Exchangeable cations (cmol(+)/kg)	Low	Medium	High
Ca ²⁺	<input type="checkbox"/> 5	5 - 10	<input type="checkbox"/> 10
Mg ²⁺	<input type="checkbox"/> 1	1 - 5	<input type="checkbox"/> 5
K ⁺	<input type="checkbox"/> 0.5	0.5 - 1.0	<input type="checkbox"/> 1.0
Na ⁺	<input type="checkbox"/> 0.3	0.3 - 1.0	<input type="checkbox"/> 1.0
Al ³⁺	<input type="checkbox"/> 0.1	0.1 - 1.0	<input type="checkbox"/> 1.0
Cation balance %	Low	Normal	High
CEC			
Ca ²⁺	<input type="checkbox"/> 40	40 - 80	<input type="checkbox"/> 80
Mg ²⁺	<input type="checkbox"/> 10	10 - 40	<input type="checkbox"/> 40
K ⁺	<input type="checkbox"/> 3	3 - 10	<input type="checkbox"/> 10
% CEC	Low	Medium	High
Na ⁺ (ESP)	<input type="checkbox"/> 6	6 - 15	<input type="checkbox"/> 15
Al ³⁺	<input type="checkbox"/> 5	5 - 20	<input type="checkbox"/> 20

Addendum 4.4 Critical limits for the presence of sodium in the profile (from Nicholas, 2004).

Critical limits for soil degradation due to sodicity (for pedal and clayey soil)				
sodicity hazard	ESP%	SAR _e	SAR 1:5	soil microstructure stability
non sodic	0 - 6	0 - 6	0 - 3	generally stable
sodic	6 - 15	6 - 15	3 - 7	susceptible to damage when wet may be damaged spontaneously by irrigation
highly sodic	<input type="checkbox"/> 15	<input type="checkbox"/> 15	<input type="checkbox"/> 7	and rainfall i.e. dispersion of clays occurs

Addendum 4.5. Effect of pH on relative availability of nutrient elements (Maschmedt, 2005).



Addendum 4.6 Depth-weighted soil properties and number of roots contacts per 20 cm soil depth for WBCH and WPKCH.

Chardonnay			Soil properties								Roots			
Farm	Soil form	Depth cm	Ca:Mg	Mg		%ESP		pH (KCl)	Rest	clay %	<2mm	≥ 2 mm	RATIO	TOTAL
WBCH1	Glenrosa	A (0-20)	4.80	5.06	m	0.77	ns	8.1	770	6	58	3	19	61
	Gs 1112	B (20-40)	7.61	6.63	m	0.68	ns	8.1	890	4	106	4	27	110
		C (40-60)	7.61	6.63	m	0.68	ns	8.1	890	4	94	7	13	101
		D (60-80)	7.61	6.63	m	0.68	ns	8.1	890	4	32	3	11	35
WBCH2		Augrabies	A (0-20)	4.28	13.26	h	0.46	ns	8.1	570	6	75	5	15
WBCH2	Augrabies	B (20-40)	3.28	15.98	h	1.60	ns	8.2	420	4	75	8	9	83
		C (40-60)	3.28	15.98	h	1.60	ns	8.2	420	4	61	2	31	63
		D (60-80)	3.28	15.98	h	1.60	ns	8.2	420	4	5	0	5	5
		E (80-100)	3.28	15.98	h	1.60	ns	8.2	420	4	0	0	0	0
		WBCH3	Glenrosa	A (0-20)	5.29	9.42	h	0.88	ns	8.2	607.5	4	124	7
WBCH3	Gs 1212	B (20-40)	5.08	11.15	h	1.37	ns	8.1	360	4	70	8	9	78
		C (40-60)	5.08	11.15	h	1.37	ns	8.1	360	4	68	5	14	73
		D (60-80)	5.08	11.15	h	1.37	ns	8.1	360	4	12	2	6	14
		WPKCH1	Escourt	A (0-20)	1.10	2.23	l	3.82	ns	5.4	1222.5	12.5	26	0
WPKCH1	Es 1100	B (20-40)	0.45	3.41	l	7.30	s	6	1110	20	67	5	13	72
		C (40-60)	0.88	11.47	h	2.72	ns	7.3	820	32	61	1	61	62
		D (60-80)	0.88	11.47	h	2.72	ns	7.3	820	32	22	0	22	22
		E (80-100)	0.88	11.47	h	2.72	ns	7.3	820	32	0	0	0	0
		WPKCH2	Sepane	A (0-20)	1.24	1.52	l	7.68	s	5.5	1645	7	58	7
WPKCH2	Se 2211	B (20-40)	0.55	2.43	l	18.13	hs	6	1120	22	22	6	4	28
		C (40-60)	0.55	2.43	l	18.13	hs	6	1120	22	6	1	6	7
		D (60-80)	0.55	2.43	l	18.13	hs	6	1120	22	0	0	0	0
		E (80-100)	0.20	3.64		47.75	hs	7	420	16	0	0	0	0
		WPKCH3	Escourt	A (0-20)	1.34	1.37	l	3.78	ns	5.7	2057.5	5.5	52	0
WPKCH3	Es 1100	B (20-40)	0.97	2.16	l	4.59	ns	5.6	1570	10	15	4	4	19
		C (40-60)	0.64	4.16	l	7.26	s	6.4	730	14	20	5	4	25
		D (60-80)	0.64	4.16	l	7.26	s	6.4	730	14	14	3	5	17
		E (80-100)	0.64	4.16	l	7.26	s	6.4	730	14	4	1	4	5

l = low; m =medium; h = high; ns = non sodic; s = sodic; hs = highly sodic.

Addendum 4.7 Depth-weighted soil properties and number of roots contacts per 20 cm soil depth for STVCH and KDCH.

Chardonnay cont.			Soil properties								Roots			
Farm	Soil form	Depth cm	Ca:Mg	Mg		%ESP	pH (KCl)	Rest	clay %	<2mm	≥ 2 mm	RATIO	TOTAL	
STVCH1	Etosha	A (0-20)	2.93	19.50	h	1.25	ns	8.2	530	12	90	18	5	108
		Et 2220	B (20-40)	3.57	15.33	h	1.70	ns	8.1	350	12	90	14	6
		C (40-60)	2.79	14.99	h	3.37	ns	8.1	315	7	66	11	6	77
		D (60-80)	1.97	14.64	h	5.96		8.1	280	2	42	3	14	45
		E (80-90)	1.97	14.64	h	5.96		8.1	280	2	7	0	7	7
STVCH2	Oudsthoorn	A (0-20)	2.42	9.71	h	2.09	ns	8	532.5	9.5	90	18	5	108
		Ou 2211	B (20-40)	2.56	10.08	h	3.14	ns	8.1	600	14	91	44	2
		C (40-60)	2.56	10.08	h	3.14	ns	8.1	600	14	58	16	4	74
		D (60-80)	0.97	2.60		39.86	hs	6.6	310	2	20	0	20	20
STVCH3	Augrabies	A (0-20)	2.08	5.93	h	4.23	ns	7.9	420	1	55	1	55	56
		Ag 2110	B (20-40)	1.87	5.30	h	4.84	ns	8	390	8	126	18	7
		C (40-60)	1.87	5.30	h	4.84	ns	8	390	8	79	11	7	90
		D (60-80)	1.13	2.55	h	26.56	hs	6.7	230	6	60	4	15	64
		E (80-90)	1.13	2.55	h	26.56	hs	6.7	230	6	8	4	2	12
KDCH1	Etosha	A (0-20)	2.00	5.78	h	3.39	ns	7.4	617.5	6.5	37	7	5	44
		Et 2221	B (20-40)	1.31	3.64	m	11.06	s	6.6	370	8	83	27	3
		C (40-60)	1.31	3.64	m	11.06	s	6.6	370	8	61	16	4	77
		D (60-80)	0.48	2.23		63.66	hs	5.2	190	4	24	3	8	27
		E (80-90)	0.48	2.23		63.66	hs	5.2	190	4	0	0	0	0
KDCH2	Tukulu	A (0-20)	1.75	3.64	m	3.54	ns	7	600	4	50	4	13	54
		Tu 2120	B (20-40)	1.84	2.37	m	5.85	ns	6.3	705	8.5	40	18	2
		C (40-60)	1.89	1.94	m	7.13	s	6.0	740	10	18	8	2	26
		D (60-80)	0.56	1.40		65.91		5.1	340	2	6	4	2	10
		E (80-90)	0.56	1.40		65.91		5.1	340	2	5	0	5	5
KDCH3	Prieska	A (0-20)	5.31	9.05	h	1.22	ns	7.7	377.5	3.5	46	8	6	54
		Pr 2110	B (20-40)	5.84	10.56	h	1.78	ns	7.7	340	2	61	15	4
		C (40-60)	5.52	10.79	h	3.09	ns	7.8	292.5	2	44	9	5	53
		D (60-80)	4.65	11.46	h	7.23	s	8	150	2	9	1	9	10
		E (80-90)	4.65	11.46	h	7.23	s	8	150	2	1	0	1	1

Addendum 4.8 Depth-weighted soil properties and number of roots contacts per 20 cm soil depth for WTBRSH and WTRSSH.



SHIRAZ			Soil properties								Roots			
Farm	Soil form	Depth cm	Ca:Mg	Mg		%ESP		pH (KCl)	Rest	clay %	<2mm	≥ 2 mm	RATIO	TOTAL
WTBRSH1	Glenrosa	A (0-20)	2.09	4.91	m	3.88	ns	7.5	637.5	7.5	56	1	56	57
	Gs 2211	B (20-40)	1.96	3.91	m	6.47	s	7.4	660	6	64	2	32	66
		C (40-60)	1.96	3.91	m	6.47	s	7.4	660	6	13	0	13	13
WTBRSH2	Glenrosa	A (0-20)	5.23	8.35	h	1.27	ns	7.9	615	9	23	0	23	23
	Gs 2211	B (20-40)	6.28	7.11	h	1.52	ns	7.9	420	6	56	1	56	57
		C (40-60)	6.28	7.11	h	1.52	ns	7.9	420	6	31	2	16	33
WTBRSH3	Glenrosa	A (0-20)	1.73	3.14	m	6.35	s	6.5	560	5	18	1	18	19
	Gs 2211	B (20-40)	1.79	2.70	m	8.53	s	6.2	710	2	50	1	50	51
		C (40-60)	1.79	2.70	m	8.53	s	6.2	710	2	15	0	15	15
WTRSSH1	Augrabies	A (0-20)	2.20	5.04	m	2.49	ns	8.0	570	8	32	1	32	33
	Ag	B (20-40)	2.24	5.06	m	2.84	ns	7.9	595	7	53	0	53	53
		C (40-60)	2.29	5.08	m	3.19	ns	7.8	620	6	53	0	53	53
		D (60-80)	2.29	5.08	m	3.19	ns	7.8	620	6	16	3	5	19
WTRSSH2	Augrabies	A (0-20)	3.48	8.24	h	0.88	ns	7.9	560	10	20	0	20	20
	Ag	B (20-40)	4.43	7.82	h	1.10	ns	8.0	585	12	53	3	18	56
		C (40-60)	5.49	7.40	h	1.27	ns	8.0	610	14	39	3	13	42
		D (60-80)	5.49	7.40	h	1.27	ns	8.0	610	14	15	4	4	19
WTRSSH3	Augrabies	A (0-20)	1.62	3.03	m	3.32	ns	7.2	610	14	44	0	44	44
	Ag	B (20-40)	1.54	2.47	m	6.38	s	6.9	595	14	60	8	8	68
		C (40-60)	1.42	1.91	m	11.38	s	6.6	580	14	23	0	23	23
		D (60-80)	1.42	1.91	m	11.38	s	6.6	580	14	10	1	10	11

l = low; m =medium; h = high; ns = non sodic; s = sodic; hs = highly sodic.



Addendum 4.9 Depth-weighted soil properties and number of roots contacts per 20 cm soil depth for EXSH and WVSH.

SHIRAZ cont.			Soil properties								Roots			
Farm	Soil form	Depth cm	Ca:Mg	Mg		%ESP		pH (KCl)	Rest	clay %	<2mm	≥ 2 mm	RATIO	TOTAL
EXSH1	Etosha	A (0-20)	1.69	4.38	m	1.89	ns	7.2	710	6	57	1	57	58
	Et 2221	B (20-40)	1.74	4.76	m	2.41	ns	7.4	745	4	97	2	49	99
		C (40-60)	1.78	5.13	m	2.85	ns	7.5	780	2	85	0	85	85
		D (60-80)	1.78	5.13	m	2.85	ns	7.5	780	2	55	2	28	57
		E (80-90)	2.46	22.75		1.13		8.0	480	1	0	0	0	0
EXSH2	Etosha	A (0-20)	2.03	6.23	h	2.19	ns	7.9	510	4	55	1	55	56
	Et 2221	B (20-40)	1.72	4.67	m	8.34	s	7.3	535	5	81	3	27	84
		C (40-60)	1.10	3.11	m	22.27	hs	6.7	560	6	53	0	53	53
		D (60-80)	1.10	3.11	m	22.27	hs	6.7	560	6	7	3	2	10
		E (80-100)	0.52	2.39		62.06		4.6	250	8	3	0	3	3
EXSH3	Etosha	A (0-20)	2.82	9.17	h	1.32	ns	8.0	660	4	69	2	35	71
	Et 2211	B (20-40)	2.31	7.22	h	2.79	ns	7.9	635	4	77	4	19	81
		C (40-60)	1.43	5.27	m	6.59	s	7.8	610	4	88	5	18	93
		D (60-80)	1.43	5.27	m	6.59	s	7.8	610	4	71	3	24	74
		E (80-100)	0.53	2.49		46.03		5.6	260	4	16	2	8	19
WVSH1	Swartland	A (0-20)	0.96	3.75	m	10.79	s	6.3	575	14	8	1	8	9
	Gs 2211	B (20-40)	0.77	5.79	h	14.62	s	6.4	350	14	27	3	9	30
		C (40-60)	0.77	5.79	h	14.62	s	6.4	350	14	10	0	10	10
WVSH2	Swartland	A (0-20)	1.34	4.31	m	8.60	s	6.6	427.5	12	9	0	9	9
	Gs 12 12	B (20-40)	0.61	4.48	m	21.09	hs	6.4	240	12	14	0	14	14
		C (40-60)	0.61	4.48	m	21.09	hs	6.4	240	12	15	1	15	16
WVSH3	Swartland	A (0-20)	1.30	3.71	m	9.59	s	6.6	385	8	60	1	60	61
	Gs 2211	B (20-40)	1.22	4.47	m	11.69	s	6.6	220	8	60	2	30	62
		C (40-60)	1.22	4.47	m	11.69	s	6.6	220	8	11	0	11	11

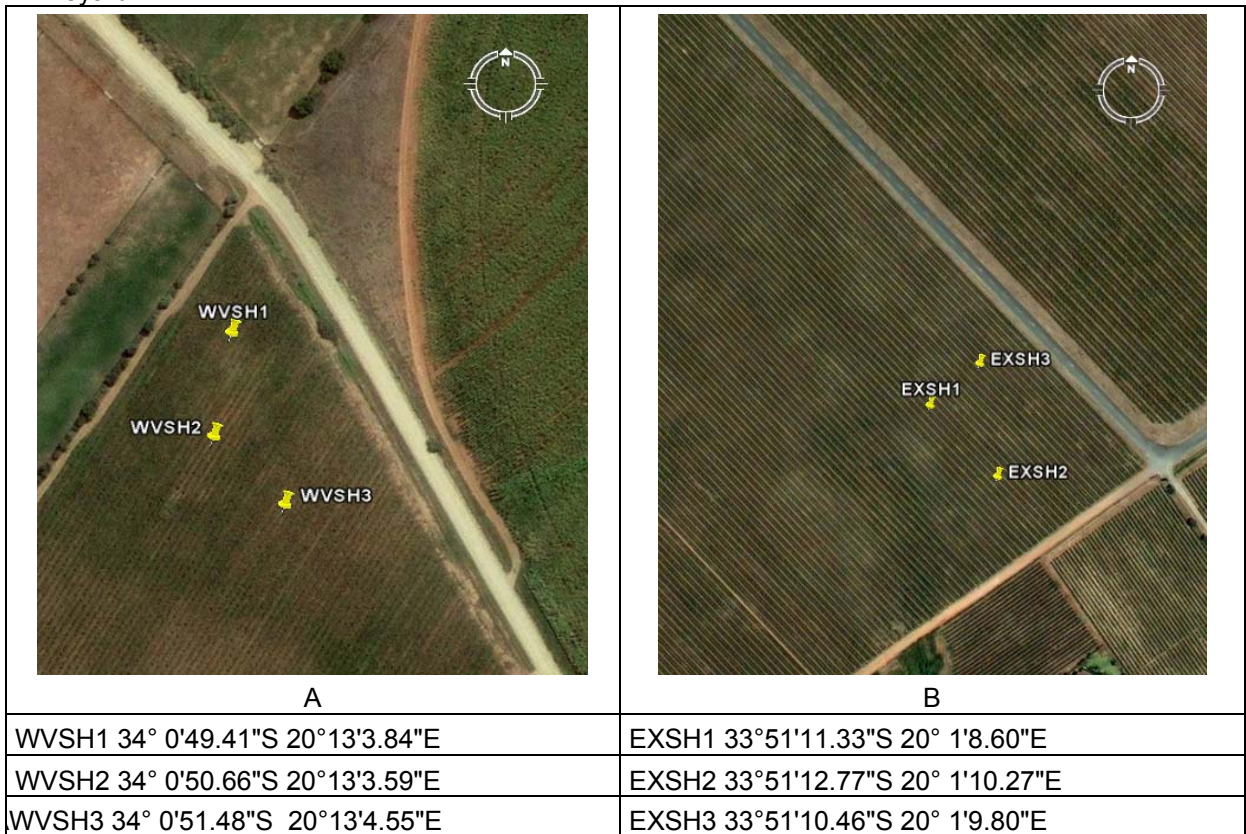
Addendum 4.10 Image of WPKCH (A) and STVCH (B) plots with the location of three miniplots in each vineyard.

 <p style="text-align: center;">A</p>	 <p style="text-align: center;">B</p>
WPKCH1 33°47'57.09"S 20° 3'9.67"E	STVCH1 33°58'13.79"S 19°54'7.19"E
WPKCH2 33°47'58.66"S 20° 3'9.30"E	STVCH2 33°58'13.49"S 19°54'7.95"E
WPKCH3 33°47'59.83"S 20° 3'9.73"E	STVCH3 33°58'13.35"S 19°54'9.10"E

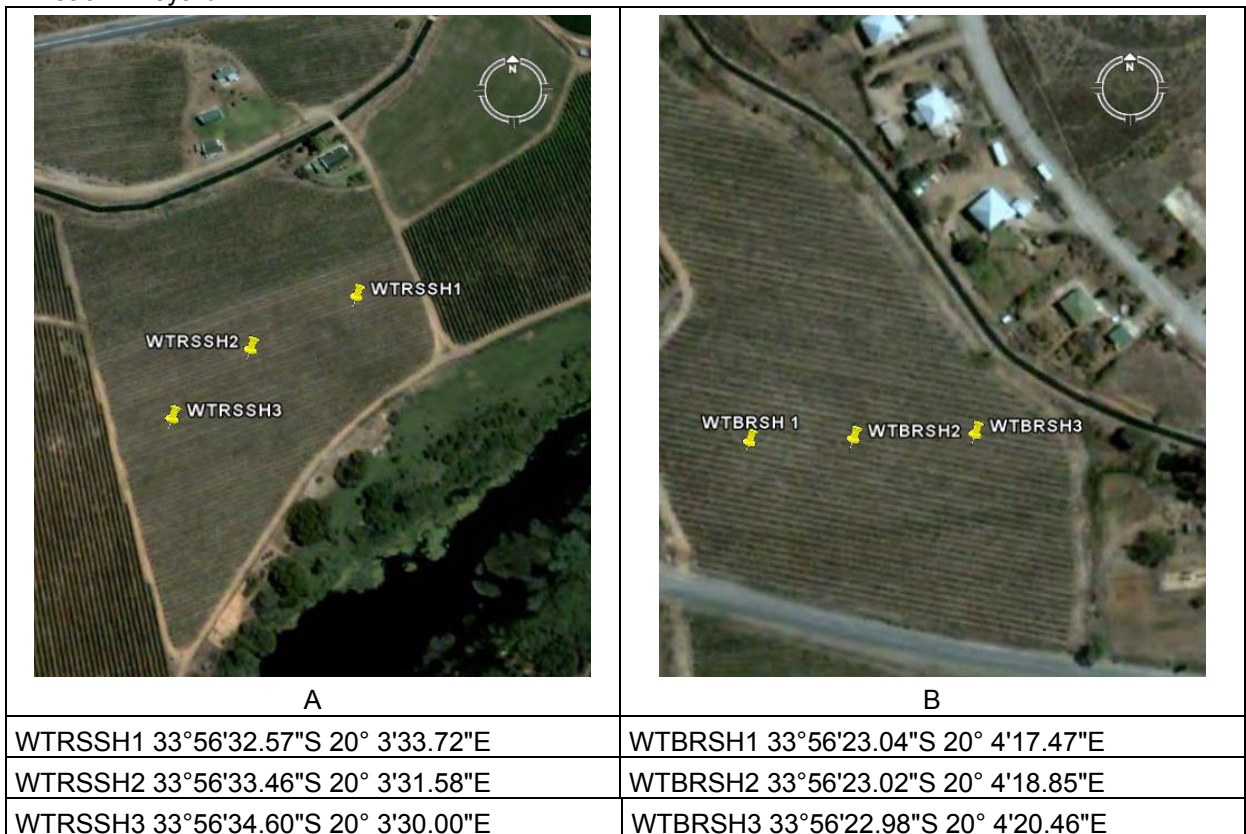
Addendum 4.11 Image of WBCH (A) and KDCH (B) plots with the location of three miniplots in each vineyard.

 <p style="text-align: center;">A</p>	 <p style="text-align: center;">B</p>
WBCH1 33°54'19.15"S 19°40'48.90"E	KDCH1 33°49'53.38"S 19°54'16.22"E
WBCH2 33°54'20.17"S 19°40'50.34"E	KDCH2 33°49'54.16"S 19°54'13.57"E
WBCH3 33°54'21.69"S 19°40'52.72"E	KDCH3 33°49'55.39"S 19°54'15.05"E

Addendum 4.12 Image of WVSH (A) and EXSH (B) plots with the location of three mini-plots in each vineyard.



Addendum 4.13 Image of WTRSSH (A) and WTBRSH (B) plots with the location of three mini-plots in each vineyard.



Addendum 5.1 Depth-weighted soil properties for the references plots of Chardonnay that are in the shallow rooting group (SR).

Plot	Depth cm	DWM clay %	Ctncty	Prmbt	pH	Rest	Mg	Ca:Mg	B	Na%
WBCH	A (0-20)	8.75	3.25	4	7.18	895	2.75	4.79	0.71	3.45
	B (20-40)	15.8	4	4	6.2	160	5.07	2.04	0.69	6.94
	C (40-60)	15.8	4	4	6.2	160	5.07	2.04	0.69	6.94
BSRCH	A (0-20)	19.8	3	4	7.3	710	5.17	2.08	0	4.1
	B (20-40)	37.2	4	2	5	680	7.18	0.75	0.6	8.26
	C (40-60)	37.2	4	2	5	680	7.18	0.75	0.6	8.26
WVCH	A (0-20)	5	3	4	6.7	600	2.93	2.59	0.64	4.58
	B (20-40)	12.8	4	2	6.1	940	4.43	0.81	0.55	5.33
	C (40-60)	12.8	4	2	6.1	940	4.43	0.81	0.55	5.33
SBVCH	A (0-20)	19.12	4	4	7.2	480	3.39	2.76	1.86	7.07
	B (20-40)	23.2	4	2	5.4	390	5.48	0.99	1.16	15.37
	C (40-60)	23.2	4	2	5.4	390	5.48	0.99	1.16	15.37

Addendum 5.2 Depth-weighted soil properties for the references plots of Chardonnay that are in the deep rooting high density group (DRH)

Plot	Depth cm	DWM clay %	Ctncty	Prmbt	pH	Rest	Mg	Ca:Mg	B	Na%
DWCH	A (0-20)	5	3	4	7.2	710	1.56	2.24	0.93	8.57
	B (20-40)	5	3	4	7.2	710	1.56	2.24	0.93	8.57
	C (40-60)	11.2	3	4	5.3	490	2.15	0.73	0.72	17.21
	D (60-80)	11.2	3	4	5.3	490	2.15	0.73	0.72	17.21
	E (80-100)	11.2	3	4	5.3	490	2.15	0.73	0.72	17.21
GLCH	A (0-20)	3.2	2	4	6.2	2930	0.77	3.69	0.24	0.91
	B (20-40)	10.4	1.25	4	5.53	4707.5	0.74	2.76	0.16	1.46
	C (40-60)	9.8	2	4	5.15	4435	1.23	1.54	0.20	3.45
	D (60-80)	6.8	3.5	4	5	3570	1.73	1.16	0.27	5.25
	E (80-100)	6.8	3.5	4	5	3570	1.73	1.16	0.27	5.25
GCH	A (0-20)	2.2	2	4	5	1510	0.93	2.57	0.41	1.35
	B (20-40)	3.2	1.5	4	4.65	1945	0.9	2.01	0.365	4.11
	C (40-60)	4.2	1	4	4.3	2380	0.87	1.41	0.32	6.87
	D (60-80)	4.2	1	4	4.3	2380	0.87	1.41	0.32	6.87
	E (80-100)	4.2	1	4	4.3	2380	0.87	1.41	0.32	6.87

Addendum 5.3 Depth-weighted soil properties for the references plots of Chardonnay that are in the deep rooting low density group (DRL).

Plot	Depth cm	DWM clay %	Ctncy	Prmbt	pH	Rest	Mg	Ca:Mg	B	Na%
GBCH	A (0-20)	12.2	3	2.5	7.3	350	3.04	5.43	1.29	2.7
	B (20-40)	17.2	1	3	7.3	320	3.32	5.02	1.2	3.04
	C (40-60)	17.2	1	3	7.3	320	3.32	5.02	1.2	3.04
	D (60-80)	17.2	1	3	7.3	320	3.32	5.02	1.2	3.04
	E (80-100)	12.7	2	2	6.85	285	3.665	3.18	1.265	5.445
KKCH	A (0-20)	1.35	3.25	3.5	5.95	3115	0.415	9.10	0.315	0.8
	B (20-40)	0	4	2	4.9	5860	0.25	6.52	0.09	1.1
	C (40-60)	0	4	2	4.9	5860	0.25	6.52	0.09	1.1
	D (60-80)	1.1	4	2	4.95	5510	0.335	5.76	0.165	1.22
	E (80-100)	2.2	4	2	5	5160	0.42	5.31	0.24	1.34
EXCH	A (0-20)	7.2	3.5	2	7	1660	2.22	3.16	0.97	1.41
	B (20-40)	9.6	4.5	2	6.2	590	2.94	1.71	2.43	12.83
	C (40-60)	9.6	4.5	2	6.2	590	2.94	1.71	2.43	12.83
	D (60-80)	9.6	4.5	2	6.2	590	2.94	1.71	2.43	12.83
	E (80-100)	5.2	4.5	1	5	240	5.77	0.60	4.22	25.08

Addendum 5.4 Depth-weighted soil properties for the references plots of Shiraz that are in the shallow rooting group (SR).

Plot	Depth cm	DWM clay %	Ctncy	Prmbt	pH	Rest	Mg	Ca:Mg	B	Na%
WVSH	A (0-20)	9.6	3.5	2	6.3	1350	4.54	1.59	0.94	3.4
	B (20-40)	9.6	3.5	2	6.3	1350	4.54	1.59	0.94	3.4
	C (40-60)	15.6	4	2	6.2	1135	4.41	1.26	1.15	6.38
	D (60-80)	21.6	4.5	2	6.1	920	4.28	0.92	1.36	9.35
DWSH	A (0-20)	5.8	3	3	7.6	690	2.77	5.22	1.78	2.26
	B (20-40)	7.3	3.5	2.5	7.55	695	2.4	5.58	1.28	3
	C (40-60)	8.8	4	2	7.5	700	2.03	6.08	0.78	3.74
	D (60-80)	8.8	4	2	7.5	700	2.03	6.08	0.78	3.74
	E (80-100)	27	4	2	6.3	240	4.32	1.82	1.26	14.34
BSRSH	A (0-20)	15	3	4	6.6	990	6.86	1.50	0.56	2.79
	B (20-40)	41.6	4	2	6.3	620	10.86	0.68	0.7	6.35
	C (40-60)	41.6	4	2	6.3	620	10.86	0.68	0.7	6.35
WBSH	A (0-20)	8.5	3.125	2.625	7.425	1000	2.78	3.24	1.3975	5.31
	B (20-40)	10	3.5	3	6.9	580	3.2	1.89	2.65	12.3
	C (40-60)	10	3.5	3	6.9	580	3.2	1.89	2.65	12.3
GLSH	A (0-20)	10.2	3	4	5.9	1290	6.48	0.69	0.55	5.55
	B (20-40)	18.2	4	2	5.2	890	9.16	0.33	0.46	8.3
	C (40-60)	18.2	4	2	5.2	890	9.16	0.33	0.46	8.3

Addendum 5.5 Depth-weighted soil properties for the references plots of Shiraz that are in the deep rooting high density group (DRH).

Plot	Depth cm	DWM clay %	Ctncty	Prmbt	pH	Rest	Mg	Ca:Mg	B	Na%
EXSH	A (0-20)	0.8	3	2.5	7.2	1520	2.2	4.14	1	1.52
	B (20-40)	3.2	3.5	3	7	840	2.74	2.77	0.47	11.6
	C (40-60)	3.2	4	2.5	7	840	2.74	2.77	0.47	11.6
	D (60-80)	*								
	E (80-100)	*								
GSH	A (0-20)	10.2	2	4	7.1	650	4.15	4.47	1.1	1.85
	B (20-40)	2.6	3	4	7.2	420	9.79	1.87	1.23	5.12
	C (40-60)	2.6	3	4	7.2	420	9.79	1.87	1.23	5.12
	D (60-80)	2.6	3	4	7.2	420	9.79	1.87	1.23	5.12
	E (80-100)	2.6	3	4	7.2	420	9.79	1.87	1.23	5.12
ESH	A (0-20)	9.9	2.75	3.25	7.3	1237.5	2.62	5.80	0.83	1.73
	B (20-40)	8.4	2	4	7.6	1140	2.45	6.44	1.06	2.60
	C (40-60)	8.35	2.63	3.5	7.55	935	2.37	5.63	1.17	4.09
	D (60-80)	8.2	3.5	2	7.4	320	2.11	2.81	1.51	8.55
	E (80-100)	8.2	3.5	2	7.4	320	2.11	2.81	1.51	8.55

Addendum 5.6 Depth-weighted soil properties for the references plots of Shiraz that are in the deep rooting low density group (DRL).

Plot	Depth cm	DWM clay %	Ctncty	Prmbt	pH	Rest	Mg	Ca:Mg	B	Na%
WPKSH	A (0-20)	10.8	3	4	6.3	1640	1.65	3.21	0.56	2.35
	B (20-40)	10.8	3	4	6.3	1640	1.65	3.21	0.56	2.35
	C (40-60)	12.8	3	4	5.9	1990	2.77	1.69	0.55	2.45
	D (60-80)	12.8	3	4	5.9	1990	2.77	1.69	0.55	2.45
	E (80-100)	12.8	3	4	5.9	1990	2.77	1.69	0.55	2.45
KKSH	A (0-20)	4.75	3.25	3.5	4.73	4325	1.3	1.59	0.15	1.37
	B (20-40)	5.8	4	2	4.2	4970	0.85	0.86	0.14	1.29
	C (40-60)	5.8	4	2	4.2	4970	0.85	0.86	0.14	1.29
	D (60-80)	5.8	4	2	4.2	4970	0.85	0.86	0.14	1.29
	E (80-100)	8.2	4	2	4	5310	2.16	0.31	0.1	1.4
LSH	A (0-20)	18.2	2	2.75	7.05	830	3.56	3.14	1.14	2.71
	B (20-40)	28.2	1	3	6.9	600	4.01	2.45	0.96	3.51
	C (40-60)	28.2	1	3	6.9	600	4.01	2.45	0.96	3.51
	D (60-80)	21.2	1.75	2.5	7.05	630	3.86	3.16	1.05	2.92
	E (80-100)	14.2	2.5	2	7.2	660	3.7	3.92	1.14	2.32

Addendum 5.7 The values given in the previous tables for consistency and permeability and the categories they represent.

Consistency	values	Permeability	values
Loose	1	slow	1
Soft	2	moderate	2
Slightly hard	3	good	3
Hard	4	rapid	4
Very hard	5		

Addendum 5.8 The number of thin (< 2 mm) and thick (> 2 mm) root contacts, the thin to thick ratio and the rootstock for Chardonnay reference vineyards in Robertson valley.

Plot code	Thin roots	Thick roots	Root ratio	Rootstock
Se RB3	67	23	2.91	101.14 Mgt
Va.EX3	159	7	22.71	101.14 Mgt
Va.STV3	306	17	18.00	101.14 Mgt
Se KD3	377	21	17.95	101.14 Mgt
Oa.DW3	465	51	9.12	101.14 Mgt
Gs.WB3	447	13	34.38	101.14 Mgt
Ag.GB2	150	21	7.14	R 110
Gs.KK2	214	20	10.70	R 110
Gs.BSR2	191	12	15.92	R 110
Gs.WV2	198	28	7.07	R 110
Ag LC2	330	28	11.79	R 110
Br AG2	305	4	76.25	R 110
Ag WTRS1	357	20	17.85	R99
Oa.GL1	701	28	25.04	R99
Sw WTPR1	413	83	4.98	R99
Oa E4	381	11	34.64	Ramsey
Oa.G5	722	53	13.62	unk.

Addendum 5.9 The number of thin (< 2 mm) and thick (> 2 mm) root contacts, the thin to thick ratio and the rootstock for Shiraz reference vineyards in Robertson valley

Plot code	Thin roots	Thick roots	Root ratio	Rootstock
Cg.EX3	590	18	32.78	101-14 Mgt
Se.RB3	207	15	13.80	101-14 Mgt
Et.WTRS3	552	21	26.29	101-14 Mgt
Va.WV3	110	9	12.22	101-14 Mgt
Gs.WTBR3	254	27	9.41	101-14Mgt
Et.KD6	495	13	38.08	Paulsen 1103
Br.KB2	236	17	13.88	R 110
Gs.BSR2	179	23	7.78	R110
Ag.E2	496	25	19.84	R110
Br.G2	510	32	15.94	R110
Gs.GB2	295	21	14.05	R110
Ag.L2	343	15	22.87	R110
Et.SBV2	289	16	18.06	R110
Gm.WB2	256	6	42.67	R110
Gs.GL1	129	3	43.00	R99
Gs.KK1	278	11	25.27	R99
Va.DW5	140	18	7.78	unk.
Oa.KR5	456	36	12.67	unk.
Oa.WPK5	207	11	18.82	unk.

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