Assessment of the possible interactions between soil and plant water status in a *Vitis vinifera* cv. Merlot vineyard

by

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DECLARATION

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SUMMARY

Irrigation scheduling decisions are based either on the direct measurement of soil water status (SWS) or on physiological measurements like plant water status (PWS). Soil based measurements are quick and easily automated, but the plant response for a particular quantity of soil moisture varies as a complex function of evaporative demand.

A plant-based approach measures the plant stress response directly, but is an integration of environmental effects as well. In contrary to soil-based methods, plant based measurements can indicate when to irrigate, but not the quantity.

Pre-dawn leaf water potential (Ψ_{PD}) is determined mostly by the soil moisture level, and can serve as a measure of static water stress in plants and an index of bulk soil water availability or even as an estimate of soil water potential at the root surface. Therefore it should be possible to establish a link between SWS and PWS, but it is largely unknown how stable the link in a heterogeneous vineyard would be, and how the grapevine vegetative and reproductive response relates to this link.

Plant water status plays a large role in determining vigour and yield of the plant. The levels of PWS are influenced by irrigation, but it was mostly affected by the season and vine location in the vineyard. More negative plant water potentials reduced vigour, but had a less pronounced effect on yield, while also reducing overall wine quality.

Vigour variability in the vineyard was largely attributed to soil heterogeneity, which seemed to have a strong effect on SWS. SWS measurements were calibrated according to the observed variability, increasing the accuracy of measurements significantly. Soil water content values were used to establish a link between SWS and PWS. This link was determined over time using nine plots, consisting of rain-fed and irrigated regimes, in variable vigour areas. A non-linear relationship was found between Ψ_{PD} and percentage extraction of plant available water for rain-fed plots. When irrigation was applied, no correlation could be found.

In this study, for Merlot in the Stellenbosch region, PWS differences affected vigour, and to a lesser extent yield, as well as wine quality. More negative plant water potentials reduced vigour more in high vigour areas than in lower vigour areas, which in turn led to unbalanced vegetative: reproductive ratios. This disturbed vine balance may have had a bigger impact on wine quality than PWS levels. Therefore a well-managed and balanced vine is able to withstand more stress, with less detrimental effects. This study also highlights the danger of limiting the assessment of soil and plant water status conditions to point measurements in vineyards with high levels of vigour variability.

OPSOMMING

Besluite rakende die skedulering van besproeiing word gewoonlik gebaseer op die direkte meting van grondwaterstatus (GWS), of op fisiologiese metings soos byvoorbeeld plantwaterstatus (PWS). Grond gebaseerde metings is relatief vinnig en maklik om te outomatiseer, maar die plantrespons vir ŉ spesifieke grondwaterinhoud varieer as ŉ komplekse funksie van dampdruktekorte.

‘n Plantgebaseerde benadering meet die plantstresreaksie direk, maar is ŉ integrasie van omgewingstoestande. In teenstelling met grondgebaseerde metodes, kan plantgebaseerde metodes aandui wanneer om te besproei, maar nie die hoeveelhede wat besproei moet word nie.

Voorsonsopkoms blaarwaterpotensiaal (Ψ_{PD}) word grootliks deur die grondwaterinhoud bepaal, en kan as ŉ maatstaf van statiese waterspanning in plante en as ŉ indeks van bulk grondwaterbeskikbaarheid dien, of selfs as ŉ benadering van die grondwaterpotensiaal by die worteloppervlak. Dit behoort dus moontlik te wees om ŉ verwantskap te bepaal tussen GWS en PWS, maar dit is grootliks onbekend hoe stabiel hierdie verwantskap sal wees in ŉ heterogene wingerd, asook hoe die wingerdstok se vegetatiewe en reproduktiewe reaksie die verwantskap kan beïnvloed.

Plantwaterstatus speel ŉ groot rol in die bepaling van groeikrag en opbrengs in die wingerdstok. Die vlakke van plantwaterstatus word deur besproeiing beïnvloed, maar word skynbaar meesal deur die seisoen en wingerdstok se ligging in die wingerd bepaal. Meer negatiewe plantwaterpotensiaalvlakke het gelei tot laer groeikrag, maar het ŉ minder uitgesproke effek gehad op opbrengs, terwyl dit in die algemeen wynkwaliteit verswak het.

Groeikrag variasie in die wingerd kon grootliks aan grond heterogeniteit toegeskryf word, wat skynbaar ŉ sterk invloed op grondwaterstatus gehad het. Grondwaterstatus metings is gekalibreer volgens die variasie wat waargeneem is, wat die akkuraatheid van metings beduidend verhoog het. Grondwaterinhoud waardes is gebruik om ŉ verwantskap aan te dui tussen SWS en PWS. Hierdie verwantskap is oor tyd bepaal vir nege persele, wat bestaan het uit droëland asook besproeide persele, in areas waarvan die groeikrag verskil het. ŉ Nie-liniêre verband is gevind tussen Ψ_{PD} en die persentasie onttrekking van plantbeskikbare water vir die droëland persele. Waar besproei was, kon geen verband gevind word nie.

In hierdie studie, vir Merlot in die Stellenbosch area, het PWS vlakke groeikrag en tot ŉ mindere mate opbrengs en wynkwaliteit beïnvloed. Meer negatiewe plantwaterpotensiaal vlakke het groeikrag meer beïnvloed in hoër groeikrag areas as in die laer groeikrag areas, wat ook gelei het tot ongebalanseerde vegetatiewe:reproduktiewe verhoudings. Hierdie versteurde balans in die wingerdstokke kon dalk ŉ groter impak op wynkwaliteit gehad het as PWS vlakke. Daar moet dus gepoog word om goed bestuurde en gebalanseerde wingerdstokke te hê, sodat strestoestande beter weerstaan kan word met minder nadelige gevolge. Die studie beklemtoon ook die gevaar verbonde daaraan om die bepaling van grond- en plantwaterstatus te beperk tot puntmetings in wingerde met groot variasie in groeikrag.

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

BIOGRAPHICAL SKETCH

Albertus van Zyl matriculated from Robertson High School in 2002. He obtained his BScAgric (Viticulture and Oenology) degree from Stellenbosch University in 2006. In 2007 he enrolled for his HonsBScAgric degree in Viticulture at the same university and obtained it at the end of 2007.

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PREFACE

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

Chapter I	**General introduction and project aims**
Chapter II	**Literature review** A review of grapevine reaction to water deficits under variable vigour conditions
Chapter III	**Research results** Assessment of grapevine reaction to water deficits under differing vigour levels: soil and plant water status interactions
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Chapter 1

Introduction and project aims

CHAPTER I: INTRODUCTION AND PROJECT AIMS

1.1 Introduction

Irrigation scheduling decisions are based either on the direct measurement of soil water status (SWS) or on physiological measurements like plant water status (PWS). Soil based measurements are quick and easily automated, but the plant response for a particular quantity of soil moisture varies as a complex function of evaporative demand (Jones, 2004).

Many studies focus on the effect of soil water regimes (Hardie & Considine, 1976; Dry & Loveys, 1998; Gomez-del-Campo *et al.*, 2002; De Souza *et al.*, 2005) or PWS (Schultz & Matthews, 1993; Myburgh, 2005; Girona *et al.*, 2006) effects on the vegetative and reproductive responses of the grapevine. Since PWS is a biological response to the environment, thresholds more closely classify water deficits in the plant. Limited research has been done regarding the relationships between SWS and PWS. Part of the difficulty lies in incorporating differences in grapevine genetic characteristics, heterogeneity in soil characteristics and climate variability (seasonal or spatial) (Deloire *et al.*, 2004).

There is some debate whether soil composition plays a significant role in the production of quality wine. That soil play an, albeit indirect, role in grape composition and quality is acknowledged by viticulturists. Viticulturists have often associated grape quality and wine quality with a soil that is well-structured, highly permeable, well aerated and which fully or partially negate or buffer the harmful effects of extreme climatic conditions. It is suggested from literature that the effect of soil type on grape quality is associated with the interaction between grapevine vigour and soil water retention properties (Reynolds & Naylor, 1994; Lanyon *et al.*, 2004; Carey *et al.*, 2008).

To assess the soil water status (SWS) and to reduce potential environmental effects, it is best to measure at night. It is assumed that the plant and soil reach equilibrium in terms of water status at night and the plant reaches the daily maximum water potential level before sunrise. Thus, the pre-dawn leaf water potential (Ψ_{PD}) is determined mostly by the soil moisture level, and can serve as a measure of static water stress in plants and an index of bulk soil water availability or even as an estimate of soil water potential at the root surface (Sellin, 1999).

By establishing a link between SWS and PWS and defining thresholds (Myburgh, 2011) it could be easier to manage irrigation scheduling to manipulate SWS and PWS levels within a vineyard to influence vigour and yield for a specific grape production target.

From this study, producers may potentially gain information on how PWS could be used to optimise irrigation scheduling to manipulate water status levels within a vineyard so as to achieve optimal balance in the vegetative and reproductive growth for optimum grape quality.

1.2 Project Aims

The main aim of this study was to investigate the relationship between soil- and grapevine water status in a heterogeneous vineyard in the Stellenbosch region, while evaluating the vegetative and reproductive response of the plant.

Objective 1: To use a multispectral image to make a qualitative assessment of vigour in order to select study plots.

Objective 2: Establish the extent of variability in the selected plots in relation to soil conditions and plant growth as well as root distribution.

Objective 3: To evaluate the effect of the noted variability on the calibration of soil water content.

Objective 4: Assessing plant water status in relation to soil water content as measured by neutron scattering.

Objective 5: To assess the plant vegetative and reproductive (grape ripening, yield) response to differing plant water status (as manipulated by irrigation).

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Chapter 2

Literature review

A review of grapevine reaction to water deficits under variable vigour conditions

CHAPTER II: A REVIEW OF GRAPEVINE REACTION TO WATER DEFICITS UNDER VARIABLE VIGOUR CONDITIONS

2.1 Introduction

Where man travelled, they brought crops with them. If the climate was inadequate for plant growth (Kirkham, 2005), irrigation was used to supplement the natural rainfall. Normally water management is based on soil measurements. Where agriculture uses supplementary irrigation to achieve economic goals, it is important to know the water status of the soil. It is relatively easy to establish soil water thresholds (Saxton *et al.*, 1986), but is it sufficient for the plant's needs? Applying water to overcome plant water deficits can be effective, but the timing of water applications is critical (Clark & Hiler, 1973), furthermore the plant response to a specific amount of available soil water varies as a complex function of evaporative demand (Jones, 2004). Another potential problem with all soil water based approaches is that many features of the plant's physiology respond directly to changes in water status in the plant tissues, whether in the roots or in other tissues, rather than to changes in the bulk soil water content or potential (Jones, 2004).

To obtain a true measure of plant water deficit, measurements should therefore be more centred on the plant (Clark & Hiler, 1973). Plant-based approaches measures the plant stress response directly, but is an integration of environmental effects as well (Jones, 2004). However, in contrary to soil-based methods, plant based measurements can indicate when to irrigate, but not the quantity.

To incorporate the soil water status (SWS) and circumvent environmental effects; it is best to measure at night. It is assumed that the plant and soil reach equilibrium in terms of water status at night and the plant reaches the daily maximum water potential level before sunrise. Thus, the pre-dawn leaf water potential (Ψ_{PD}) is determined mostly by the soil moisture level, and can serve as a measure of static water stress in plants and an index of bulk soil water availability or even as an estimate of soil water potential at the root surface (Sellin, 1999).

Soil variability is mainly attributed to texture, structure, organic material and gravel content, which may all affect the water holding capability and availability to the plant (Gruber & Schultz, 2005), in other words the SWS. Since soil heterogeneity exists even at sub-vineyard block level (Conradie *et al.*, 2002) SWS can vary significantly within vineyards, depending on the soil variability (Kramer & Boyer, 1995; Lal & Shuckla, 2004). Normally, differentiation of water application at block level is not considered; which can induce further plant variability and have drastic effects on the overall quality of the product (Lanyon *et al.*, 2004).

In literature, the differences in SWS due to soil variability are not widely acknowledged nor reported on, and therefore the overall effect of differential SWS on the plant is not clear (Lanyon *et al.*, 2004). An improved understanding of how water and mineral supply (Kramer & Boyer, 1995) manipulate plant water status (PWS) and its corresponding effect due to induced vigour differences, may provide a better understanding of how the plant will react and thus the management thereof (Gruber & Schultz, 2005).

2.2 Soil variability

Past geological processes may have profound indirect effects on vineyard performance, since such processes created soils through weathering the materials of the current landscape. *In situ* weathering of the underlying rock formations formed a few of the present vineyard soils, for instance in the Coastal winegrowing region of South Africa. Through a long continuing process of transport and weathering, formation of soil parent materials contains minerals originating from a number of rock types. Development of soils from an admixture of materials is a phenomenon commonly found in the Western Cape. It is therefore easy to find contrasting soil forms in close proximity within a single vineyard block (Conradie *et al.*, 2002). The basic soil properties is affected by soil physical and chemical characteristics; e.g., soil texture, structure, amount and degree of aggregates, amount of colloids, type of clay mineral, and the amount of soluble salts (Hillel, 1971; Kirkham, 2005).

Hutchings *et al.* (2003) found that the performance of individual plants, and their root and shoot biomass distribution, can be strongly affected by the pattern of supply of soil-based resources. Patchy distribution of soil-based resources can affect the location of roots, as roots often proliferate in nutrient-rich areas. It is essential to develop a good understanding how the individual grapevine would respond to soil variability to facilitate the prediction on the impact of variability on plant interactions and plant responses (Hutchings *et al.*, 2003). Agricultural researchers have long understood that variability between zones within an experimental area, which is often caused by natural soil variability, or previous land use practices, can significantly reduce the ability to detect experimental treatment differences (Venter *et al.*, 2009).

2.2.1 Soil water status

For the purpose of this discussion, soil water status may be divided into two components. The physical water content of the soil and the energy required to extract that water. Soil water content is expressed as volumetric soil water content, indicated by the Greek symbol theta (ϴ). Volumetric soil water content is effectively a depth-ratio that is easily related to other equivalent depths such as rainfall and evaporation, when expressed in mm/depth. Soil water content may also be described by the gravimetric soil water content (Foth, 1990). Gravimetric soil water content is the ratio of the mass of water in a soil to the overall weight of the soil, while volumetric soil water content is the product of gravimetric soil water content and soil bulk density (derived from the total mass of an undisturbed soil core in relation to its volume) (Davie, 2008).

The water-supplying ability of soils relates to the amount of available water in a soil. The total available water is the difference in the amount of water at field capacity (the amount of water held against gravitational forces in the soil matrix after saturation) and the amount of water at permanent wilting point. Permanent wilting point is not a fixed value, but is dynamic as there are a range of occasions when the rate at which the water supply to a plant is not sufficient to prevent wilting. This depends on the soil profile, the amounts of water in the soil at different depths, root distribution, the transpiration rate of a plant and the ambient and soil temperature. When the point is unknown for a specific species, it is assumed that most herbaceous species can extract water to -1500 kPa (Kramer & Boyer, 1995), which is then referred to as the permanent wilting point.

When referring to SWS, Rawls *et al.* (1982) stated that it is not sufficient to consider the water content of the soil alone, but also the energy requirements needed to extract it. This relation between soil water content and soil matrix potential is called the soil water retention curve. The soil water retention and matrix potential is related to texture, organic matter and bulk density (Rawls *et al.*, 1982). When linking soil water to plant growth, it is not only the amount of water in the soil, but the soil matrix potential that plays a significant role (Letey, 1985).

A study in Bordeaux stated that the supremacy of some classified vineyards was due to the soil's ability to regulate the water supply to the grapevine. Excess water could drain, while still retaining and supplying water at a rate that was adequate for the grapevine's need during the ripening period (Conradie *et al.*, 2002). *A priori* knowledge of the *in-situ* soil field water capacity and the soil-water retention curves for soils is important for effective irrigation management and -scheduling of many crops (Jabro *et al.*, 2009). In most soils, optimal irrigation management practices for many crops require measurement or estimation of soil water retention data in the field or laboratory to determine both the amount and timing of irrigation.

2.2.2 Factors influencing soil water status

Soil is a heterogeneous mixture of solid particles of different sizes and shapes. It is a dynamic mixture, under continuous change due to natural and human influences (Dexter, 2004). The solid particles, comprising inorganic and organic components, form the body of most soils. This mixture of solid particles is the storehouse of water and nutrient elements. The packing arrangement of solid particles influences soil bulk density, pore size distribution and pore continuity, retention and movement of fluids, and substances contained in them (Letey, 1985; Lal & Shuckla, 2004). The SWS of soils is primarily affected by the number of pores and the pore size distribution, as well as the specific surface area of the soil, which in turn can be directly ascribed to texture, structure and organic matter content (Dexter, 2004; Lal & Shuckla, 2004).

2.2.2.1 Texture

The physical and chemical weathering of rocks and minerals results in a wide range in size of particles from stones, to gravel, to sand, to silt, and to very small clay particles. The particle-size distribution determines the soil's coarseness or fineness, therefore soil texture. Specifically, texture is determined by the relative proportions of sand, silt, and clay in a soil (Foth, 1990) and is a primary soil property that may have a range of effects on key characteristics of soils. Soil texture predominately determines the water-holding characteristics of most agricultural soils (Saxton *et al.*, 1986) affecting total porosity, pore size and reactive surface of the soil matrix (Lal & Shuckla, 2004).

2.2.2.2 Structure and pore size

Structure is the underlying arrangement, orientation and organization of the textural components in soil. Between the particles, there is a complex system of pores. The arrangement of particles influences the size and distribution of these pores (Lal & Shuckla, 2004).

Structure modifies the influence of texture with regard to water and air relationships and the ease of root penetration. The macroscopic size of most aggregates (naturally formed units of soil solids) (Lal & Shuckla, 2004) results in the existence of inter-aggregate spaces that is much larger than the spaces existing between adjacent sand, silt, and clay particles (Foth, 1990). Simplified, soil porosity can be considered as having two parts: textural porosity and structural porosity. The textural porosity occurs between the primary mineral particles, whereas the structural porosity comprises micro cracks, bio-pores (pores resulting from soil biological activity) and inter-aggregate spaces (Foth, 1990; Dexter, 2004). Textural porosity is little affected by soil management, whereas structural porosity is sensitive to management factors such as tillage, compaction and cropping (Dexter, 2004). Therefore, the long-term effect of ploughing and cultivation is a more compacted soil as a result of the crushing of aggregates and subsequent settling of the soil (Foth, 1990).

2.2.2.3 Organic material

Organic matter content has a very small range (0-3%) in most agricultural soils (Saxton *et al.*, 1986). The amount is largely dependent on temperature, biological activity, soil management practices and organic inputs (Foth, 1990; Bot & Benites, 2005; Du Preez *et al.*, 2011). South-

African soils are characterized by very low organic matter levels due to high temperatures and low rainfall (Conradie *et al.*, 2002). About 58% of soils contain less than 0.5% organic carbon, 38% of the soils contain 0.5 to 2% organic carbon, and only 4%contain more than 2% organic carbon(Du Preez *et al.*, 2011). Foth (1990) found that in a specific landscape, a correlation can be found between soil texture and the organic matter content of soils as a result of the protective role that clay plays in the soil matrix (Bot & Benites, 2005). Organic material contributes to the improvement and stabilization of aggregate formation that result in better soil structure as well as an increase in porosity. Therefore, the presence of organic material enhances the soil water holding capabilities of a soil. The organic matter content of soils is therefore a key attribute to both soil health and soil quality (Du Preez *et al.*, 2011), and a decrease in organic matter content is associated with increasingly unfavourable soil physical conditions (Dexter, 2004). In general, grapevine vigour is enhanced by soils containing high amounts of organic carbon (Conradie *et al.*, 2002).

2.2.2.4 Gravel content

Gravel has a strong impact on the soil hydrological, physical and mechanical properties. It lowers the physical volume of the soil in the profile and thus reduces the water holding capacity (Saxton & Rawls, 2006). However, if the gravel is of a porous nature, it can increase soil water retention capabilities (Lal & Shuckla, 2004).

2.2.2.5 Water retention and soil matrix potential

Water retention refers to the water holding capacity of the soil, and soil matrix potential to the energy with which the soil retains water (Lal & Shuckla, 2004), and thus the energy requirements of the plant roots to extract the water from the soil (Kramer & Boyer, 1995; Kirkham, 2005). The strength of the soil matrix potential is dependent on the adsorption and capillary effects of the soil on water (Munoz-Carpena *et al.*, 2004), in other words, the amount of water present and the pore size distribution within the soil. Because of this relationship, it is possible to find out pore size distribution characteristics of a soil by evaluating soil moisture content changes at a given soil water retention. This can be used to create a soil moisture retention curve (Davie, 2008). There is a relationship with soil water content for a given soil, and thus it is possible to deduce the matrix potential if the water content is measured, if the relationship is known between the two (Letey, 1985). The gradient of the soil retention curve depends on textural and structural differences (Saxton & Rawls, 2006). The particle size, shape and arrangement as well as the pores determine the water retention ability of the soil (Lal & Shuckla, 2004). The pore size, and therefore the structure, regulates the initial ease of water extraction. Removing water from larger pores requires less energy (Lal & Shuckla, 2004; Saxton & Rawls, 2006). As the soil dries out the matrix potential becomes more dependent on textural differences. Smaller particle sizes have smaller pores. If the pore size becomes too small, the energy requirement to extract the water from it becomes too large, and it becomes inaccessible to the plant (Kramer & Boyer, 1995; Lal & Shuckla, 2004; Kirkham, 2005; Saxton & Rawls, 2006).

2.2.3 Measuring soil water status

There are a few ways to measure SWS, each with their advantages and disadvantages. Direct measurement is labour intensive, requiring many samples obtained at various depths, resulting in considerable disturbance of the soil.

2.2.3.1 Neutron probes

Soil water content gauges based on neutron scattering have been a valuable tool for soil water measurements for just more than 50 years (Evett *et al.*, 2002). The neutron probe has become standard for use in the agricultural industry to directly measure soil water content due to precision and its non-destructive measurement technique that can be repeated at the same points at various depths over time (Zazueta *et al.*, 1994; Evett & Steiner, 1995; McDougall *et al.*, 1996).

The neutron probe uses a radioactive source that is lowered into a PVC or aluminium tube placed in the soil. The radioactive source emits fast neutrons in a sphere, with a mean diameter of 20 cm, which then collide with atoms in the soil. These neutrons lose energy and are deflected back to the probe where it is counted by the detector. Hydrogen is the main atom responsible for neutron scattering and changes in hydrogen in the soil are mainly due to changes in soil water content. Therefore the neutron count is directly proportional to the volumetric water content of the soil (Evett, 2003).

Organic material and most clay contain significant amounts of hydrogen that may not always be in the form of water. Also, some atoms like chlorine, iron and boron absorb the neutrons. These are termed neutron thermalizers (Kramer & Boyer, 1995; Dane & Topp, 2002). This needs to be rectified with separate calibrations or adjustments in data interpretation.

The use of the neutron probe is limiting due to the manual nature of the measurement and therefore its labour intensity, cost, the need for special calibration for different sites as well as special registration of the equipment storage area. It however remains the best method for repeated non-destructive measurements of soil water content (Dane & Topp, 2002).

2.2.3.2 Capacitance probes

A capacitance probe (CP) has characteristics that would make it seem to be an ideal alternative to neutron probes. Evett & Steiner (1995) did a study to determine the relative precision of the neutron probe against capacitance probes in a field calibration exercise. The average 95% confidence intervals on volumetric water content predictions were three to five times higher for the CP than for the neutron probe gauges. Although poorly correlated with soil water content, readings were reproducible among the capacitance probe gauges. Neutron probe gauges provided acceptable precision but the capacitance probe gauge had poor precision and was unacceptable for routine soil water content measurements (Evett & Steiner, 1995). The current design produces a soil moisture profile in a similar way to the neutron probe, over which it has the following advantages: the output is obtained almost instantly and there is no random counting error; readings are repeatable and fast, there is no nuclear radiation hazard and therefore no legal constraint and the depth resolution is more precise than that of the neutron probe.

A disadvantage is that the calibration is non-linear and hence less simple to determine and to apply. Because the sphere of influence is small, the presence of gaps, cavities, stones or roots in proximity to the access tube can create inconsistent results, but the sensor configuration can vary in size so sphere of influence or measurement is adjustable. Access tubes for the CP must be installed with exceptional care and experimental rigor to avoid the introduction of errors. Small scale heterogeneity of soil moisture is also more significant than for the neutron probe and more measurements are required to represent the mean moisture content of a soil body to the same precision. If the ionic content of the soil changes over time, it can cause discrepancies (Bell *et al.*, 1987; Zazueta *et al.*, 1994).

2.2.3.3 Time-domain reflectometry

Time-domain reflectometry (TDR) determinations involve measuring the propagation of electromagnetic waves or signals. Propagation constants for electromagnetic waves in soil, such as velocity and attenuation, depend on soil properties, especially water content and electrical conductivity. The dielectric constant, measured by TDR provides a good measurement of soil water content. This water content determination is essentially independent of soil texture, temperature, and salt content. It is also able to take long-term automated *in situ* measurements, but can be very costly (Zazueta *et al.*, 1994).

2.2.3.4 Tensiometers

Another approach to measuring SWS is using tensiometers as an indicator of the soil water deficit experienced by the plant (Wery, 2005). Tensiometers measure the soil water matrix potential, which includes both adsorption and capillary effects of the soil. The matrix potential is one component of the total soil water potential that also incorporates gravitational (position with respect to a reference elevation), osmotic (salts in soil solution), and gas pressure (from entrapped air) factors. The sum of matrix and gravitational potentials is the main driving force for soil water movement (Munoz-Carpena *et al.*, 2004), which in turn can be related to the volumetric water content (Kirkham, 2005; Jabro *et al.*, 2009). A tensiometer is a small ceramic cup on the end of a sealed tube of water. The dry soil extract the water from the water-filled tube through the ceramic cup, creating a vacuum that a negative pressure gauge (vacuometer) measures at the top of the tube in units of kilopascal (kPa) (Davie, 2008).

The drawback of the tensiometer is that it only has a range of 0 to -80 kPa, and a measurement sphere radius of about 10 cm (Munoz-Carpena *et al.*, 2004), which makes it more suitable for measurements under intensive irrigation where soils are kept in a wetter range between irrigations. If the matrix potential of the soil becomes more negative, air enters the cup which results in cavitations and the water column in the tube break. It also requires regular maintenance (Zazueta *et al.*, 1994; Kramer & Boyer, 1995; Lal & Shuckla, 2004; Munoz-Carpena *et al.*, 2004).

2.3 Grapevine water status variability

Soil heterogeneity leads to variability in soil water content and -retention. Soil water retention and the ability of the plant to extract it from the soil in turn may have an effect on the water status of the grapevine. Plant water status is a critical factor affecting the physiological processes in a plant, considering that many aspects of grapevine physiology respond to changes in water status in the plant (Jones, 2004). Thus variability in grapevine water status can alter plant performance and may influence the overall plant vigour. This is expressed in the differences in pruning mass (Dry & Loveys, 1998), shoot growth rate (Van Zyl, 1984; Matthews *et al.*, 1987) as well as leaf number and leaf area (Matthews *et al.*, 1987; Bertamini *et al.*, 2006) amongst other factors.

2.3.1 Physiological indicators of variability in grapevine water status

Physiological indicators are measurements of PWS. There are many physiological indicators that can be used. Each has its specific advantages and shortcomings. These are stomatal conductance (measured by a porometer), sap flow (measured by sap flow meters) and PWS (measured by a pressure chamber) (Jones, 2004).

Stomatal closure is among the first processes occurring in the leaves in response to changes in soil moisture. This affects the gas exchange and photosynthetic activity of the plant (Cifre *et al.*, 2005). Therefore stomatal conductance is a good and sensitive indicator of early water deficits, since stomatal closure occur at even low water deficits in the plant and soil (Jones, 2004; Cifre *et al.*, 2005; Kirkham, 2005).

An alternative is to use the rate of sap flow in the plant that is sensitive to changes in soil moisture levels. It gives direct and continuous estimates of plant or shoot water loss (depending on the measurement location), and therefore gives an estimate of the rate of transpiration. Since transpiration and gas exchange are correlated, it also gives an indication of whole-canopy gas exchange (Jones, 2004; Cifre *et al.*, 2005).

Plant water status can be derived from measurements of leaf water potential (Ψ_L), stem water potential (Ψ_S) and pre-dawn leaf water potential (Ψ_{PD}). Leaf water potential is affected by a combination of factors. It reflects the measured leaf's water requirements, soil water availability, hydraulic conductivity and stomatal regulation (Choné *et al.*, 2001). To circumvent the variability of leaf water potential, it has been proposed by researchers in the field that a better indicator of water need in the plant is to measure the Ψ_S (Jones, 2004). This parameter gives an indication of the whole plant transpiration and the hydraulic conductivity of the plant and soil (Choné *et al.*, 2001). The Ψ_{PD} measures the plant water when there are no external factors influencing the water balance in the plant. Consequently, it indicates the soil water potential around the soil-root interface, since the PWS should equilibrate with the SWS (Choné *et al.*, 2001; Jones, 2004). Also, Ψ_{PD} has been found to be insensitive to variation in soil water content between soil layers in the root profile (Jones, 2004). It can be that the grapevine Ψ_{PD} equilibrates with the wettest layer of the soil (Sellés & Berger, 1990). The problem with the above-mentioned indices is that the grapevine is able to control its water status to some degree (which can even vary between different cultivars of *Vitis vinifera*), along with its different possible rootstock combinations, as the soil dries out or evaporation demand increases. This is achieved by changes in leaf angle, stomatal conductance, hydraulic properties of the plant and hormone production in the roots (Smart, 1974; Jones, 2004; Dodd *et al.*, 2008). In prolonged cases of water deficit this is further controlled by decreased leaf area, increased root proliferation and reduced canopies (De la Hera-Orts *et al.*, 2004; Jones, 2004). Isohydric plants are able to control its endogenous system to a large degree and thus can maintain a stable leaf water status over a wide range of conditions. Anisohydric plants are less effective in that regard. As mentioned, even *Vitis vinifera L.* cultivars and rootstocks have shown a difference in their isohydricity abilities due to differing hydraulic behaviour (Jones, 2004; Cifre *et al.*, 2005; Soar *et al.*, 2006).

2.3.2 Vegetative indicators of grapevine water status variability

Many studies have shown that stomatal closure is an early indicator of water deficits in the vineyard. As the season progresses in conjunction with an increase in soil water deficit, non-stomatal effects can occur: e.g., changes in leaf angle and orientation (Smart, 1974), decreased leaf area (Gomez-del-Campo *et al.*, 2002; Jones, 2004), decreased leaf dry matter (Gomez-del-Campo *et al.*, 2002; Bertamini *et al.*, 2006) and reduced canopies (Dry & Loveys, 1998; De la Hera-Orts *et al.*, 2004; Jones, 2004). These effects can be short term, or if the deficit continues over an extended period of time, can become permanent.

Grapevines are euphotometric, meaning that the leaf is normally oriented perpendicular to the sun. However, during levels of progressive stress it can alter its leaf angle relative to the sun. The angle at which solar energy is received is controlled by the leaf orientation and therefore the photosynthesis rate can be adjusted (Smart, 1974). With a gradual increase in water deficit the grapevine is able to protect itself against water stress by morphological means (Schultz & Matthews, 1993) and leaf abscission (Hardie & Considine, 1976; Flexas *et al.*, 1998).

With declining soil water content the grapevine's water demand can exceed the water uptake from the roots during peak hours. New growth at the top of the shoot have more positive water potentials than the rest of the shoot (Kramer & Boyer, 1995; Patakas & Noitsakis, 1997). The plant's lack of water cannot sustain the turgor of these parts and it wilts (Hardie & Considine, 1976). With continuing water deficits the plant adapts to accommodate a lower water supply, but still maintain turgor and its physiological functions. It usually manifests in restricted new growth in apical regions and confining expansion of previously formed organs (Schultz & Matthews, 1993). Thus shoot growth declines or stops completely and leaf area is smaller for stresses plants (Matthews *et al.*, 1987; Gomez-del-Campo *et al.*, 2002). In severe cases of water deficits shoot tips desiccate and leaves and tendrils abscise (Hardie & Considine, 1976).

2.3.3 Reproductive aspects of grapevine water status variability

Berry growth is characterized by two successive sigmoid curves. The first cycle is berry formation, where cell division in the pericarp, which determines the berry's final size, starts. It then gives way to cell enlargement which slows as it reaches the second lag phase. This is when malic acid accumulates. The second phase, berry ripening, begins with berry softening and enlargement, berry colouring, sugar accumulation and anthocyanin accumulation in red cultivars (Coombe & McCarthy, 2000) (Figure 1).

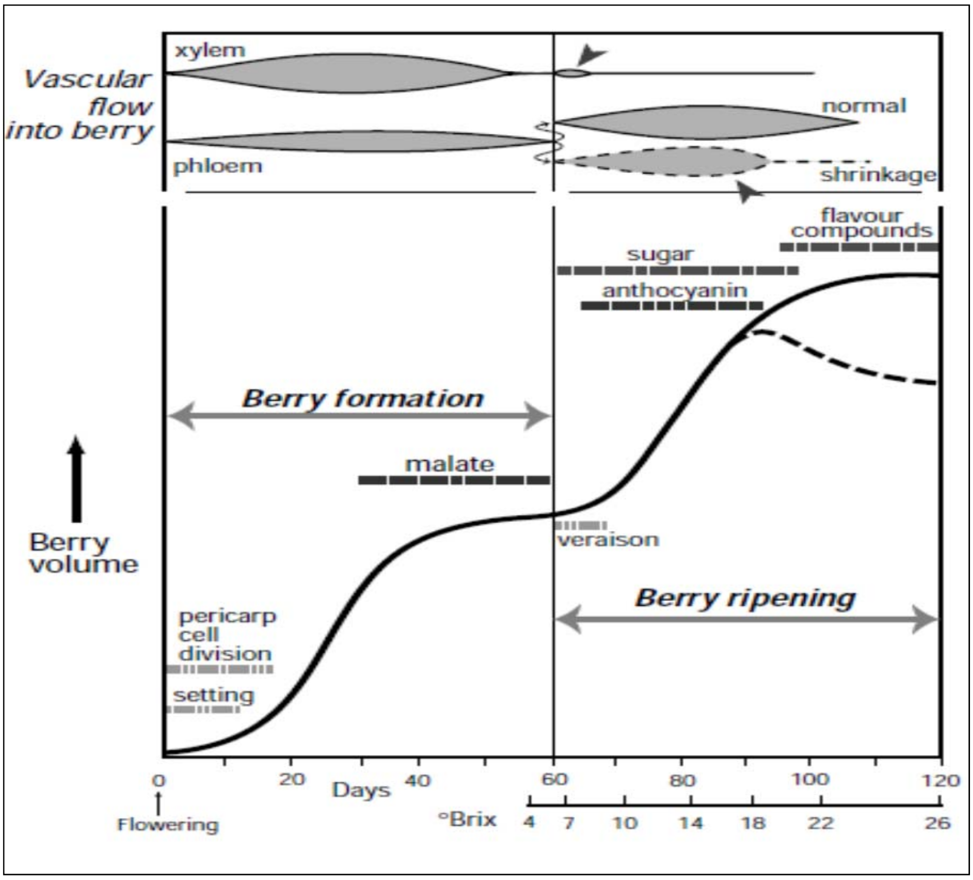

Figure 1 Diagram showing berry physical and chemical possesses during berry ripening (Coombe & McCarthy, 2000).

Reproductive growth is dependent on PWS (Matthews & Anderson, 1989), but is less sensitive than vegetative growth (Stevens *et al.*, 1995) to PWS. A water deficit experienced during the berry growth phase will adjust cell division and expansion and cause an alteration in yield (Stevens *et al.*, 1995). The timing and extent of the deficit during the berry growth phase may also play a role (Hardie & Considine, 1976). Berry growth is more sensitive to water deficits pre-véraison, reflected in smaller berries at harvest (Ojeda *et al.*, 2002). Deloire *et al*. (2005) stated that this is most likely due to an irreversible modification of the cell's ability to expand, and possibly not by modifying cell division. This all depends on the severity of the stress, since berry growth seems to be affected differentially, depending on the extent of the water deficits (Kennedy *et al.*, 2002; Roby *et al.*, 2004; Deloire *et al.*, 2005).

The negative effect of water stress can also have an effect on fertility, as expressed by fewer clusters per vine and berry set, expressed through fewer berries per cluster (Matthews & Anderson, 1989; De la Hera-Orts *et al.*, 2004). Cluster counts was previously shown to be influenced by the season, but the magnitude of the changes depended upon the timing and severity of the water deficits (Matthews & Anderson, 1989).

2.4 Integrating soil and plant water status

Through the years, man used irrigation as a method for overcoming water stress in plant cultivation. Irrigation may be effective in reducing stress; however, the timing of water applications is critical. To date irrigation timing has been based mostly on SWS, not on PWS (Clark & Hiler, 1973).

Water form a continuous hydraulic system from the soil, via the plant, to the atmosphere. With constant transpiration the water potential in the leaf decreases due to water loss to the atmosphere. This is replenished by water in the xylem. Thus it causes a lower water potential in the plant shoot and root system than in the bulk soil. The driving force for water movement in the soil-plant-atmosphere continuum from the soil to the plant is therefore due to a gradient in water potential (Schulze *et al.*, 2002; Gregory, 2006). The intensity of root development and physical contact between the root and soil are important physical considerations. When the upper part of the root zone becomes comparatively dry and water is available in the lower zone, the uptake of water per unit volume of soil has been observed to be proportional to the rooting density (Anonymous, 1991).

PWS represents an integration of the atmospheric demand, soil-water potential, rooting density and distribution, as well as other plant characteristics. During the day water transpires faster than the roots can extract it from the soil. Thus, a deficit builds up in the plant and the water potential gradient between leaves and soil increases. During the night, the plant absorbs water faster, and the water potential gradient between leaves and soil decreases. By the next morning, the water potential gradient between the leaves and soil is eliminated. As this pattern is repeated, the soil dries, the hydraulic conductivity decreases rapidly and the distance water must move to roots increases. In essence, the availability of soil water decreases over time. Consequently, each day the potential for water uptake decreases and the plant increasingly develops more water stress. Eventually, leaves may wilt in midday and not recover its turgidity at night (Foth, 1990). Plainly, this means that with continued water uptake, the soil water becomes so immobile that water movement to plant roots is too slow to meet the transpiration needs of the plant. To eliminate the atmospheric effect, Ψ_{PD} would therefore best reflect the soil water content (Williams & Araujo, 2002).

The seasonal development of Ψ_{PD} as well as its short-term dynamics is strongly influenced by soil water status, and therefore also potentially by soil water status variability induced by other variable soil factors (physical, chemical or biological). A vineyard planted in a soil with a lower soil water holding capacity is less buffered against sudden atmospheric changes, and would experience more rapid changes in Ψ_{PD} during the season compared to a vineyard planted in a well buffered soil (Gruber & Schultz, 2005). The hydraulic conductivity, influenced strongly by soil texture, also play a role (Foth, 1990). Bruwer (2010) found that the relationship between SWS and PWS differed between two contrasting soil textures. PWS in grapevines decreased substantially more as the SWS in sandy soils decreased than in sandy loamy soils. The reasoning is that unsaturated hydraulic conductivity in sandy soils decreases more rapidly as SWS decreases compared to heavier soils. Therefore grapevines in lighter textured soils would experience greater levels of stress than in heavier textured soils, even though both SWS values are the same.

Findings in the literature are contradictory regarding the relationship between soil and PWS. A direct relation between soil and PWS would seem to be the exception, rather than the rule (Cowan, 1965). Gruber & Schultz (2005) found that weekly measurements of soil water content and Ψ_{PD} revealed no clear correlation between Ψ_{PD} and the total soil water content, soil water content of different soil layers or the fraction of plant available water respectively, whereas Myburgh (2011) found a clear correlation between Ψ_{PD} and soil water content. With respect to these findings, it would be beneficial to further investigate the physiological mechanisms as well as internal regulating factors behind these relationships, also taking into account the often variable nature of root distribution as well as soil properties between different grapevines.

2.4.1 Neutron probe calibration

The term "calibration" implies the establishment of a precise relationship between a new system of measurement and one which is long established and accepted as a standard method for measuring the same variable (Bell *et al.*, 1987). The simplest and most accurate means for the measurement of soil water is the gravimetric method. The difference between the wet and dry mass of soil indicates its physical water content. Gravimetric analysis is simple and accurate but is a destructive sampling method and therefore it cannot be repeated on the same soil sample. When there is a requirement for long-term monitoring of soil moisture, a non-destructive moisture sampling method is required. The three most common methods were explained earlier in this chapter. The neutron scattering method may be considered the most suitable method, but like all indirect methods, it requires calibration against the gravimetric technique (Davie, 2008). Calibration is laborious and difficult to perform, and in general regression coefficients between count-ratio and volumetric soil water content range between 0.80 and 0.95 (Reichardt *et al.*, 1997) (Figure 2).

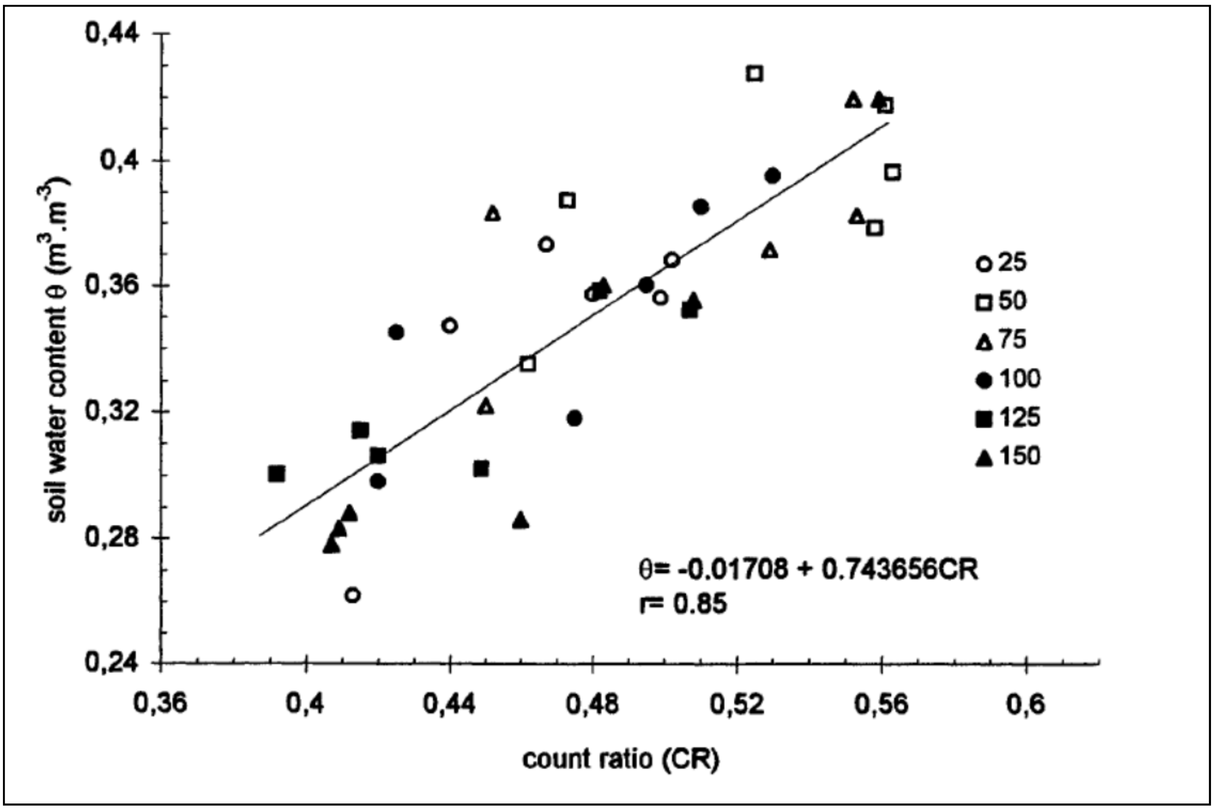

Figure 2 Relationship between neutron probe count ratios and volumetric soil water content for six soil depth levels (25 cm to 150 cm) (Reichardt *et al.*, 1997).

General calibration equations are supplied by the manufacturers. However, the use of a constant calibration equation on different soils can lead to systematic errors (Reichardt *et al.*, 1997). It was found that these equations overestimate the relative differences in volumetric soil moisture on light textured soils by up to 11.3% and to underestimate the differences on heavy clays by up to 7.1% (McDougall *et al.*, 1996). Therefore, it is prudent to create unique calibration equations for specific soil types. Small relative differences in volumetric soil moisture were found using the individual site calibrations as well as using the textural class equations. These results indicate that textural class calibrations may be used instead of individual site calibrations (McDougall *et al.*, 1996). Soil water potential relationships with soil water content are needed for many plant and soil water studies (Saxton *et al.*, 1986). Unfortunately tensiometers can only measure up to -85 kPa and laboratory measurement of soil water potential is costly and laborious. There is a viable alternative for estimating soil water hydraulic characteristics from readily available physical parameters. It was found that there are significant relationships between soil water characteristics and parameters such as soil texture and organic content (Saxton & Rawls, 2006). Rawls *et al.* (1982) found that it is possible to establish relationships for the theoretical estimation of soil water properties using texture, organic matter and bulk density for particular soil water tensions. This was further improved by Saxton *et al.* (1986) to provide equations that give continuous soil water potential estimates.

2.4.2 Soil-root interface

Roots and their associated flora and fauna are the link between the visible parts of plants and the soil, and are the organs through which many of the resources necessary for plant growth must pass (Gregory, 2006). The intricate environment where the root and the soil interact is known as the rhizosphere. The soil environment also influences root growth; consequently, root distribution and density are a function of both the kind of plant and the nature of the root environment (Clark & Hiler, 1973). The plant can be defined as an integrator of a complex and ever changing set of environmental conditions (Foth, 1990). The total above-ground growth of plants is strongly dependent on the developmental stage of the root. Only when the root can fully develop will the above-ground plant reach its full potential (Gregory, 2006).

2.4.3 Root morphology, root growth and development and root water and nutrient absorption

Plants utilise the plant growth factors in the soil byway of the roots. The density and distribution of roots affect the amount of nutrients and water that roots extract from soils. As the plant continues to grow and roots elongate throughout the topsoil, root extension into the subsoil is likely to occur. The subsoil environment will be different in terms of the supply of water, nutrients, oxygen, and in other growth factors(Foth, 1990), especially in conditions where soils are more variable in a vineyard.

The growth of root systems in soils is affected by a wide range of soil properties. Soil physical properties can affect the development and activity of the grapevine root system. Soil type influences the depth of roots and aspects such as an increase in bulk density, poor water infiltration, and soil acidity can potentially decrease the number of roots. Morlat and Jacquet (2003) also emphasised that soil water content has a strong effect on grapevine rooting.

There is a fairly uniform distribution of roots throughout the root zone unless there is some barrier to root extension or roots encounter an unfavourable environment (Foth, 1990). Grapevine roots have relatively low densities in soils and extensive lateral and vertical spreads. Thus, grapevines may colonize a more extensive rooting zone at low rooting densities than do some plant functional types considered in more general analyses, such as grasses, herbs, and shrubs (Smart *et al.*, 2006).

The pH of a soil is one of the most important properties involved in plant growth. There are many soil pH relationships, including those of ion exchange capacity and nutrient availability as seen in Figure 3 (Foth, 1990). For plant nutrients in general, good overall nutrient availability occurs near pH 6.5. In intensively weathered soils, some nutrients such as boron and zinc may be in very short supply and become deficient at lower pH than for minimally and moderately weathered soils. As a consequence, a desirable pH is typically 5.5 in an intensely weathered soil (Foth, 1990). Most of the soils used for grape production in the Western Cape is acidic, with pH levels of below 5.0 (Saayman & van Huyssteen, 1981; Conradie, 1983). In acidic soils diminutive shoot and root growth occur when the pH is below 5.0. By raising the pH increased vigour and root growth occur depending on the rootstock (Conradie, 1983). In contrast to this, soil salinity could also have adverse effects on the vigour of the grapevine, and lead to high levels of within-vineyard variability (Strever, 2003).

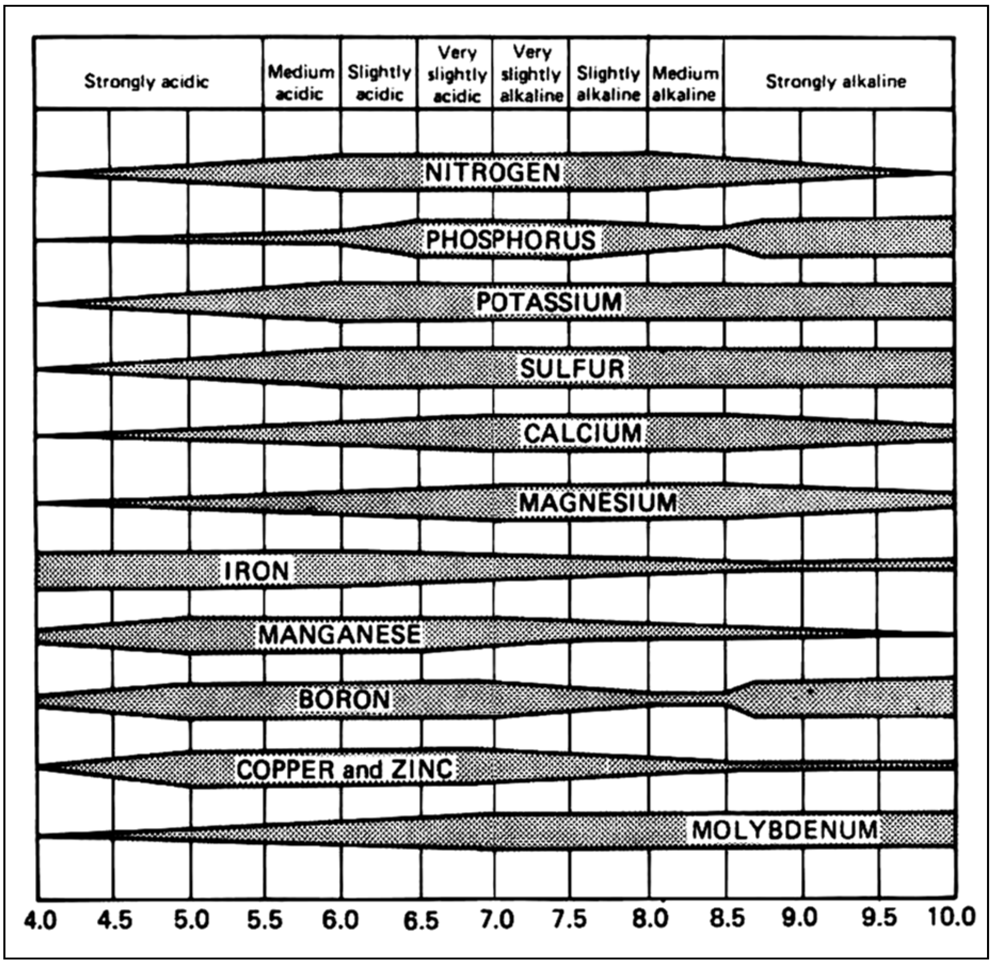

Figure 3 The general relationship between soil pH and availability of plant nutrients (Foth, 1990).

The strength of most soils increases as they dry, so that shortage of soil water and hard soils are commonly interlinked (Gregory, 2006). Both root and shoot growth is often slower in plants grown in soils with high bulk density. In such soils, various physical and biological factors may limit root growth. These include the availability of oxygen and water to the root, and the mechanical resistance of the soil to deformation by the growing root. Mechanically impeded roots are not only thicker, but are differently shaped, continuing to increase in diameter for a greater distance behind the root tip than in unimpeded roots. The osmotic potential becomes more negative in mechanically impeded roots (Bengough *et al.*, 1997). As a general indication, root growth will be severely impeded if bulk densities exceed 1.55, 1.65, 1.80 and 1.85 g/cm^3 on clay loams, silt loams, fine sandy loams and loamy fine sands, respectively (Gregory, 2006).

The limited mobility of water and most of the nutrients in moist and well-aerated soil means that only the soil that is colonised by roots can contribute significantly to the growth of plants. Plant uptake of water reduces the water content of the soil and greatly decreases the hydraulic conductivity. Thus, as soil dries, water movement to roots becomes slower (Foth, 1990). When water around the root becomes limiting, some roots (i.e. those experiencing drying soil conditions) may shrink to create an air gap to reduce contact between the root and the soil (Mapfumo *et al.*, 1994; Vandeleur *et al.*, 2009). This leads to cortex shrinkage and in prolonged cases, collapse and eventually to suberisation of the root. In well watered plants, the ratio between thin and thick roots is lower, probably since water transport takes precedence, where as it is higher in stressed plants as water uptake becomes more important (Mapfumo *et al.*, 1994; Soar *et al.*, 2006). Grapevine root systems in dry soil can survive because water is transferred from regions of high water availability to those of low availability (Morlat & Jacquet, 2003). This was confirmed by showing that isotopic labelled water moves from roots in the wet zone into roots surrounded by dry soil (Foth, 1990).

Rootstocks differ in rooting pattern, and is an important factor determining the above-ground performance of the grapevine. This is due to a correlation between root density, distribution and the ability to utilise the soil environment (Swanepoel & Southey, 1988). Therefore, different rootstocks have a diverse capability to promote vigour (Swanepoel & Archer, 1988; Swanepoel & Southey, 1988; Wooldridge *et al.*, 2010). This is of importance when rootstock adaptation within vineyards are considered, which can lead to more uniform growth on soils with different vigour inducing capabilities.

Overall wine quality is not directly linked to yield, but may be inversely related to vigour (Wooldridge *et al.*, 2010). Vines with well-developed and distributed root systems, containing fine roots in particular, supported canopies that are characterized by sufficient lateral shoot development. The lateral shoots are responsible for a significant number of young leaves in the canopy during ripening. Younger leaves at véraison sustain and improve grape composition during this period. The quality of the grapevine root system is important for the eventual quality of the grapes and wine. The ratio between fine and thick roots may be a way in which the quality of a root system can be quantified. The ratio of > 3.5 for good and < 3.0 for poor quality root systems coincide with results of other root studies done in different vineyards in the past (Archer & Hunter, 2005).

2.4.4 Soil water status variability – effect on grapevine water status

SWS exerts an effect on grapevine water status ($\Psi_{S,}$ Ψ_{PD}) (Williams & Araujo, 2002). As the soil dries out, Ψ_S (Stevens *et al.*, 1995) and Ψ_{PD} (Myburgh, 2011) becomes more negative. The progression of grapevine water status during the season, as well as short-term fluctuations is strongly influenced by the soil water holding capacity.

2.4.5 Potential effects of variable grapevine water status on plant vegetative and reproductive performance

It may be assumed that if grapevines in a vineyard would have had very similar vigour, and experience differential water stress during the growing period (due to i.e. differing soil conditions or rooting patterns within a vineyard), the vigour and yield will change accordingly in these zones, leading to more variability. This is often observed when aerial photography of vineyards is assessed, especially late in the growing season (Strever, 2003). Matthews *et al.* (1987) found that despite variability in grapevine water status during the season, that there were no significant differences in the timing or duration of grapevine phenological stages (Matthews & Anderson, 1989). Unlike phenology, vegetative and reproductive growth is dependent on grapevine water status. Both parameters decrease with an increase in water stress (Matthews *et al.*, 1987; Matthews & Anderson, 1989; Stevens *et al.*, 1995; Lebon *et al.*, 2006), but the severity depends on the phenological stage and duration of the occurring stress (Matthews *et al.*, 1987; Matthews & Anderson, 1989; Shellie, 2006). Under non-irrigated conditions, vigour is strongly related to soil water availability (Acevedo-Opazo *et al.*, 2008). As long as the root distribution and water uptake is sufficient, stress will be limited in vines (Archer & Hunter, 2005; Myburgh, 2005). When a situation arise that limits the water supply to or in the grapevine, it cannot support the water demand and stress increase, which may affect the vegetative as well as reproductive response in the grapevine (Matthews *et al.*, 1987). Therefore, when a vineyard containing two different soil forms are irrigated in the same manner; in the long-term the vigour will normalize to the soil's ability to supply water to the plant (Van Zyl, 1984; Winkel & Rambal, 1993), which can mean that variability increase in time, also due to the secondary effects on plant reserve status, which has the potential to carry over to next seasons.

2.4.6 Grape composition and wine quality considerations with variation in soil and plant water status

Berry size is widely acknowledged as an important factor determining wine grape quality (Roby *et al.*, 2004). Berry size may also be important in determining the extraction and/or the dilution of the cell contents, which are clearly the primary site of several important solutes for winemaking. Grapevine water deficits generally lead to smaller berries and changes in fruit and wine composition (Roby *et al.*, 2004).

Past literature has shown conflicting results on water deficit and sugar accumulation (Hardie & Considine, 1976; Matthews & Anderson, 1989; Stevens *et al.*, 1995; Kennedy *et al.*, 2002; Ojeda *et al.*, 2002; Roby *et al.*, 2004). The literature focused on inducing stress in vines. None however standardised the stress levels in the vines, and a broad range of Ψ_{PD}, Ψ_L and Ψ_S was achieved in a stressed grapevine. This, in addition to possible differences in experimental conditions (i.e. the duration, intensity as well as timing of the water deficits applied) may have led to researchers finding positive and negative results in sugar accumulation or other reproductive parameters in stressed vines. Sugar transporters and enzyme activity involved with sugar distribution can be reduced with severe stress. This could then lead to a reduction in sugar loading (Deloire *et al.*, 2005). Considering this, and applying stress thresholds (Deloire *et al.*, 2005), sugar accumulation is facilitated by absent to moderate stress levels (Roby *et al.*, 2004) and inhibited by severe stress levels (Matthews & Anderson, 1989).

Variable results was found for pH (Stevens *et al.*, 1995). It increased or remained unaffected by water deficits (Matthews & Anderson, 1989). Titratable acidity decreased with an increase in water deficits, due to a reduction in malate (Van Zyl, 1984; Matthews & Anderson, 1989; Stevens *et al.*, 1995; Shellie, 2006), probably induced by increased canopy exposure under such conditions.

In red cultivars, anthocyanins accumulate in the berry at the beginning of véraison (Coombe & McCarthy, 2000). Water deficits pre-véraison increased accumulation after véraison (Kennedy *et al.*, 2002; Ojeda *et al.*, 2002; Roby *et al.*, 2004), but severe water deficits can negate the effect (Ojeda *et al.*, 2002). Phenol biosynthesis is dependent on the level and timing of water deficits. Ojeda *et al*. (2002) found that pre-véraison stress inhibited phenol biosynthesis, but Matthews &

Anderson (1989) found that phenol biosynthesis was stimulated by pre- as well as post véraison stress. Skin tannins increased with water deficit pre-véraison (Roby *et al.*, 2004).

Myburgh (2006) found that irrigation during berry ripening tended to negatively affect wine aroma or fullness, which might increase the risk of reduced overall wine quality in Sauvignon blanc and Chenin blanc grapes. Furthermore, it was shown that strong water stress in grapevines was not detrimental to wine quality. However, this might not be the case in vineyards on soils where plant available water is limited due to sandy soil texture or where root systems are either restricted by soil physical limitations or partial soil wetting under drip irrigation (Myburgh, 2006).

The possibility exists to consider SWS and PWS in a more integrated manner. With the phenological stages of the grapevine held in mind, a controlled irrigation regime can be implemented to achieve optimum wine quality (Van Zyl, 1984).

2.5 Conclusions

Soil heterogeneity is common within vineyards found in Western Cape; South Africa, and is mainly caused due to textural and structural differences (Conradie *et al.*, 2002). These inherent soil properties affect the SWS and have a great effect on the water supply capabilities of any given soil (Saxton *et al.*, 1986). The physical (Foth, 1990) and chemical (Conradie, 1983) properties and SWC (Morlat & Jacquet, 2003) also influence grapevine root growth, creating heterogeneous vigour areas in a vineyard, making irrigation strategies difficult.

Traditionally irrigation was applied with the aid of SWS based measurements, but lacked the capacity to quantify the grapevine's water need. On the other hand, PWS measurements show when the grapevine needs water, but not the amount (Jones, 2004). To address the drawbacks of these measurements, a relationship must be further explored between SWS and PWS (Myburgh, 2011) and this need to be quantified in further studies on both a temporal and spatial level.

A need also exist to optimise the assessment as well as management of soil and plant water status in the variable conditions often found in local vineyards, which can be done with the help of new technologies such as thermal satellite remote sensing as well as aerial remote sensing.

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Chapter 3

Research results

Assessment of grapevine reaction to water deficits and vigour variability: soil and plant water status interactions.

CHAPTER III: ASSESSMENT OF GRAPEVINE REACTION TO WATER DEFICITS AND VIGOUR VARIABILITY: SOIL AND PLANT WATER STATUS INTERACTIONS

3.1 Introduction

Past geological processes may have profound indirect effects on vineyard performance, since such processes created soils through weathering the materials of the current landscape. It is therefore easy to find contrasting soil forms in close proximity within a single vineyard block for the coastal winegrowing region of South Africa (Conradie *et al.*, 2002). The performance of individual plants, and their root and shoot biomass distribution can be strongly affected by the heterogeneity of soil-based resources (Hutchings *et al.,* 2003).

Soil heterogeneity leads to variability in soil water content and -retention. Soil water retention and the ability of the plant to extract it from the soil in turn may have an effect on the water status of the grapevine. Plant water status is a critical factor affecting the physiological processes in a plant, considering that many aspects of grapevine physiology respond to changes in water status in the plant (Jones, 2004).

Plant water status can be assessed from measurements of leaf water potential (Ψ_L), stem water potential (Ψ_S) and pre-dawn leaf water potential ($\Psi_{\mathbf{PD}}$). The problem with the above mentioned indices is that the grapevine is able to control its water status to some degree as the soil dries out or evaporation demand increases. This may even vary between different grapevine cultivars, as well as different cultivar-rootstock combinations. *Vitis vinifera L*. cultivars have shown a difference in their isohydricity abilities due to differing hydraulic behaviour (Jones, 2004; Cifre *et al.*, 2005; Soar *et al.*, 2006).

Water form a continuous hydraulic system from the soil, via the plant, to the atmosphere. With constant transpiration the water potential in the leaf decreases due to water loss to the atmosphere. This is replenished by water in the xylem. Thus it causes a lower water potential in the plant shoot and root system than in the bulk soil. The driving force for water movement in the soil-plant-atmosphere continuum from the soil to the plant is therefore due to a gradient in water potential (Schulze *et al.*, 2002; Gregory, 2006). The intensity of root development and physical contact between the root and soil are therefore important physical considerations, serving as a connection between soil and plant water status.

Findings in the literature are contradictory regarding the relationship between soil and plant water status. A direct relation between soil and PWS would seem to be the exception, rather than the rule (Cowan, 1965). Gruber & Schultz (2005) found that weekly measurements of soil water content and Ψ_{PD} revealed no clear correlation between Ψ_{PD} and the total soil water content, soil water content of different soil layers or the fraction of plant available water respectively, whereas Myburgh (2011a) found a clear correlation between Ψ_{PD} and soil water content. It is largely unknown how stable the relation between soil- and grapevine water status in a heterogeneous vineyard would be, and how the grapevine vegetative and reproductive response will adapt. Vigour variability is considered to play an important role in vineyards, also with regards to plant water status (Strever, 2003), and in a practical setting the goal should be to manipulate soil and plant water status levels within a vineyard so as to achieve balance in vegetative and reproductive growth for optimum grape quality.

The main aim of this study was to investigate the relationship between soil- and grapevine water status in a heterogeneous vineyard in the Stellenbosch region, while evaluating the vegetative and reproductive responses of the plant.

3.2 Materials and Methods

3.2.1 Vineyard characteristics

The study was conducted during the 2007/08 and 2008/09 growing seasons in the Stellenbosch region, Western Cape, South Africa. The vineyard was planted in 2000 with *Vitis vinifera* L. cv. Merlot clone MO 9, grafted onto R110 (*Vitis Berlandieri* x *Vitis rupestris*) rootstock. The predominant soil form is an Oakleaf 2110 (Soil Classification Working Group, 1991). The area has a Mediterranean climate with hot, dry summers and cold, rainy winters. Grapevines were spaced 2.7 x 1.5 m in an ENE-WSW row direction on a seven-wire hedge trellis system with moveable canopy wires. Canopy management included shoot positioning, mechanical shoot topping (once off in November) and spur-pruning was applied.

3.2.2 Experiment layout and treatments

Multispectral aerial photography, acquired15 February 2008, was used to characterise vigour variability in the vineyard. Images were classified using a normalized difference vegetation index (NDVI). These areas were further divided in 48 subplots, which also formed part of a larger project, and for which soil characteristics were not studied at each plot in detail. These plots also incorporated two irrigation regimes (rain-fed or irrigated). Each subplot consisted of four rows with 12 vines each. The two side rows were used as buffer rows, as well as the first three vines at both ends of each row, and the two middle rows were used as measurement rows. Irrigation was applied by drip irrigation at a delivery of 2.6 l/h, with a spacing of 75 cm between drippers.

Nine plots (Table 1) were chosen that were representative of the differing vigour levels in the vineyard, according to the multispectral image) (Figure 4 and Figure 5). The rationale for the selection of these nine plots was to perform more detailed soil and plant water status related measurements for plots representing a range of visually differing soils and grapevine vigour levels. Due to logistical reasons and project limitations these analyses could not be performed on all 48 plots.

Irrigation scheduling was done according to pre-dawn leaf water potential (Ψ_{PD}) measurements, where irrigated vines were watered when Ψ_{PD} measurements were between -200 and -300 kPa, therefore avoiding water deficits as much as possible. The rain-fed treatments received no water, except from rainfall.

Table 1 Description of soil characteristics per 30cm depth and irrigation treatment for the 9 experimental plots.

Irrigation treatment	Plot	Visually observed vigour	Soil characteristics		
			0 - 30 cm	30 - 60 cm	60 - 90 cm
Rain-fed	1	Moderate	SaLm*	SaLm	SaLm
	2	Moderate	LoSa**	LoSa	SaLm
	3	Moderate	LoSa	SaLm	SaLm
	4	Moderate	SaLm	SaLm	SaLm
Irrigated	5	High	SaLm	SaLm	SaLm
	6	Moderate	SaLm	SaLm	SaLm
	7	High	LoSa	SaLm	SaLm
	8	Moderate	LoSa	SaLm	SaLm
	9	Low	LoSa	LoSa	LoSa

*SaLm= Sandy loam; **LoSa= Loamy sand

Figure 4 Multispectral NDVI image used to perform plot layout. NDVI classification: white - lowest NDVI values (corresponding to lower vigour levels), green - medium NDVI values, blue - highest NDVI values (corresponding to higher vigour levels).

Figure 5 Experiment plot layout showing the selected plots in this study. Yellow plots (1-4) represent rain-fed and blue plots (5-9) represent irrigated treatments.

3.2.3 Soil measurements

3.2.3.1 Profile pits

Profile pits were dug at the nine experimental plots selected for soil-based measurements. The hole was dug 50 cm from the base of a representative vine within the plot, stretching from the base of adjacent vines to a depth of one meter. Soil-based measurements consisted soil textural, organic material carbon (%) and pH(KCl) analyses, bulk density measurements and root profiling, of which the former four where a pooled sample representing the profile.

3.2.3.2 Soil samples

Soil samples were collected to 90 cm depth over 30 cm increments in each of the nine profile pits. Soil particle distribution, organic material carbon (%) and pH(KCl) were determined by a commercial laboratory (Bemlab Pty. Ltd., Strand). Soil textural class was determined according to the Soil Classification Working Group (1991).

3.2.3.3 Bulk density

Bulk density is a measure of the dry mass of the soil per unit volume, expressed in g/cm^3. Bulk density measurements were collected to 90 cm depth over 30 cm increments according to the undisturbed core method. A cylinder core with a volume of 250 cm^3 was used to take an undisturbed soil sample at 30, 60 and 90 cm depths, from the profile wall, for each of the nine plots. The samples were oven dried at 105°C until constant mass was attained. Bulk density was calculated as follows:

$$\rho_b = \frac{M}{V} \qquad \text{Eq 1}$$

Where ρ_b is bulk density (g/cm^3), M is air dry soil mass (g) and V is the cylinder volume (cm^3) (Blake, 1965).

3.2.3.4 Gravimetric soil water content

This is a direct measurement of soil water content expressed in gram of water per gram of soil. Soil samples were obtained with a soil auger (one sample for each depth), at the same time as determining neutron probe measurements at 30, 60 and 90 cm soil depths, over time. Each sample was placed in a sealable plastic bag. After determining the wet mass, the samples were oven dried at 105°C until stable mass was achieved. By subtracting the dry mass from the wet mass, the water content of the soil was calculated. Gravimetric soil water content was then calculated from the water content relative to the dry mass of the soil (g water/g soil).

The product of the gravimetric water content and bulk density is known as the volumetric water content (mm water/mm soil), or Θ_v. Gravimetric soil water content was calculated as follows:

$$\Theta_m = \frac{M_w - M_d}{M_d} \qquad \text{Eg 2}$$

Where Θ_m is gravimetric soil water content (g water/g soil). M_w is wet soil mass (g) and M_d is oven dry mass (g).

Volumetric soil water content was calculated as follows:

$$\Theta_v = \Theta_m \times \rho_b \qquad \text{Eq 3}$$

whereΘ_v is volumetric soil water content (mm water/mm soil), Θ_m is gravimetric soil water content (g water/g soil) and ρ_b is bulk density (g/cm^3).

3.2.3.5 Neutron probe readings

An indirect measurement of soil water content was performed using a neutron probe (503 DR Hydro probe neutron depth moisture gauge, Campbell Pacific Nuclear International Inc., USA). Polyvinyl chloride (PVC) access tubes were installed in a central position at each of the experimental plots, 50 cm from a grapevine chosen to be representative of the plot. Neutron count values were measured at 30, 60 and 90 cm soil depths. A “water standard”, consisting of 20 measurements inside a drum filled with water in which a PVC tube was installed, was taken at the beginning of each neutron measurement session. This standard was used to obtain a complete water saturated neutron measurement. To absolve neutron scattering drift between dates, the neutron count is divided by the water standard to express the water content as a count ratio (CR). These measurements (30, 60 and 90 cm) were collected at two-weekly intervals during the whole growing season.

3.2.3.6 Tensiometer readings

A direct measurement of soil matrix potential was performed by using a tensiometer. A tensiometer was installed 30 cm from each of the neutron probe PVC access tubes in the nine experimental plots dedicated to soil based measurements at 30, 60 and 90 cm depths. The readings on the tensiometers were collected simultaneously with each gravimetric sampling.

3.2.3.7 Soil water status calculations

In order to properly quantify soil water status (SWS), a few parameters need to be calculated. When water movement due to gravitational forces has stopped and the water content has stabilised, it is referred to as field water capacity (FWC). Grapevines are assumed to be able to extract water until levels of -1500 kPa are reached (Kirkham, 2005). This point is referred to as permanent plant wilting point (PPWP). The water content between FWC and PPWP is referred to as the plant available water (PAW). The water content at -85 kPa is termed as the lower level of readily available water (RAW).Soil samples for each plot and depth were used to calculate FWC, RAW and PPWP using soil retention curve.

The percentage of PAW extraction is calculated as follows:

$$\%\ \mathrm{PAW} = \left(\frac{\Theta_{\mathrm{v}}}{\mathrm{PAW}}\right) \times 100 \qquad \text{Eq 4}$$

where PAW is plant available water (mm) and Θ_v is volumetric soil water content (mm water/mm soil). This gives the percentage water in the soil profile that is theoretically available for use by the grapevine. Zero values would indicate no extraction, whereas 100% indicates total extraction of PAW (Foth, 1990).

3.2.4 Vegetative Measurements

3.2.4.1 Winter pruning mass

Pruning was done in mid-July (2007 and 2008) with grapevines in full dormancy, for the nine selected plots. All the vines in the experimental plots were pruned to two-bud spurs. Each vine's canes were counted and weighed separately. Pruning mass (cane mass) was used to validate vigour variability between the experimental plots.

3.2.4.2 Fertility

Fertility was measured by dividing the number of bunches with the number of main shoots, for each vine, for each of the nine selected plots.

3.2.4.3 Shoot measurements

Primary shoots were monitored to follow vegetative growth in the different treatments. Four visually representative grapevines in each of the four most extreme vigour plots, according to pruning mass and NDVI-imaging were chosen for these measurements. Two representative shoots were marked on four vines, and some parameters recorded during the growing season. This consisted of weekly measurements of shoot length (cm). To accommodate the effect of mechanical topping actions, topped shoots were not included in the final dataset.

3.2.4.4 Root profiling

Root profiling is used to quantify the below-ground component of the grapevine. The profile pits were dug next to the vine, one meter deep and 0.5m from the trunk. A few millimetres of soil was then gently removed to expose the roots (Bohm, 1979). A grid (1.0 m x 1.5m), subdivided into smaller grids (10 cm x 10 cm), was then overlaid on the profile wall with the trunk as a central point as shown in Figure 6. The exposed roots were then plotted on a scaled-gridded paper, using a classification system with symbols indicating five classes as indicated in Table 2. The roots were spray-painted white to simplify counting and enhance detection on photographs. Root ratios are calculated by dividing the total fine roots with the total thick roots. This is done to give an indication of how effective the root system is (Swanepoel & Southey, 1989), where ratios above 3.5 is considered as desirable (Archer & Hunter, 2005).

Table 2 Classification of grapevine roots for profile wall analysis (Richards, 1983).

Class			Diameter (mm)
1	Fine Roots	Very fine	< 0.5
2		Fine	0.5 - 2
3	Thick Roots	Medium	2 - 5
4		Large	5 - 7
5		Very large	> 7

Figure 6 An example of a profile wall with an overlaying grid (1m x 1m) and spray-painted roots. The red dot represents the vine position.

3.2.5 Plant water status measurements

3.2.5.1 *Pre-dawn leaf water potential*

Pre-dawn leaf water potential (Ψ_{PD}) was measured at weekly intervals, two hours before the break of dawn during both growing seasons in the experimental plots. Five healthy, fully-expanded leaves on main shoots, taken randomly through the whole plot (but excluding buffer grapevines), were removed by a single cut with a sharp blade. Each leaf was measured in a Scholander type pressure chamber (Scholander *et al.*, 1965) within 30 seconds of making the cut. The pressure measurement (-kPa) was noted when the first sign of moisture was visible from the petiole.

The measured values can be categorised according to stress thresholds to define the amount of stress the grapevine experience, and the subsequent effects that would have on vegetative and reproductive responses (Table 3).

Table 3 Relationships between pre-dawn leaf water potential, vegetative and fruit growth, berry physiology, and biochemistry of *Vitis vinifera* L. (Deloire *et al.*, 2005).

Ψ_{PD} (kPa)	**Vegetative growth**	**Berry growth**	**Photosynthesis**	**Berry maturation**
0 to -300	normal	normal	normal	normal
-300 to -500	reduced	reduced	normal or slightly reduced	higher than normal
-600 to -900	inhibited	reduced or inhibited	reduced or inhibited	reduced or inhibited
<-900	inhibited	inhibited	inhibited	inhibited

3.2.6 Reproductive measurements

3.2.6.1 Weekly berry sampling

Berry sampling was performed weekly during the 2008/9 season from véraison up to the harvest date. A single sample of one hundred and fifty berries were sampled randomly from both the morning and midday-sun sides of the canopy and from different sides and sections, top, middle and bottom, of bunches for each of the nine experimental plots, over time. The samples were stored at 4°C until it could be processed on the same day.

In the laboratory, one hundred berries per sample were weighed using a JW-1000 counting scale (UWE electronic scales, Taiwan). The same berries were then used to determine berry volume using a marked cylinder and the water displacement. Samples were hand-crushed in a plastic bag to obtain juice. The juice was used to measure total soluble solids (°B), using a pocket refractometer (ATAGO Pal-1 refractometer, ATAGO Co LTD., Tokyo) zeroed with distilled water. Titratable acidity (TA) was measured with a 785 DMP Metrohm Titrino automatic titration instrument (Metrohm AG, Herisau, Switzerland) using 50 ml fresh juice.

3.2.6.2 Yield at harvest

Yield was determined at harvest by counting and weighing each vine’s bunches within each experimental plot. Second-crop bunches were discarded.

3.2.7 Yield:pruning mass ratios

Corresponding yield and pruning mass was used to determine the ratios between the two parameters for both seasons.

3.2.8 Statistical analysis

Where applicable, data were subjected to an analysis of variance (ANOVA) using Statistica 11.0 (Tulsa, OK, USA). Statistica was also used to calculate regression equations as well as calculating basic statistics (i.e. standard errors, means or confidence intervals as stated for specific graphs).

3.3 Results and discussion

3.3.1 Season characteristics

Both the 2007/8 and 2008/9 seasons seemed to have experienced similar maximum temperatures (Figure 7). The 2007/8 season did however display a tendency to have slightly higher temperatures on a monthly average (Figure 8). The 2008/9 season had lower temperatures in January, but higher in February. The largest differences between the seasons were the rainfall (Figure 9 and Figure 10). Although roughly the same rainfall occurred during the growing season, 2007/8 had significantly more rainfall post-véraison. The 2008/9 season had virtually no rainfall during the same time period. Pre-season rainfall was significantly less in the 2008/9 season which could have led to less growth and more water deficits.

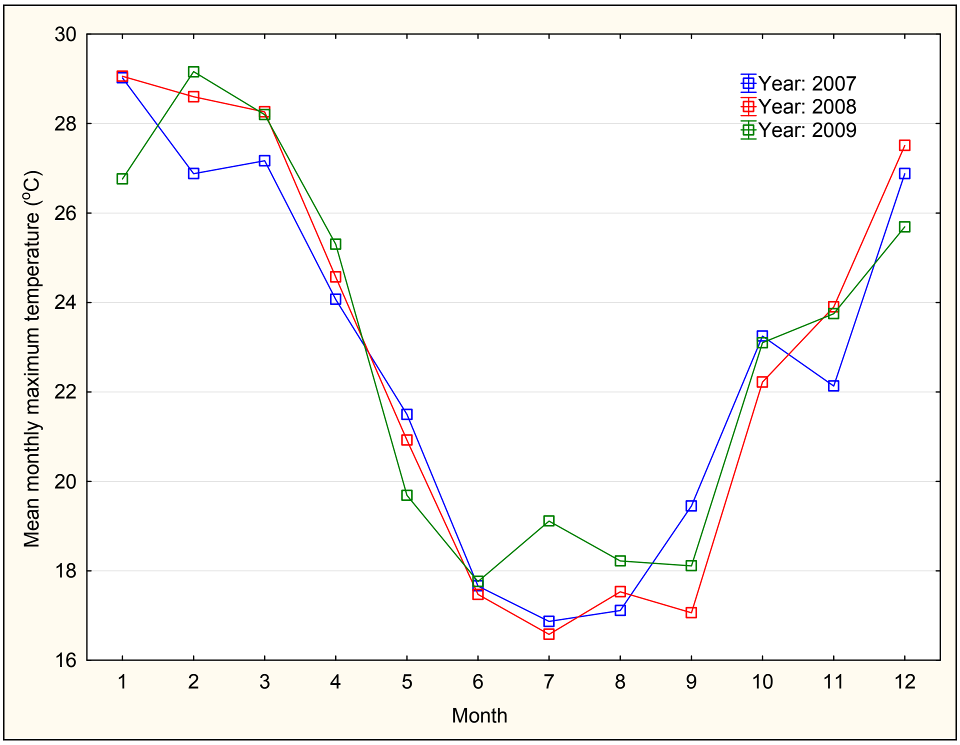

Figure 7 Mean monthly maximum temperatures for the Merlot vineyard near Stellenbosch from 2007 to 2009.

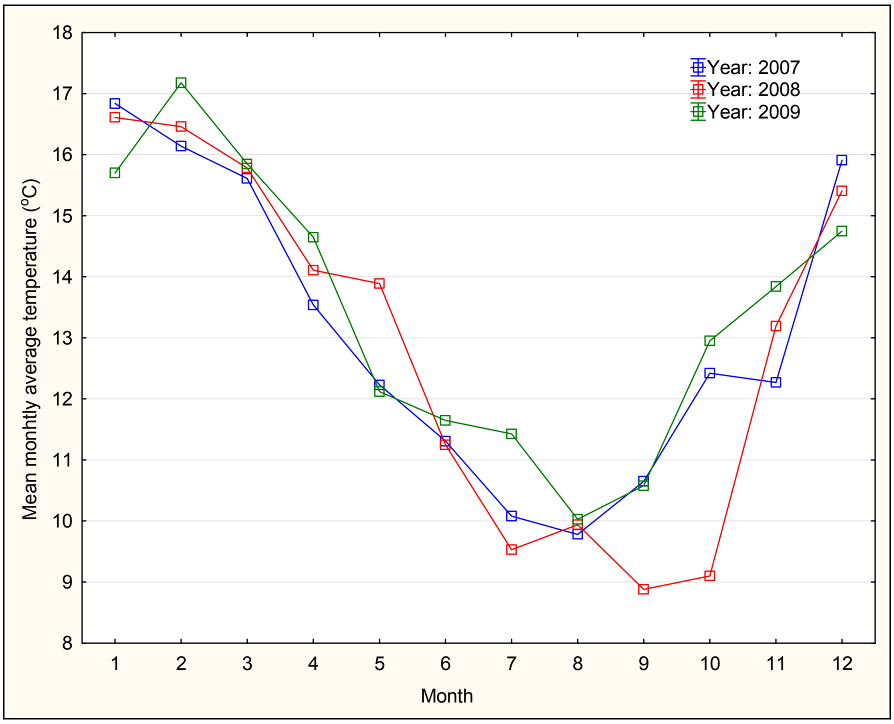

Figure 8 Mean monthly average temperatures for the Merlot vineyard near Stellenbosch from 2007 to 2009.

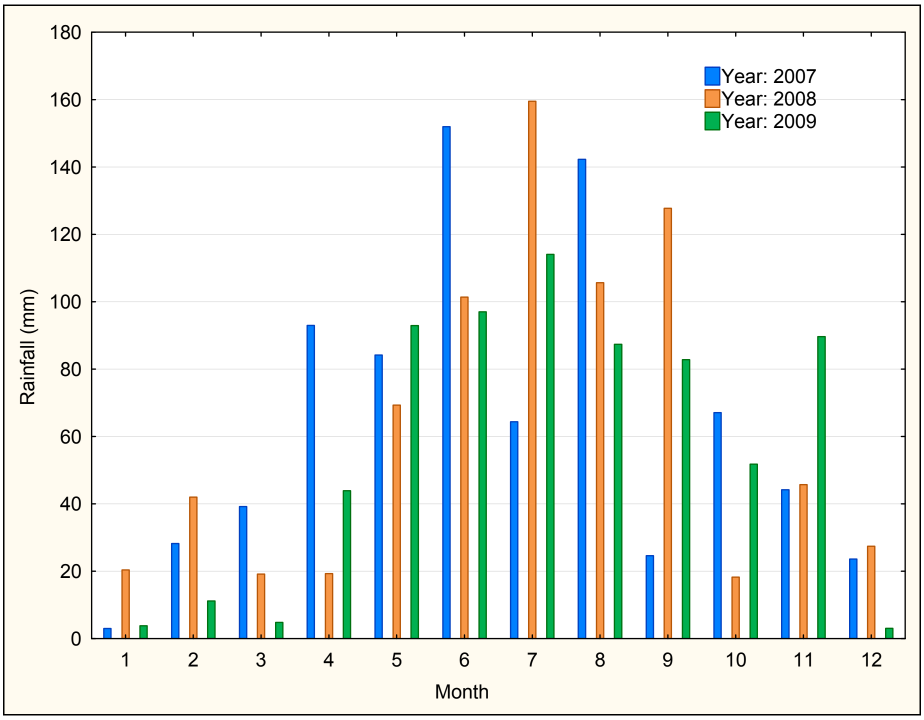

Figure 9 Monthly rainfall for the Merlot vineyard near Stellenbosch from 2007 to 2009.

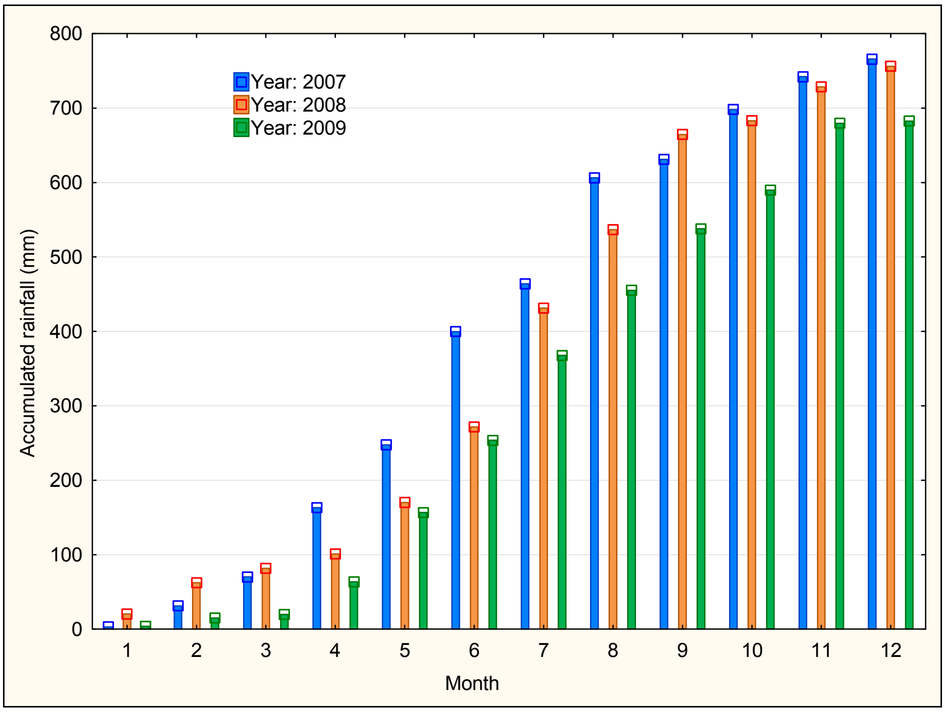

Figure 10 Accumulated rainfall for the Merlot vineyard near Stellenbosch from 2007 to 2009.

3.3.2 Soil variability

The marked difference between the vigour areas in the vineyard is most probably due to the variance in soil physical properties (Table 4), with clay percentage and organic material content being the main contributing factors. This is visible from the lowest vigour plot (9) exhibiting low levels of clay through the whole profile (Table 4 and Table 5). With such low clay levels the buffer capacity of the soil is severely limited and as such it cannot support the vine growth with the same capability of the other areas in the vineyard, even during a wetter season such as the first one in this study. An increase in the amount of clay in the subsoil is desirable, especially where irrigation is not applied, as the amount of water and nutrients stored in that zone can also be increased (Foth, 1990). Plots (i.e. 3,5,6) with higher vigour, also showing higher clay contents, would probably be able to support more vigorous growth. It is however difficult to see a clear relationship between individual plot vigour (as measured using pruning mass) and soil physical characteristics. Therefore the vigour differences could possibly also be attributed to other parameters. It is however also clear that in this case soil heterogeneity exists at the sub-vineyard level, as also observed in Conradie *et al.* (2002). Therefore it is important to look at the intrinsic qualities of the soil, for these do not only influence the water holding capacity of the soil, but also the growth characteristics of the plant itself (Foth, 1990; Gregory, 2006b). Large variability is apparent for the clay and the organic material contents between all plots. This was still apparent when the soil depths were separated (Table 4). These values do not correspond to other areas near Stellenbosch (Conradie *et al*., 2002).

Table 4 Means, standard deviation (Std.Dev) and Coefficient of variation (Coef.Var) of soil characteristics for the nine plots and split into three depths

Parameters /Plot	Depth (cm)	Bulk density (g/cm^3)	Clay %	Silt %	Total Sand %	Fine Sand %	Medium Sand %	Coarse Sand %	Organic material carbon (%)	pH
Mean	All	1.458	9.8	13.7	76.4	45.1	15.9	15.4	0.60	5.5
Std.Dev.		0.055	4.4	1.8	4.3	5.0	2.0	2.6	0.27	0.6
Coef.Var.		3.747	45.0	13.5	5.6	11.1	12.3	17.2	45.64	11.3
Mean	0-30	1.475	6.6	15.2	78.2	47.3	16.5	14.4	0.90	5.7
Std.Dev.		0.061	2.6	1.8	3.3	4.4	1.4	2.1	0.13	0.5
Coef.Var.		4.113	39.2	12.0	4.2	9.4	8.7	14.7	15.07	8.7
Mean	30-60	1.435	10.4	13.3	76.4	44.5	15.7	16.1	0.47	5.5
Std.Dev.		0.031	3.8	1.7	4.4	4.7	2.0	2.6	0.21	0.7
Coef.Var.		2.175	36.7	12.7	5.7	10.6	12.9	16.1	44.50	12.9
Mean	60-90	1.464	12.6	12.6	74.8	43.7	15.4	15.7	0.42	5.3
Std.Dev.		0.064	4.7	0.9	4.7	5.6	2.4	3.1	0.16	0.6
Coef.Var.		4.362	37.0	7.0	6.4	12.9	15.3	19.7	38.37	12.0

Table 5 Soil characteristics for the nine plots across three depths

Parameters/ Plot	Depth (cm)	Bulk density (g/cm^3)	Clay %	Silt %	Total Sand %	Fine Sand %	Medium Sand %	Coarse Sand %	Organic material carbon (%)	pH
1	0 - 30	1.516	8.4	13.6	78	48.3	15.1	14.6	0.84	6.1
	30 - 60	1.467	13.8	12.2	74	40.3	13.2	20.5	0.33	6.4
	60 - 90	1.473	14.4	12.6	73	44.4	13.3	15.3	0.46	6.4
2	0 - 30	1.456	7.4	13.4	79.2	50.1	15.4	13.7	0.75	4.6
	30 - 60	1.389	9	11.8	on><p50	50.4	15.4	13.4	0.66	4.4
	60 - 90	1.581	12	12.8	75.2	46.2	14.4	14.6	0.54	4.6
3	0 - 30	1.486	6.8	15.4	77.8	46.6	15.7	15.5	0.98	5.9
	30 - 60	1.476	13.6	12.2	74.2	42.9	14.8	16.5	0.4	5.7
	60 - 90	1.447	15.6	12.8	71.6	39.3	14	18.3	0.36	5.8
4	0 - 30	1.568	10	15.2	74.8	39.6	17.3	17.9	0.77	5.5
	30 - 60	1.439	8.4	14.6	77	42.3	17.4	17.3	0.17	6.1
	60 - 90	1.387	11.4	13.8	74.8	41.1	17	16.7	0.47	5.8
5	0 - 30	1.503	8	15	77	43.1	17.8	16.1	0.75	5.6
	30 - 60	1.468	12.4	13.4	74.2	41.4	15.6	17.2	0.4	5.6
	60 - 90	1.485	12	13.4	74.6	42.9	15.3	16.4	0.48	5.4
6	0 - 30	1.492	7.6	19.4	73	44.7	15.8	12.5	0.95	5.8
	30 - 60	1.438	11.6	16.8	71.6	41.5	14.8	15.3	0.73	5.8
	60 - 90	1.387	19.4	12.8	67.8	35.8	14	18	0.26	5.3
7	0 - 30	1.349	5.8	16	78.2	47.6	15.2	15.4	0.85	6.3
	30 - 60	1.427	10.2	11.8	78	45.5	14.6	17.9	0.37	6.1
	60 - 90	1.528	13.6	10.6	75.8	43.4	13.8	18.6	0.12	5.3
8	0 - 30	1.473	2.6	15.6	81.8	52.6	17.1	12.1	1.1	6.1
	30 - 60	1.417	12.6	14.4	73	41.8	15.6	15.6	0.39	4.5
	60 - 90	1.467	13	12.6	74.4	43.5	16.2	14.7	0.42	4.8
9	0 - 30	1.435	2.4	13.6	84	53.3	19.3	11.4	1.07	5.8
	30 - 60	1.396	1.6	12.4	86	54.1	20.3	11.6	0.81	5.1
	60 - 90	1.418	2	12.4	85.6	56.3	20.8	8.5	0.68	4.4

The water holding capabilities of the soil is texture dependent, but it is also influenced by other factors. Organic material has a positive influence on water holding capacity, soil quality and vine growth (Saxton *et al.*, 1986; Conradie *et al.*, 2002; Dexter, 2004; Du Preez *et al.*, 2011). Foth (1990) found that clay protects organic matter from decomposition and therefore organic matter is positively correlated with the clay content and negatively correlated with the sand content in some grassland soils in Wyoming, USA. The contrary was found for soils analysed in this study (R = 0.76; $r^2 = 0.58$; $p \leq 0.001$), organic material showed a negative correlation with an increase in clay content (Figure11). For all nine plots the top 30 cm of soil had lower clay content (Table 5). This will also be where the most organic material would accumulate due to mulching practises. It is also possible that the translocation of organic material is slower towards deeper layers, than the accumulation in the top layer. This can be one of the reasons why organic material is negatively correlated with clay content in this study. It may be that an increase in organic material in sandy soils can negate to a degree the decreased water retention capacity (Foth,1990).

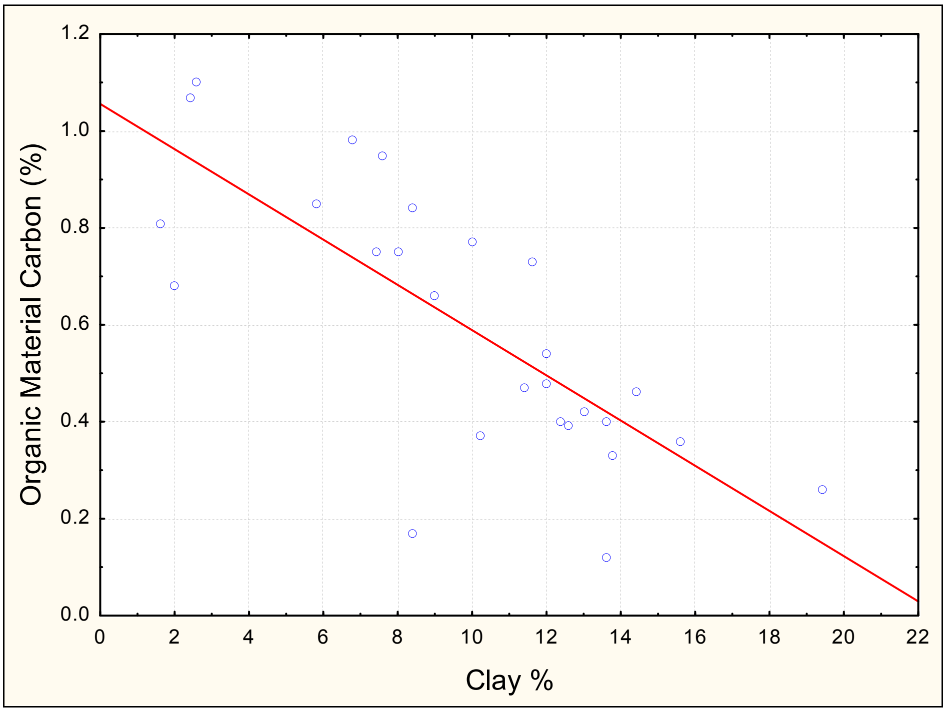

Figure11 Relationship between organic material content and clay content for all the studied plots (R = 0.76; $r^2 = 0.58$; $p \leq 0.001$).

Gravel and stones lower the physical volume of the soil in the profile and thus may reduce the water holding capacity (Saxton & Rawls, 2006). This may be prominent in the stony profile (4) shown in Figure12. Even though most of the profile consists of stone, the soil is still able to support a canopy characterised by strong growth (as seen previously in the pruning mass results) under rain-fed conditions. This may be largely attributed to a relatively high clay content (Table 4 and Table 5) and possible higher water holding capacity.

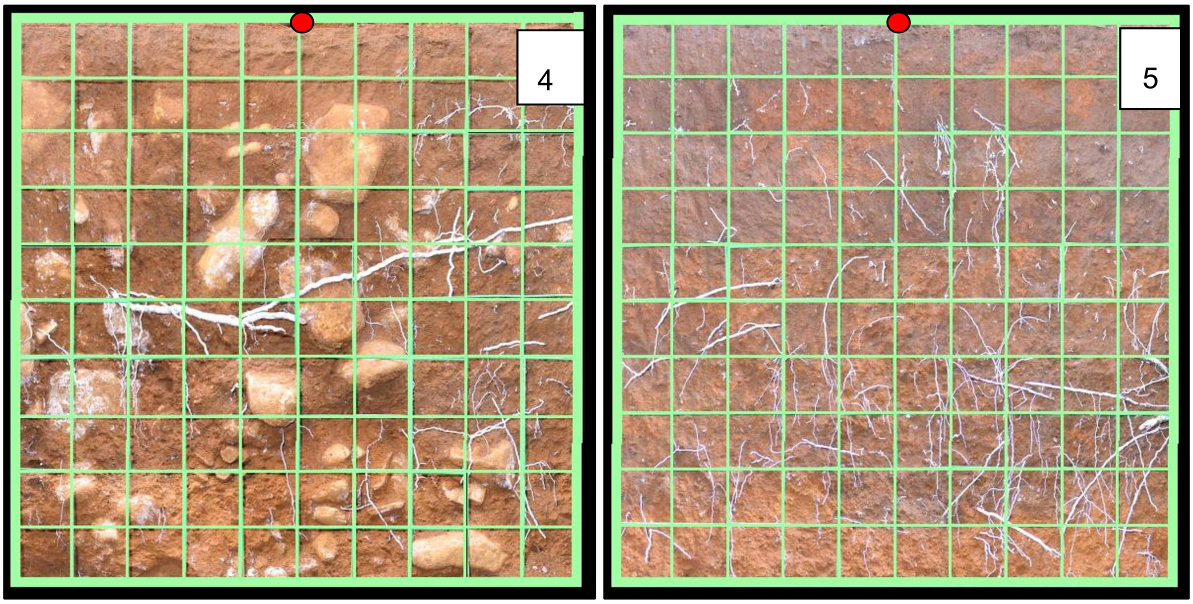

Figure12 Soil profile 4 (1m x 1m) illustrating the extent of soil variability that may be encountered due to natural causes versus a normal soil profile 5 (1m x 1m). The red dots represent the vine trunk positions.

The aim of soil manipulation is to alleviate a particular soil constraint, in order to improve grapevine performance. By doing so it tends to change a number of other soil properties, such as porosity and structure. Erroneous soil preparation can lead to insufficient amelioration of the soil. The aim is to create a homogeneous zone where roots can develop freely. This can be seen in Figure 13, where the top-soil horizon was mixed into the sub-soil, creating a zone for the roots to proliferate, but due to ineffective soil preparation, unfavourable sub-soil zones remained. This can lead to a modification of the total soil water available to the vine in this particular location.

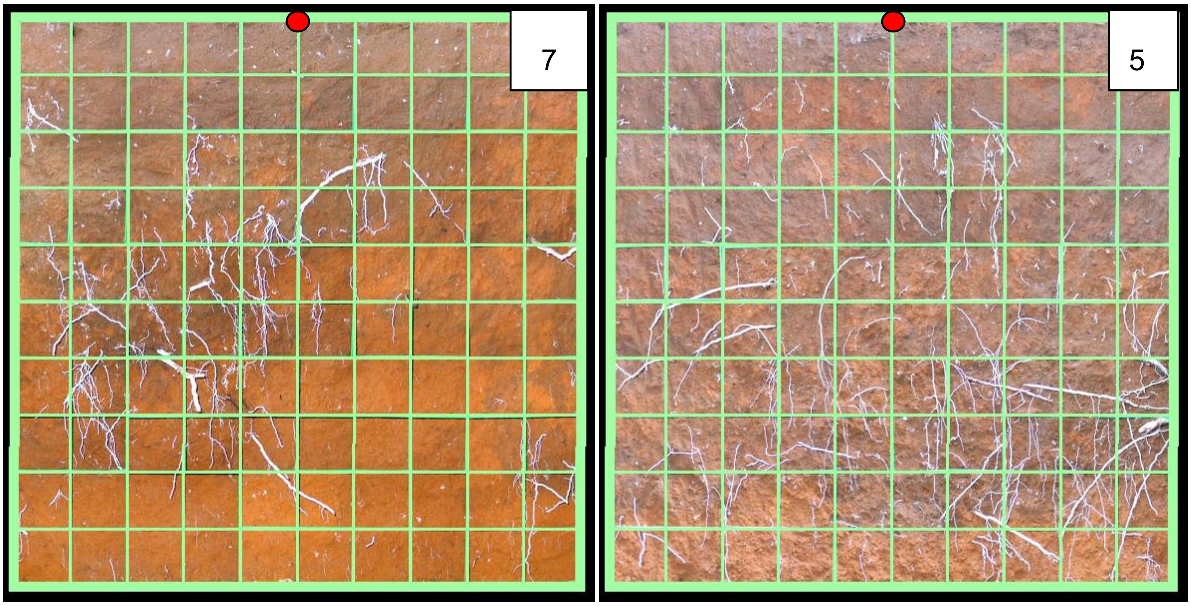

Figure 13 Soil profile 7 (1m x 1m) illustrating the effect of poor soil preparation on the variability of soil composition as well as root distribution versus a well prepared soil profile 5 (1m x 1m). The red dots represent the vine trunk positions.

Soil variability may stem from natural causes or from human interference, but both causes may have a profound effect on the overall composition of the soil. Human factors include erroneous planting practices or plant material related problems such as graft union failure. Even over small distances significant variability in the soil can lead to vigour differences and can be detected through visual means (Figure 4). This in turn influences the capacity of the soil to supply water and nutrients to the grapevine, which makes it essential to evaluate these areas in a vineyard individually (Figure12 and Figure 13). It is clear from the above figures that soil heterogeneity exists in the vineyard, which may lead to vigour variability. This soil heterogeneity can also potentially impact soil water status and its measurement.

3.3.3 Soil water status

3.3.3.1 Neutron probe calibration

A strong correlation was found between Θ_v (mm/m) and the neutron count ratio (CR) for all the studied plots and depths ($R = 0.9$, $r^2 = 0.81$, $p \leq 0.001$) (), but the neutron scattering method has a high accuracy and should therefore give r^2 values higher than 0.90 (Hignett & Evett, 2002).

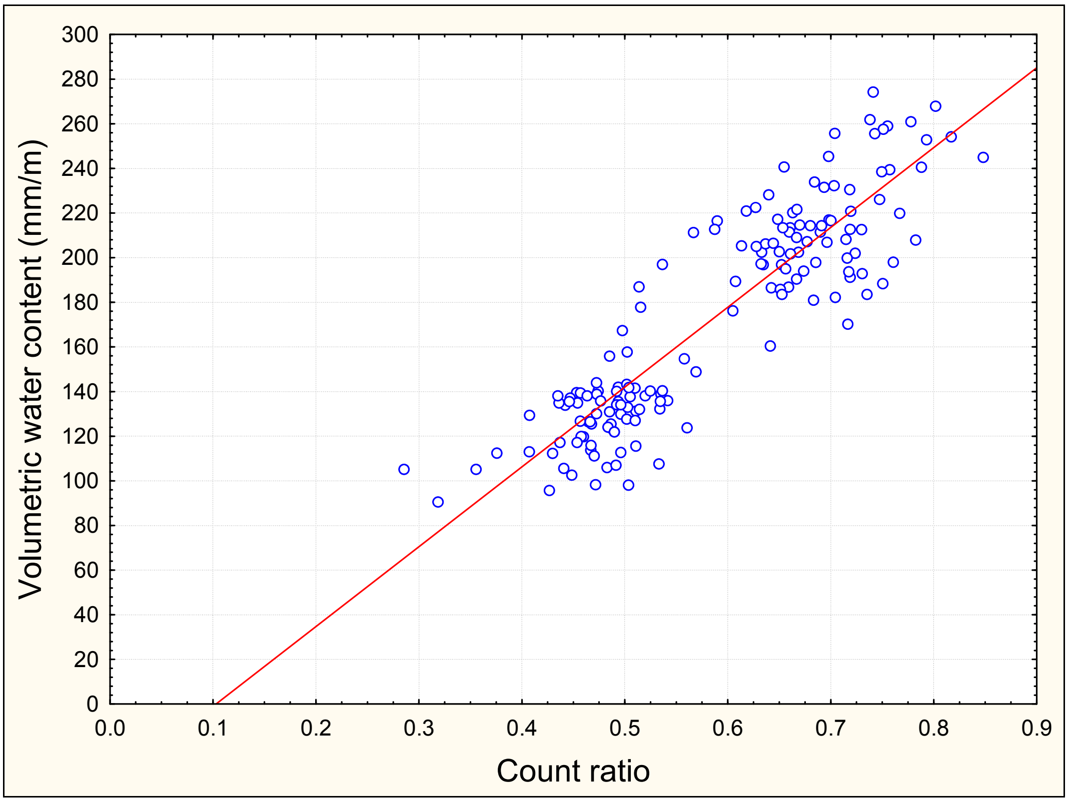

Figure 14 Relationship between Θ_v and count ratios for all the studied plots and depths ($R=0.90$, $r^2=0.81$, $p \leq 0.001$).

In a heterogeneous vineyard a global calibration will therefore not be possible. Heterogeneity does occur, due to some locations and depths exhibiting textural and soil composition differences in the soil profile. To achieve higher accuracy, calibrations need to be performed for each location and depth that displays the variability seen in Table 4 and Table 5. Therefore the calibration's accuracy should further improve, increasing the precision of SWS and PWS integration. Practically this will also help in irrigation scheduling, reducing over- or underestimation of Θ_v in the soil. Taking location and depth into account, the r^2 values increased to above 0.90, thus increasing accuracy of Θ_v estimation (

Table 6). These results correspond with findings for calibrations done between different soil types, horizons and depths (McDougall *et al.*, 1996; Evett *et al.*, 2002), but in this study it was also found for similar classified soil types within a vineyard.

Table 6 Results from a regression between Θ_v and neutron count ratio (CR) for all studied plots and depths (the y-intercepts, slope, Pearson's coefficients, p-values and the correlation coefficients).

Plot	Depth	y-intercept	slope	R	p value	R^2
General	30	-0.0349	0.3542	0.89	0.00	0.79
	60	-0.0444	0.3780	0.91	0.00	0.83
	90	-0.0377	0.3529	0.90	0.00	0.81
1	30	-0.0688	0.4259	0.97	0.00	0.95
	60	-0.0298	0.3777	0.96	0.00	0.93
	90	-0.0781	0.4304	0.99	0.00	0.99
2	30	-0.0789	0.4322	0.99	0.00	0.98
	60	-0.0843	0.4487	0.95	0.00	0.90
	90	-0.0327	0.3940	0.96	0.00	0.92
3	30	-0.0606	0.4030	0.93	0.01	0.87
	60	-0.0327	0.3885	0.98	0.00	0.97
	90	-0.0534	0.3671	0.99	0.00	0.98
4	30	-0.0772	0.4138	0.98	0.00	0.96
	60	-0.0837	0.4025	0.98	0.00	0.97
	90	-0.0699	0.3462	0.99	0.00	0.97
5	30	-0.0539	0.3819	0.95	0.00	0.91
	60	-0.0692	0.4012	0.93	0.01	0.87
	90	-0.0586	0.3970	1.00	0.00	0.99
6	30	0.0796	0.1733	0.80	0.06	0.64
	60	0.0016	0.3072	0.84	0.03	0.71
	90	-0.0927	0.4371	0.96	0.00	0.92
7	30	-0.0227	0.3101	0.88	0.02	0.77
	60	-0.0515	0.3886	0.93	0.01	0.86
	90	-0.0627	0.4150	0.99	0.00	0.99
8	30	-0.0813	0.4043	0.97	0.00	0.94
	60	-0.0243	0.3243	0.97	0.00	0.95
	90	-0.0037	0.2830	0.96	0.00	0.92
9	30	-0.0441	0.4121	0.89	0.02	0.79
	60	-0.0796	0.4515	0.94	0.01	0.88
	90	-0.0331	0.3344	0.89	0.02	0.79

Hydrogen is the main atom responsible for neutron scattering, and thus the neutron count is directly proportional to the volumetric water content of the soil (Evett, 2003). Organic material and most clays contain significant amounts of hydrogen that may not always be in the form of water (Kramer & Boyer, 1995; Dane & Topp, 2002). Lower correlation coefficients were strongly influenced ($R=-0.81$, $p < 0.001$; $r^2=0.65$) by soil organic material content (Figure 15). Accuracy increased with a lower organic material content. This was expected due to the presence of carbon in organic material, which is relative efficient as a neutron thermalizer (Hignett & Evett, 2002).

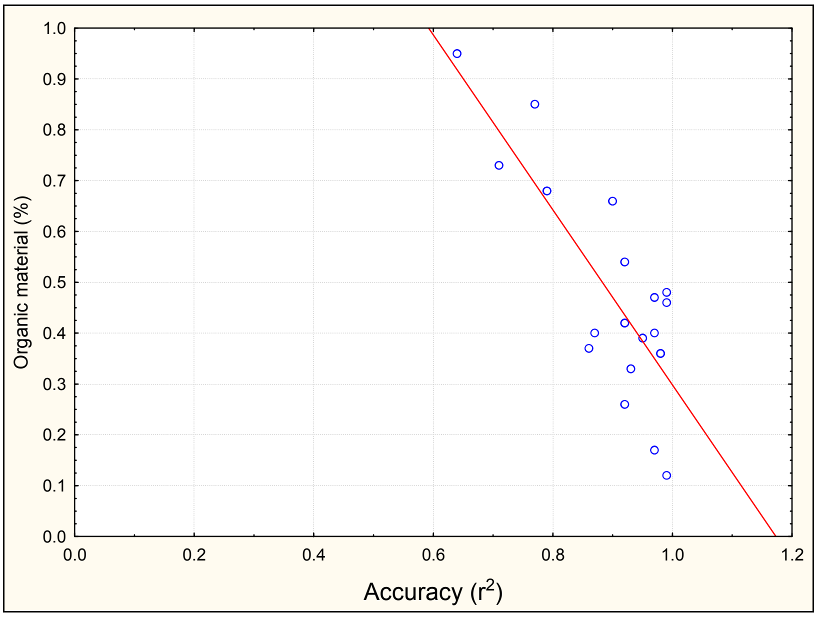

Figure 15 Relationship between organic material and the correlation coefficients (r^2) of the count ratio and Θ_v relationship (R= -0.81, p < 0.001; r^2 = 0.65).

As previously stated, there was no clear distinction seen between the soil physical characteristics for most of the plots. Linking to this, there seems to not be large differences in the total plant available water (PAW), with the exception of plot 1 (**Error! Reference source not found.**). The mean PAW values correspond to some soils found in surrounding areas near Stellenbosch (Conradie, *et al.*, 2002). The reason for that could probably be a lower silt component, irrespective of similar clay contents in the profile (Reichert *et al.*, 2010). Interestingly, the lowest vigour plot (9) has more plant available water than the higher vigour plots. This may be ascribed to higher organic material present in the soil profile.

Table 7 Soil water holding capabilities for all studied plots in the vineyard.

Plot	Field water capacity (mm/m)	Lower level of easily accessible water (mm/m)	Permanent plant wilting point (mm/m)	Plant available water (mm/m)
1	158.9	108.4	66.1	92.8
2	222.0	145.7	85.2	136.8
3	230.1	156.5	95.5	134.6
4	227.0	147.4	86.7	140.3
5	220.3	145.7	87.1	133.2
6	244.0	164.3	101.1	142.9
7	214.4	142.3	84.5	129.9
8	221.2	141.6	82.8	138.4
9	189.3	94.3	43.3	146.0

It seems that, with respect to vigour variability, soil water content may not be the only important parameter; soil water retention possibly plays an important role as well. The clay percentages in plot 6 increase in depth, as does the soil water holding capacity. Plot 6 contains higher clay content than plot 9, and the effect on the soil water retention curve can clearly be seen in **Error! Reference source not found.**. With an increase in depth, water holding capacity increases, albeit at a higher water retention. Although both plots have the same amount of plant water available to them, plot 9 has a much higher sand content, with lower water retention through the whole profile. The water is easier to extract, but in turn does not create a good buffer capacity for the grapevine (Figure 16). This can explain why there is a clear distinction between the most extreme vigour areas in the vineyard.

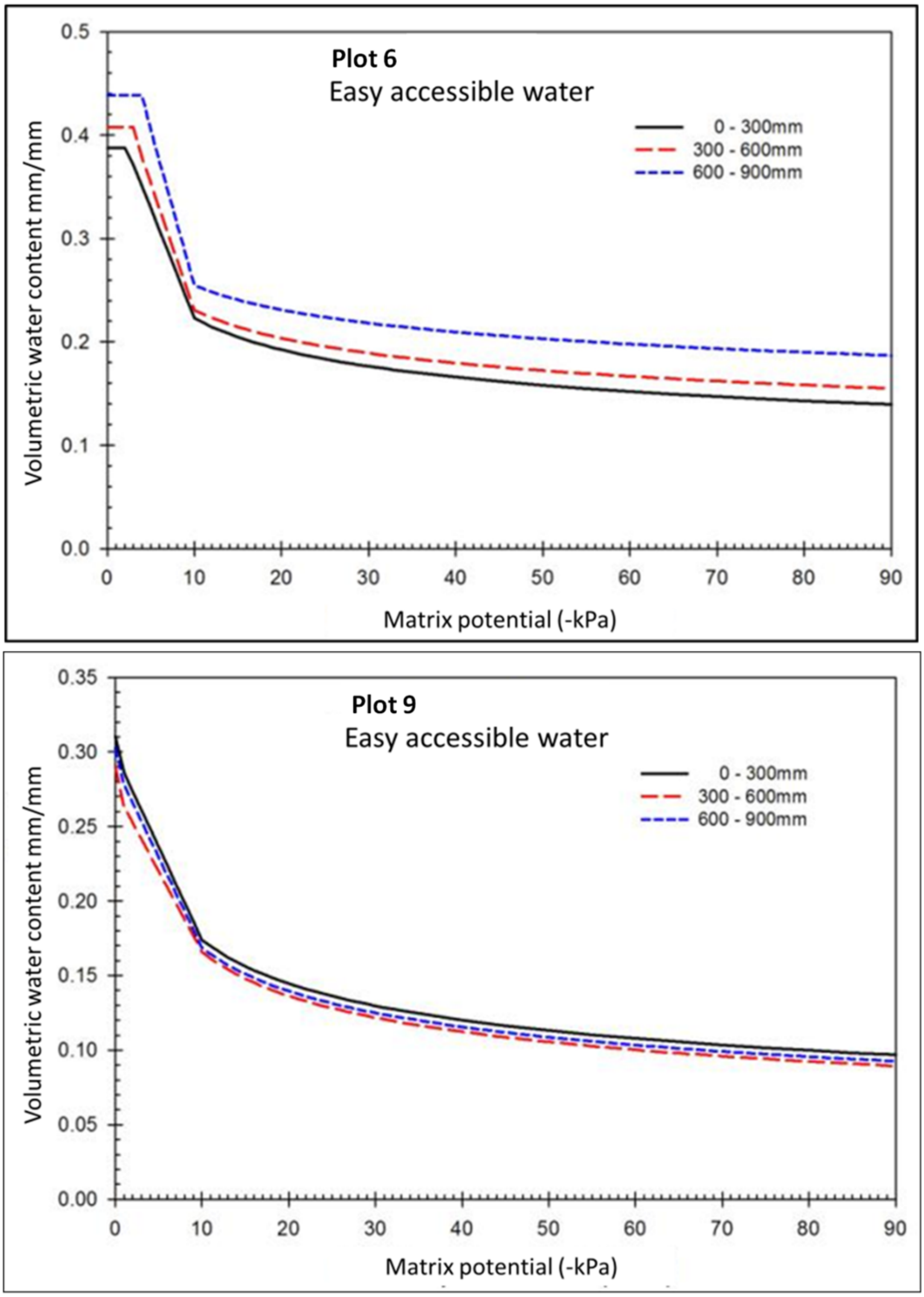

Figure 16 Estimated soil water retention curves for the two most extreme plots (6 and 9) in a Merlot vineyard, Stellenbosch.

3.3.3.2 Treatment effects

The 2007/8 season did not show differences with respect to percentage soil water extraction between irrigation treatments (Figure 17). The irrigation plots (5, 6, 7, 8, 9) showed less variability between plots than the rain-fed ones (1, 2, 3, 4), as was expected since irrigation was applied, possibly neutralising some natural occurring differences in soil water status. It seemed that rain-fed plots depleted less of the soil water content. No differences between irrigated and rain-fed plots were apparent for the 2008/9 season (Figure 18). It may be that the irrigated plots' water requirement exceeded the amount applied, and thus reached water extraction points similar to rain-fed plots.

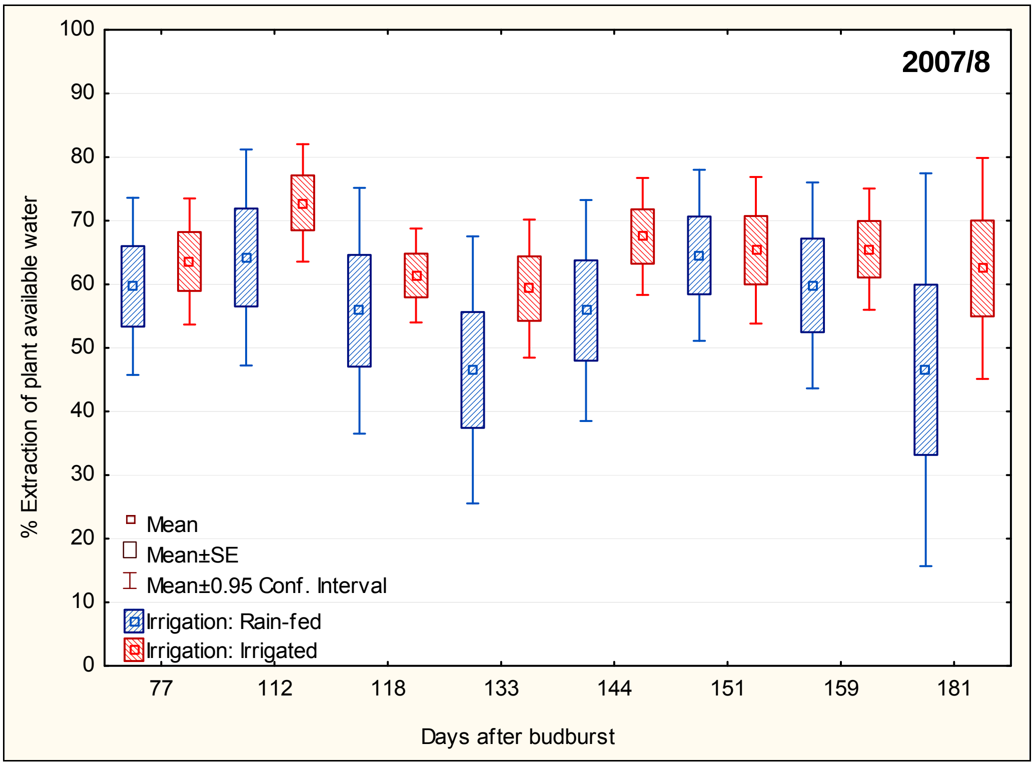

Figure 17 Percentage extraction of plant available water for the respective treatments for the 2007/8 season in a Merlot vineyard near Stellenbosch.

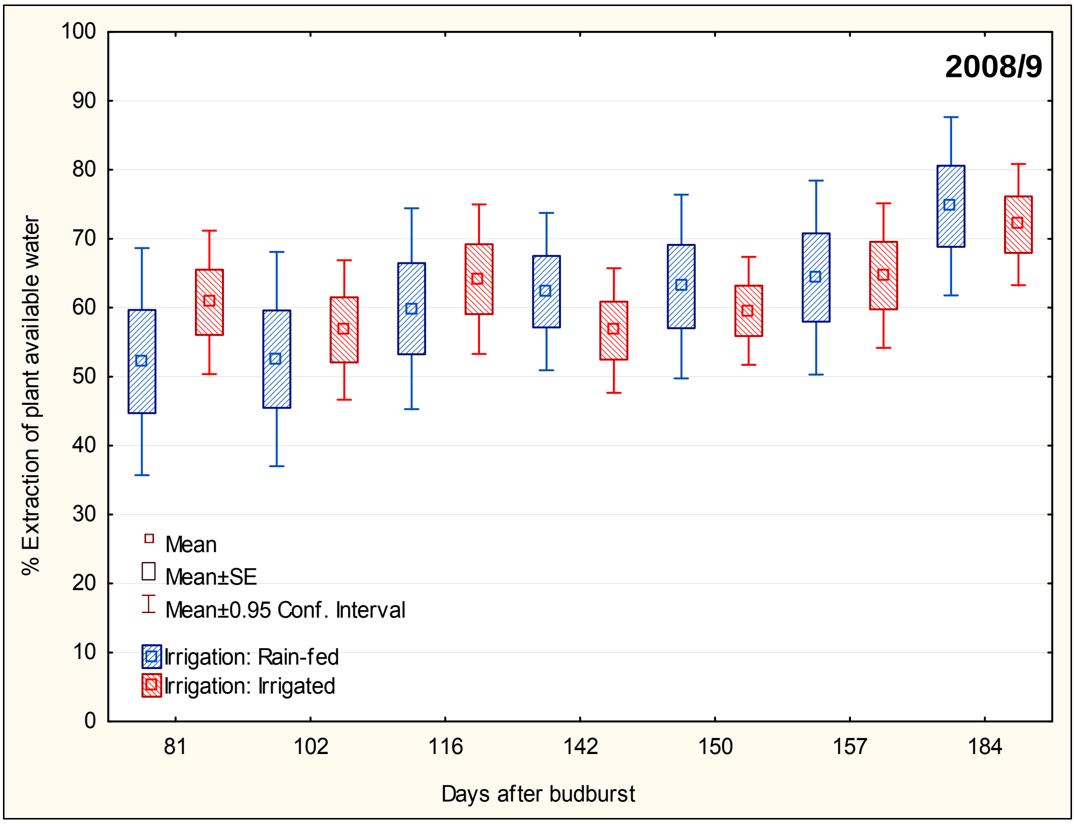

Figure 18 Percentage extraction of plant available water for the respective treatments for the 2008/9 season in a Merlot vineyard near Stellenbosch.

3.3.3.3 Observations at selected plots

Some of the plots with distinctive differing water holding capabilities (high clay content soil, 6; high sand content soil, 9; intermediate soil, 1) (see **Error! Reference source not found.**) were selected to illustrate seasonal change in plant water extraction. In the 2007/8 season plot 1 extracted a minimum percentage (maximum 30%) of plant available water (PAW) (Figure 19), showing some increases during the season, that may have been the effect of rain. Plot 9 showed a linear decrease in PAW during the season, converging with plot 6 at the end of measurement. PAW extraction remained constant after DAB 146 for plot 6, after showing a decline initially.

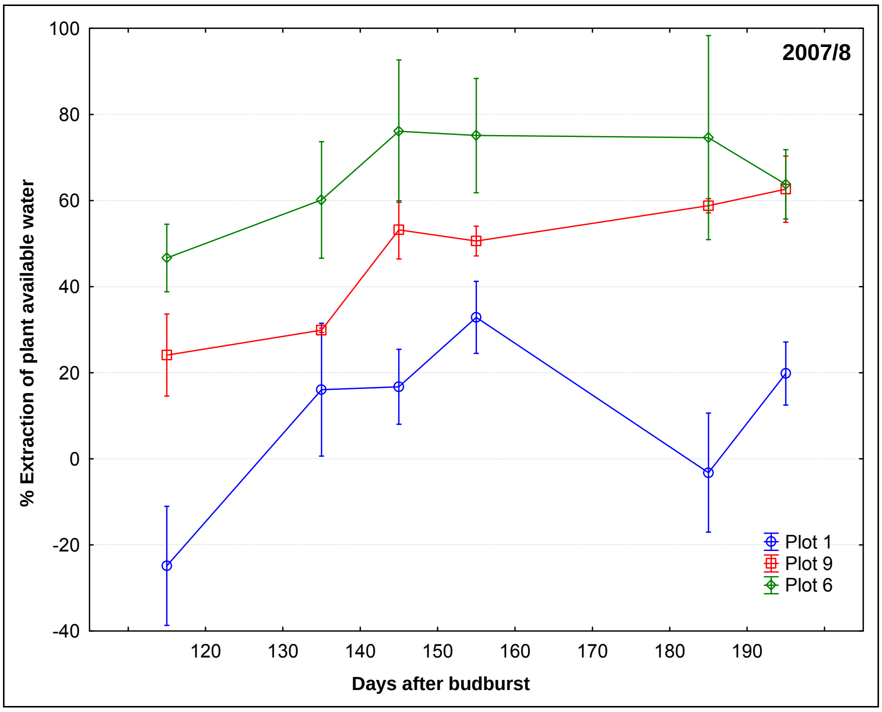

Figure 19 Percentage extraction of plant available water for the respective plots for the 2007/8 season in a Merlot vineyard near Stellenbosch. PAW dates correspond with PWS measurements. Vertical bars indicate standard errors over different depths.

In the 2008/9 season plot 1 showed a rapid decline in PAW during the season, converging with plot 9 at the end of the season (Figure 20). Plot 9 also showed a steady decline in PAW, although at a slower rate than plot 1. Plot 6 seemed to have the same level of PAW extraction as the previous year. The negative % extraction of PAW (plot 1) was probably due to the inaccurate estimation of PAW from soil textural analysis.

Considering that plot 6 has the highest water holding capacity, but also seemingly the highest extraction of soil water, corresponds with the theory that high vigour in this area would also lead to high extraction of soil available water. This stresses the importance of careful water management in high vigour scenarios such as that found in this plot. The consequence of the amount of water extraction for this plot in the drier season was also a lower vigour of the plot in this season compared to the other season.

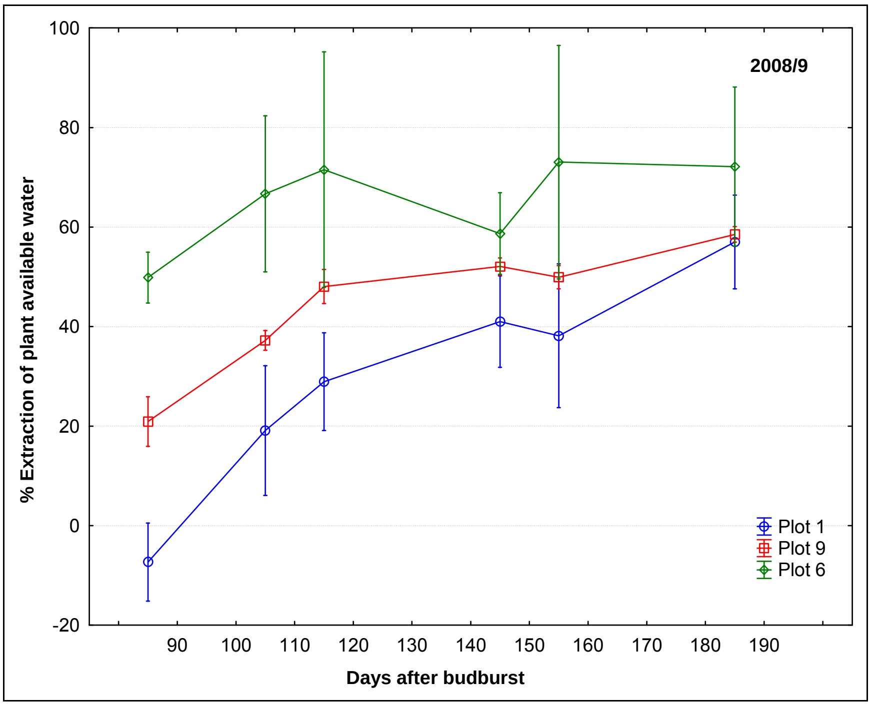

Figure 20 Percentage extraction of plant available water for the respective plots for the 2008/9 season in a Merlot vineyard near Stellenbosch. PAW dates correspond with PWS measurements. Vertical bars indicate standard errors over different depths.

3.3.4 Plant water status

3.3.4.1 Pre-dawn leaf water potential – treatment effects

The 2007/8 season was very mild (Section 3.3.1), as can be seen from pre-dawn leaf water potentials (Ψ_{PD}). During conditions of warmer weather (before 139 DAB), distinctions were apparent between rain-fed (1, 2, 3, 4) and irrigated (5, 6, 7, 8, 9) plots (Figure 21). The latter part of the season had higher incidences of rain, which probably negated the effects of irrigation.

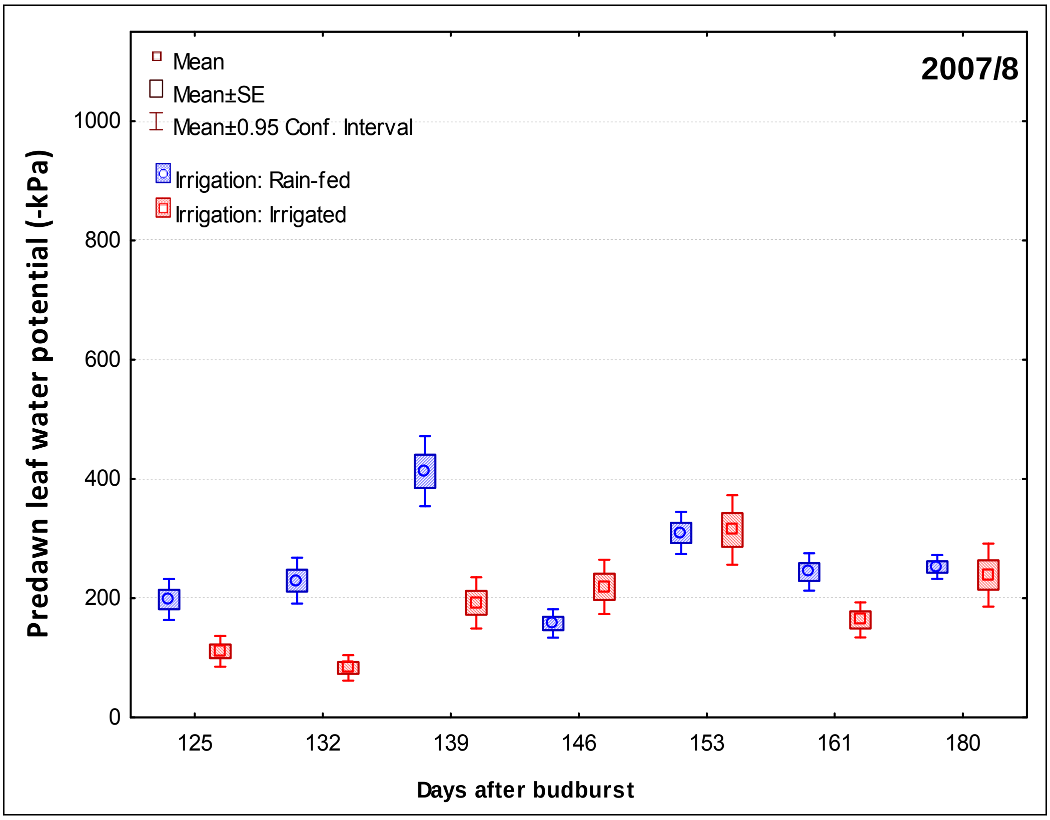

Figure 21 Pre-dawn leaf water potentials for the respective treatments for the 2007/8 season in a Merlot vineyard near Stellenbosch.

As opposed to the 2007/8 season, the first part of the 2008/9 season was cooler, and no differences between irrigation regimes could be found (Figure 22). As soon as the temperature increased (Section 3.3.1), differences appeared, although it did not seem to be as clear on all dates of measurement. The irrigated plots showed less variability between plots than the rain-fed ones with respect to plant water status. Irrigated plots also did not show the rise in predawn leaf water potential levels that was visible in the rain-fed plots.

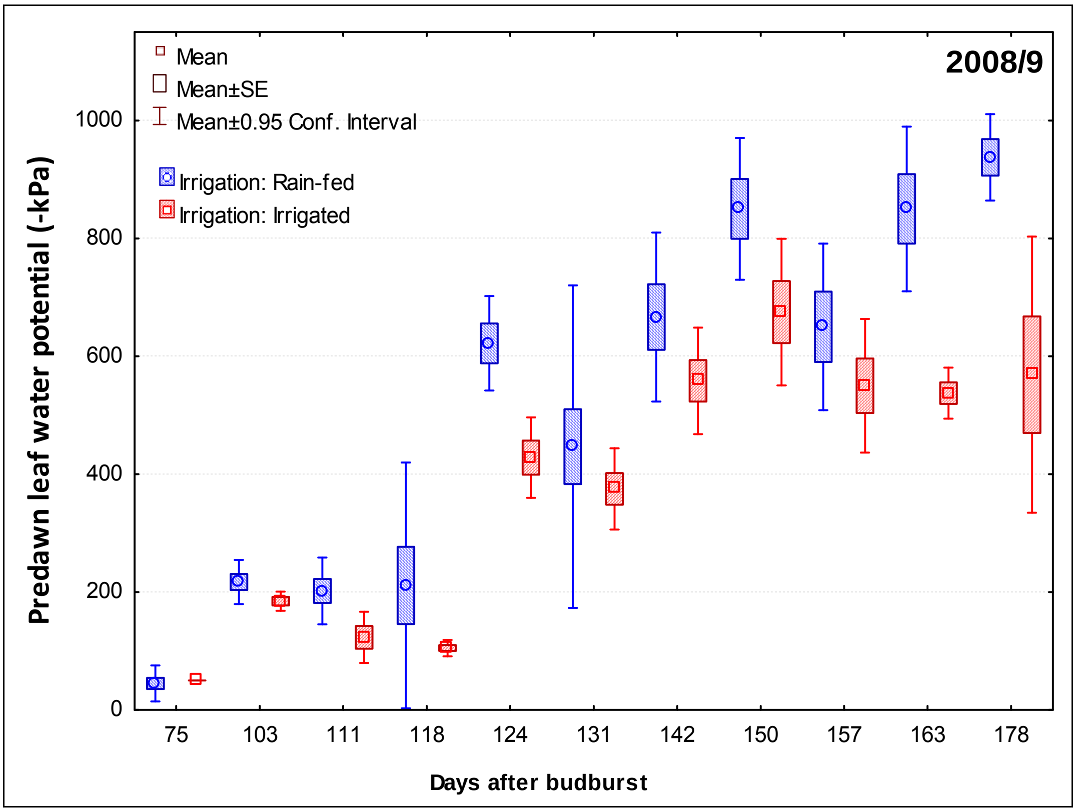

Figure 22 Pre-dawn leaf water potentials for the respective treatments for the 2008/9 season in a Merlot vineyard near Stellenbosch.

3.3.4.2 Pre-dawn leaf water potential – observations at specific plots

Season 2007/8 experienced no stress during the whole season, which makes drawing conclusions difficult. Only tendencies can be reported on. Some of the plots with distinctive differing water holding capabilities (clay soil, 6; sandy soil, 9; intermediate, 1) (see **Error! Reference source not found.**) were used. The season started with rain-fed plot 1 having a more negative PWS than irrigated plots 6 and 9. Plot 9 had a more negative PWS than plot 6 (Figure 23). It will seem that irrigated plots led to lower PWS levels in the grapevine. Soil heterogeneity also seems to have an effect of PWS, as the sandy plot 9 had more negative PWS than higher clay content plot 6. At 146 DAB it started to rain regularly in large quantities, and PWS varied little between plots.

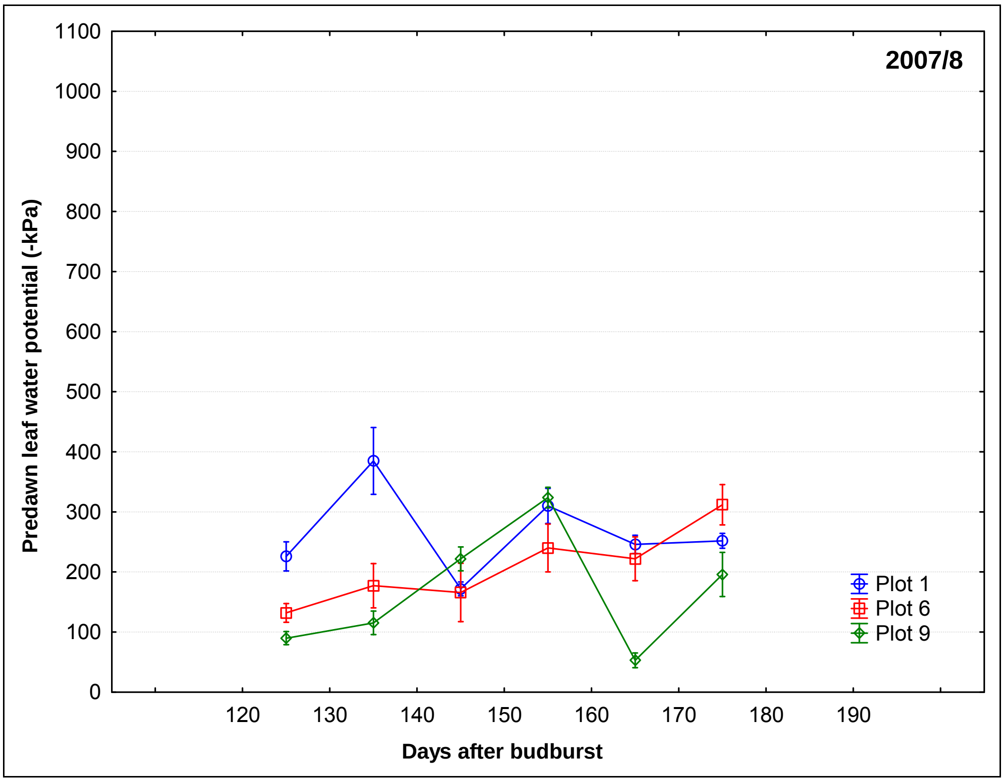

Figure 23 Pre-dawn leaf water potentials for the respective plots for the 2007/8 season in a Merlot vineyard near Stellenbosch. Vertical bars indicate standard errors.

The 2008/9 season experienced more stress than the 2007/8 season. In the 2008/9 season the plots behaved as expected, since as soil water was depleted, which lead to more negative PWS. Plot 1experienced the most negative PWS values, and plot 6 the least. It would seem that the soil water buffer capacity (based on water holding capacity and retention capabilities) of plot 6 helped to keep the PWS constantly lower during the last third of the season, with less of an effect seen in plot 9. The observed results stress the importance of irrigation to control the water status in high vigour conditions. Both irrigated plots (6, 9) received the same amount of water in the same intervals, which was stopped just before harvest. The last date in Figure 24 shows the divergence of PWS for the irrigated plots. For this study, grapevines in a sandy soil, used to a well-supplied source of water are unable to control PWS.

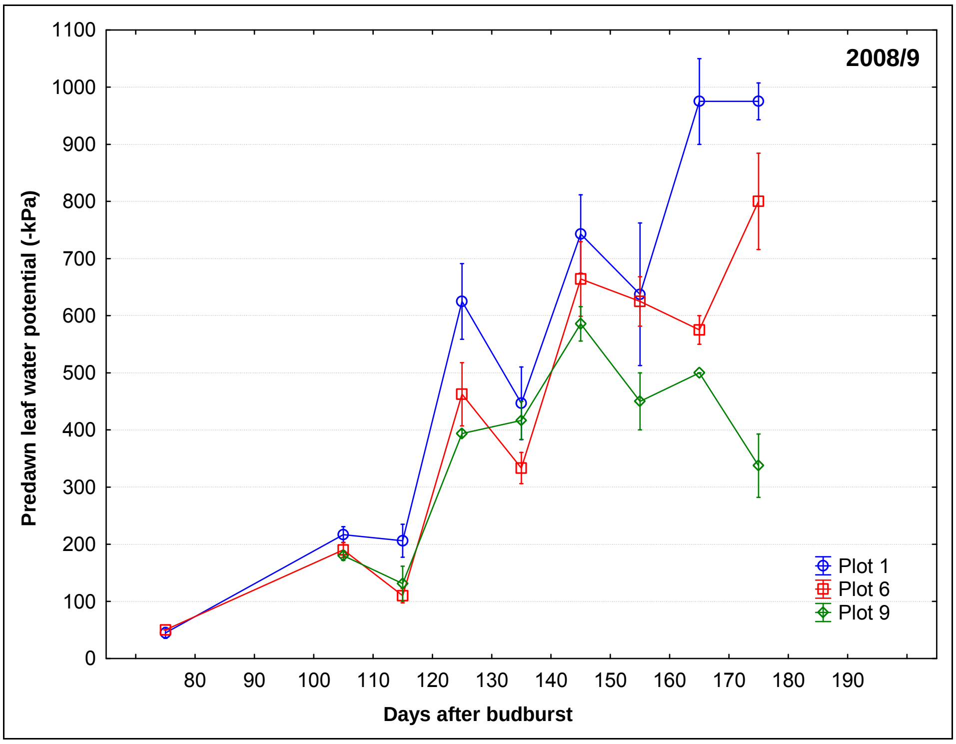

Figure 24 Pre-dawn leaf water potentials for the respective plots for the 2008/9 season in a Merlot vineyard near Stellenbosch. Vertical bars indicate standard errors.

3.3.5 Vegetative and reproductive responses to plant water status

3.3.5.1 Root effects

Irrigation probably influenced the root ratio in this study (Figure 25), but this is difficult to quantify due to a possible carryover effect of a previous study performed on the grapevines in the previous year shows the irrigation influence on the density of thin (a) and thick (b) roots. When the vines are cultivated under rain-fed conditions, fine root densities was higher compared to vines under irrigation (Figure 26). Results in this study were lower than root densities found in surrounding areas near Stellenbosch (Conradie *et al*., 2002). The rain-fed and irrigated treatments had a root ratio of 9.7 and 5.5 respectively. A good root system has a root ratio (fine roots : thick roots) of 3.5 and higher (Archer & Hunter, 2005).These results imply that both have a quality root system, but the rain-fed root system is better adapted in exploiting soil water and mineral reserves. Rain-fed vines need to utilise the soil volume to a higher degree, since soil utilisation is implied with a higher fine root component (Swanepoel & Southey, 1989). The irrigation treatments started in 2006/7, which may have had an effect on root development. When the vines are cultivated under rain-fed conditions, it is most likely that fine root densities would be higher compared to vines under irrigation. Dry *et al*. (2000) found that root densities increased with partial root zone drying when compared to treatments that received full irrigation. Grapevines also have the ability to translocate water from the wettest soil level to roots in drier areas (Sellin, 1999; Stoll *et al*. 2000). The results suggest that fine root development for water acquisition is a priority. The inverse is true for irrigated vines. Due to adequate water supply, thicker roots acquire priority for translocation of soil supplied water. That may be why root ratios and densities are higher under rain-fed conditions than irrigated vines. The root system plays a role in the link between SWS and PWS.

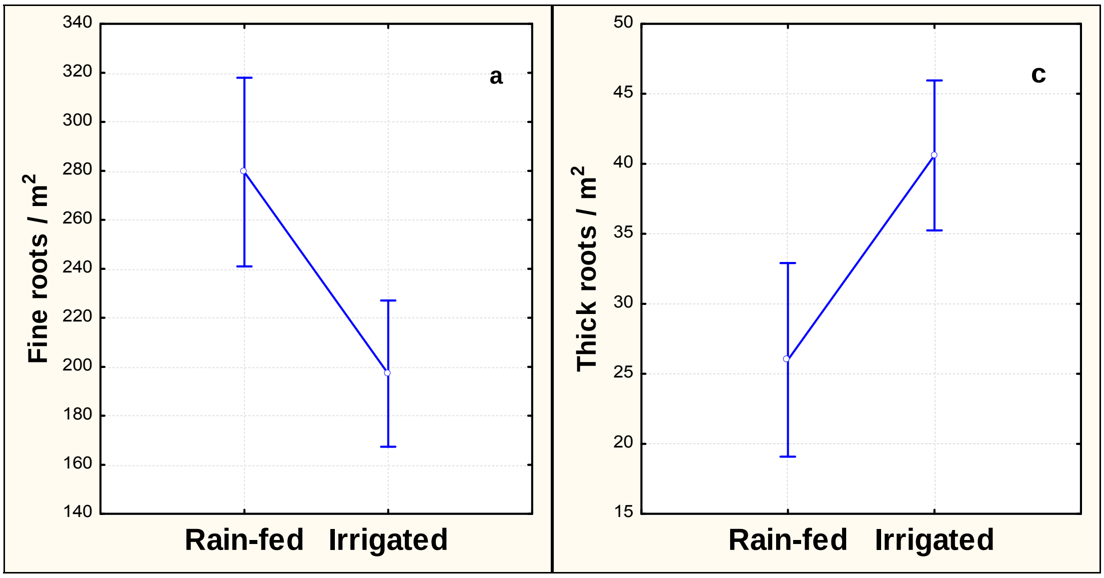

Figure 25 Density of (a) fine roots and (b) thick roots ($p \leq 0.01$) for rain-fed and irrigated plots for a Merlot vineyard, Stellenbosch. Spreads indicate 95% confidence intervals.

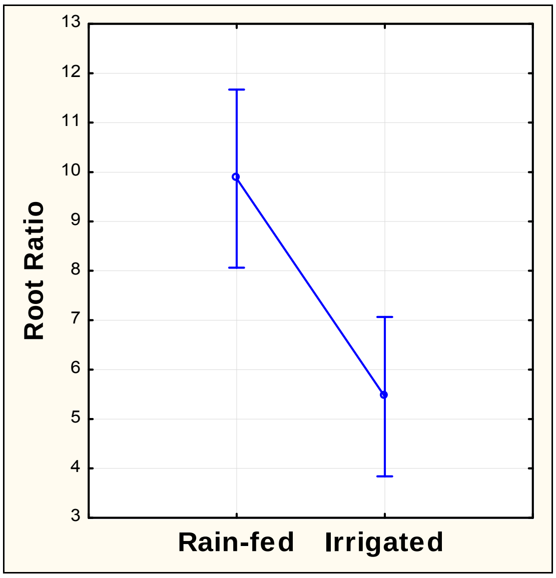

Figure 26 Root-ratio between irrigated and rain-fed treatments for a Merlot vineyard, Stellenbosch ($p<0.001$). Spreads indicate 95% confidence intervals.

Water is essential to the growth of plants. It carries nutrients in the soil to the roots. For most plants, the soil is the major source of water (Gregory, 2006a) when taken up through the root system. Above-ground growth of the grapevine is largely correlated to density, spatial distribution and efficiency of roots. The rooting pattern is an important factor determining the above-ground performance of the grapevine(Swanepoel & Southey, 1989).

The relationship in Figure 27 between pruning mass and total roots between 0-90 cm, show that there is a close correlation with root density for fine roots ($R = 0.86$; $r^2 = 0.75$; $p \leq 0.01$), but not for thick roots ($R = -0.41$; $r^2 = 0.16$; $p \geq 0.05$). The above-ground vigour increased with an increase in total roots, but the major contributor was the fine root component. Myburgh (2011b) found that a constant ratio developed between root density and pruning mass, but may differ between cultivars. In terms of pruning mass, there was no statistical difference ($p \geq 0.10$) between rain-fed and irrigation regimes. This correlation held regardless of irrigation treatment or soil variability, since the grapevine root system has an almost unlimited capacity to vary its own growth according to different growing conditions (Hunter & Le Roux, 1992). This is also an interesting result, considering that it was expected that a link would exist between the longer-term vigour potential and thicker roots. This may be due to the seasonal nature of pruning mass measurements, and measurement of, for instance, stem circumference may be more correlated to the amount of permanent roots in the grapevine.

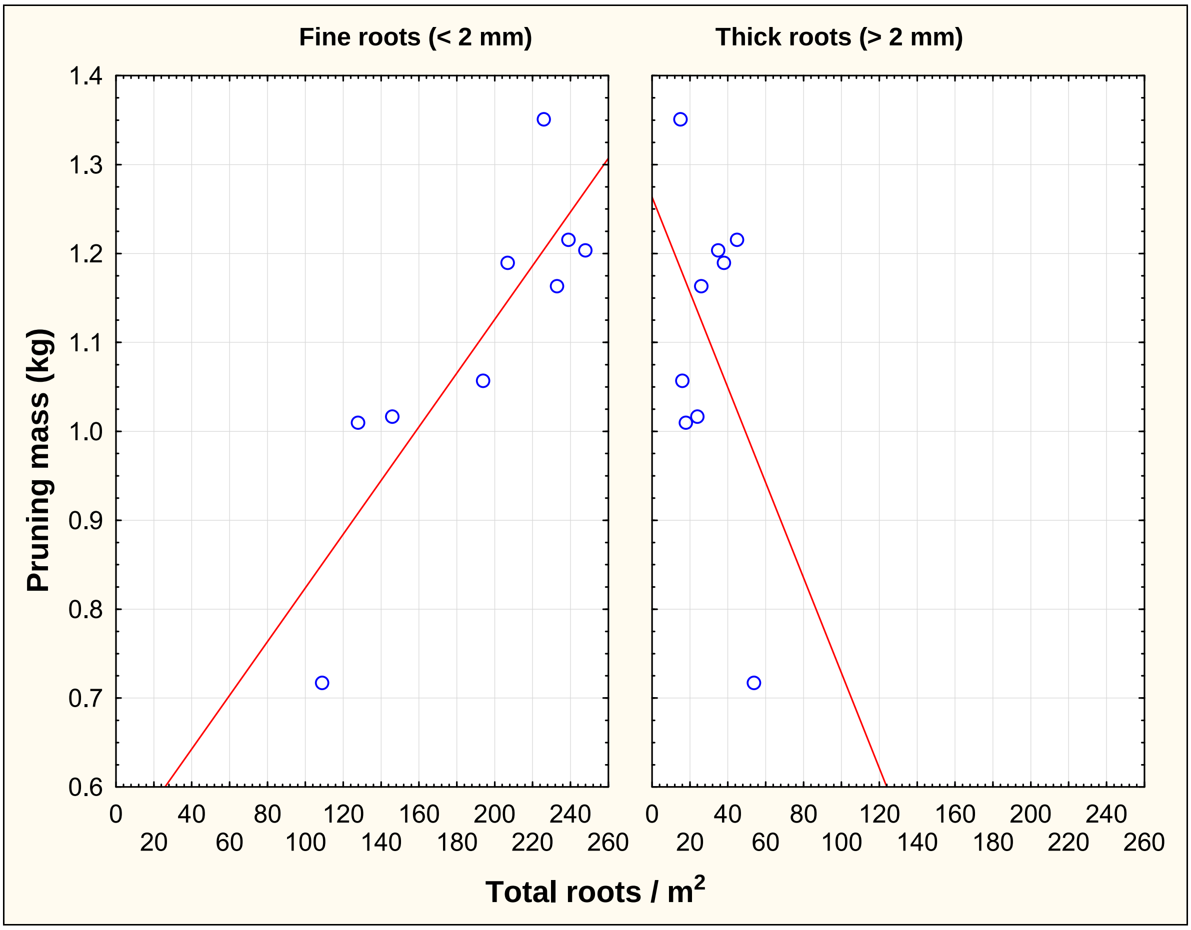

Figure 27 Relationships between total fine roots per m2 profile wall and pruning mass (kg) (R = 0.86, r2 = 0.75, p ≤ 0.01), as well as total thick roots per m2 profile wall and pruning mass (kg) (R = -0.41, r2 = 0.16, p ≥ 0.05).

3.3.5.2 Vegetative growth

3.3.5.2.1 Shoot growth

Shoot growth measurements progressed until topping occurred (58 DAB). In the 2007/8 season (Figure 28) shoot growth progressed at the same tempo between rain-fed and irrigated until the second last date of measurement, where the shoots in rain-fed plots seemed to display earlier reduction in shoot growth tempo. There was an interesting tendency in both seasons for rain-fed shoots to be longer than irrigated plots' shoots. This may be due to the inclusion of plot 9, with significantly lower vigour in both seasons, in the irrigated plot group. Vigour differences between plots had no significant effect on measured shoot length (data not shown).

In the 2008/9 season (Figure 29) shoot length was significantly longer for rain-fed plots, except initially. Vigour differences between plots had no significant effect on measured shoot length (data not shown).

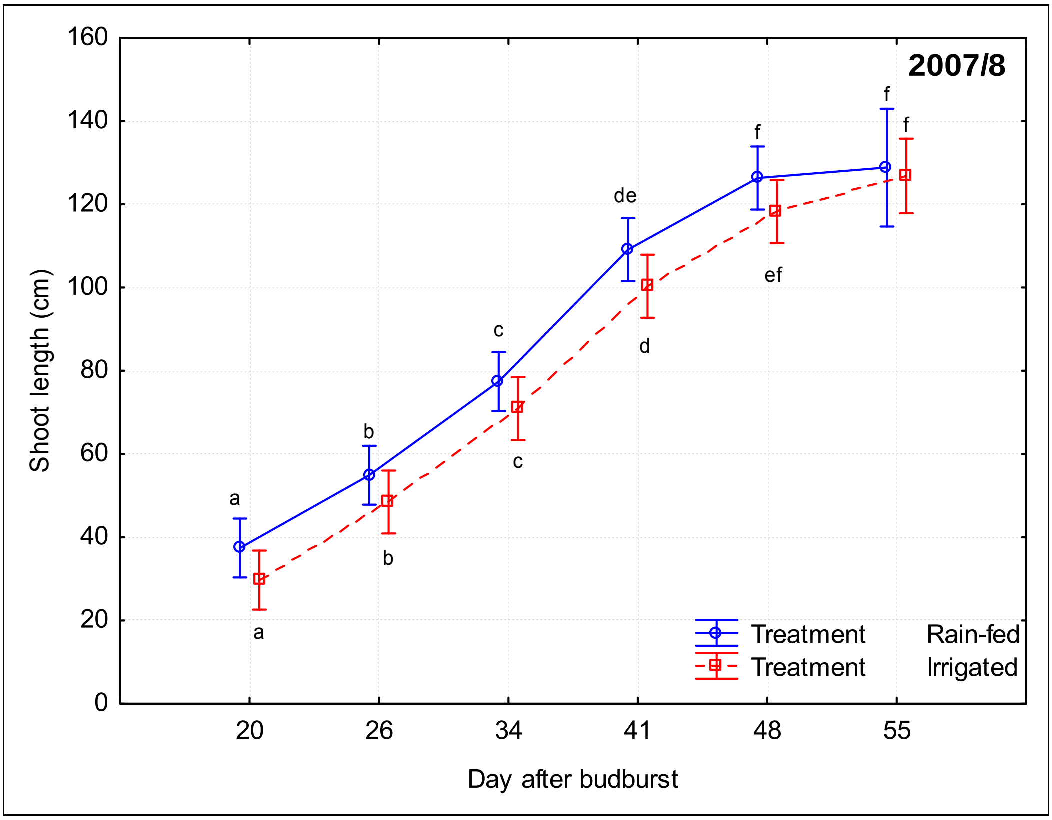

Figure 28 Shoot lengths (cm) for the respective treatments for the 2007/8 season in a Merlot vineyard near Stellenbosch (different letters indicate significant differences at the p ≤ 0.05 level, whiskers show 95% confidence intervals).

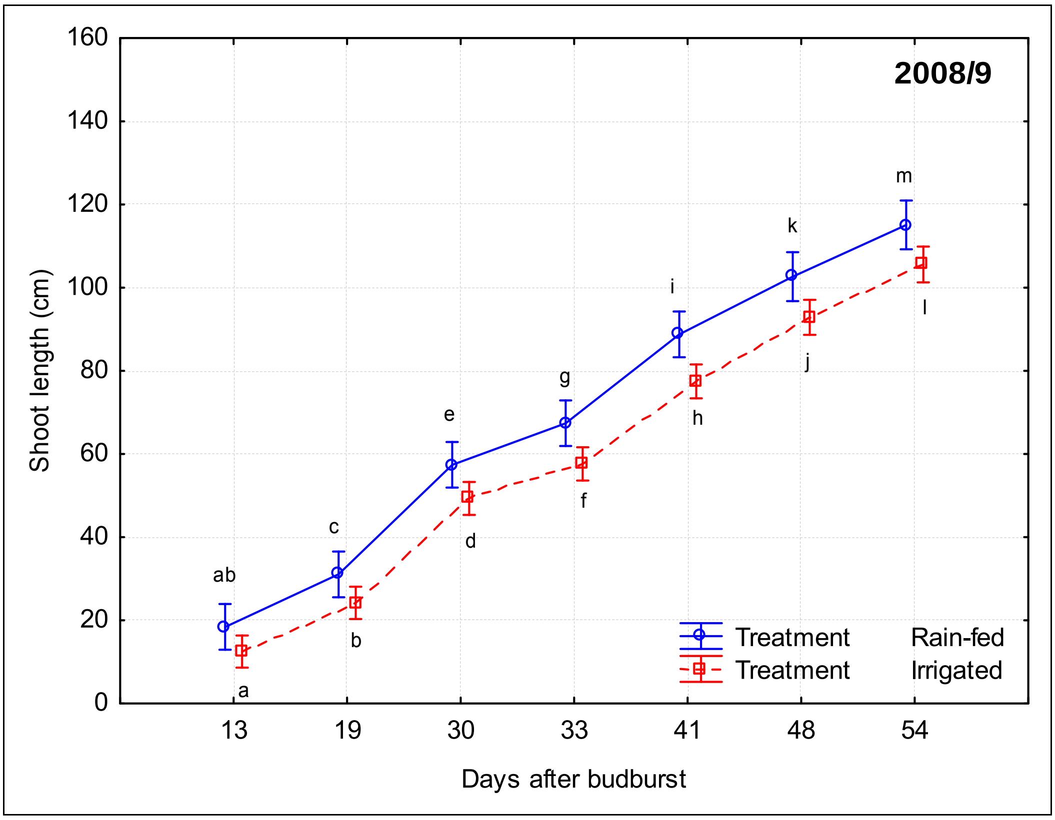

Figure 29 Shoot lengths (cm) for the respective treatments for the 2008/9 season in a Merlot vineyard near Stellenbosch (different letters indicate significant differences at the p ≤ 0.05 level, whiskers show 95% confidence intervals).

3.3.5.3 Pruning mass

Figure 30 shows differences in pruning mass between the plots, which in general corresponds to vigour differences as observed in Figure 4. Larger differences occurred between vigour levels for the 2007/8 season than the 2008/9 season (Figure 31), as well as lower overall pruning masses realising in the latter season. This may be attributed to the season characteristics discussed in the previous section (2008/9 being the drier season). It is interesting to note that during the wetter season, the lowest vigour plot (9) was the only consistent plot with regards to pruning mass. Irrigation did not seem to increase vigour in general, even though it was targeted at achieving relatively low water deficit levels in the irrigated plots.

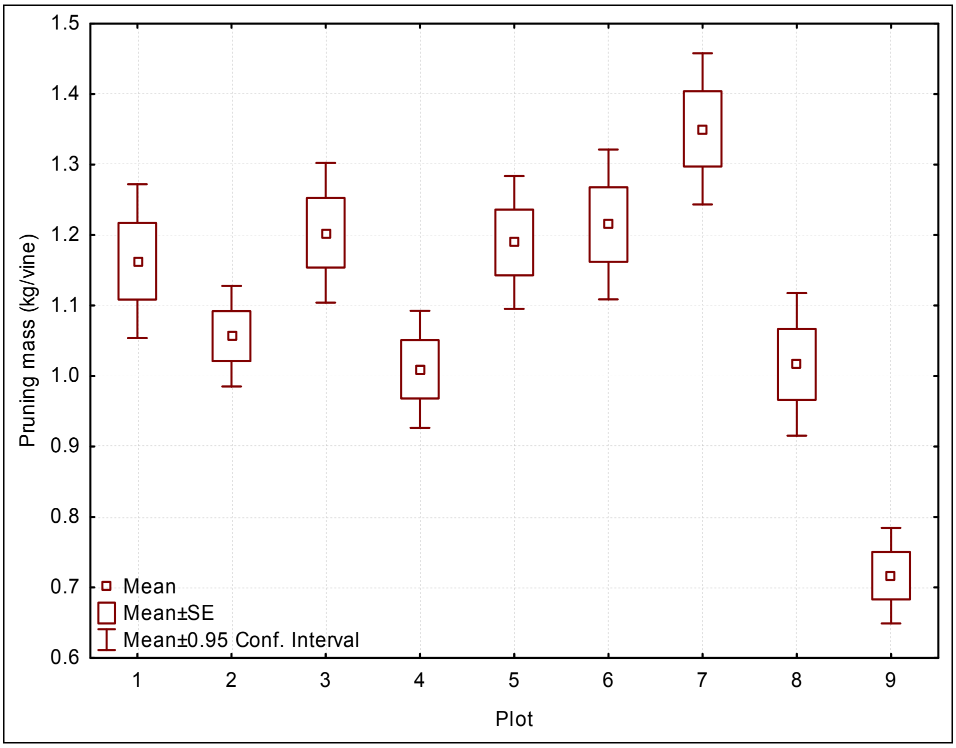

Figure 30 Pruning mass (kg/vine) for the respective plots for the 2007/8 season in a Merlot vineyard near Stellenbosch.

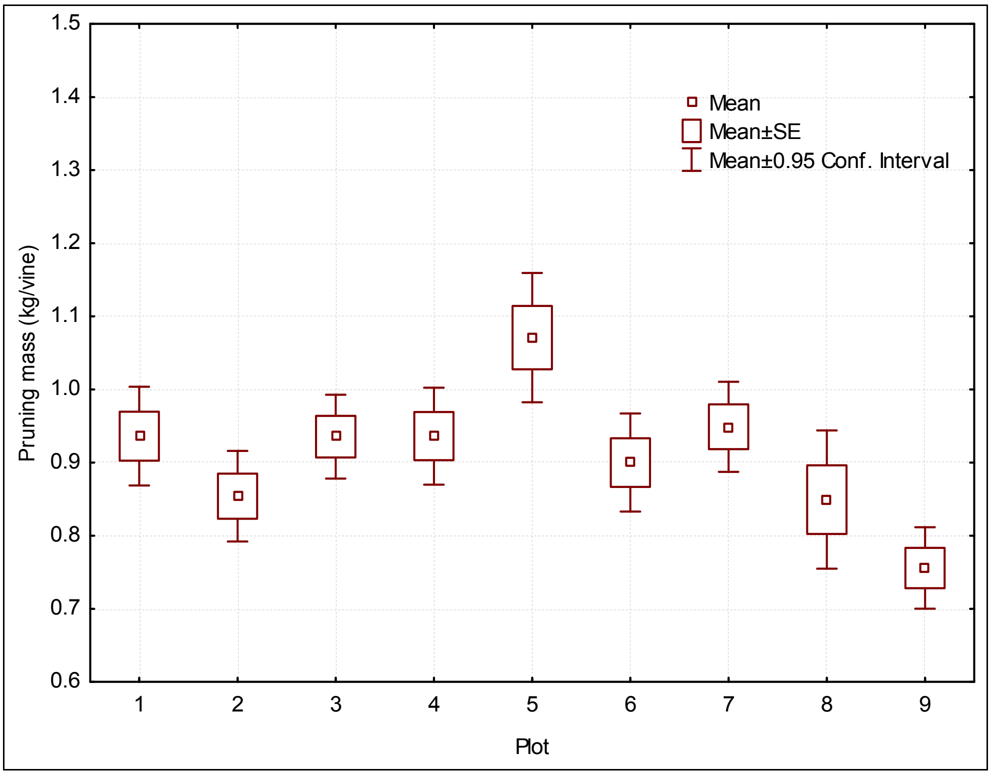

Figure 31 Pruning mass (kg/vine) for the respective plots for the 2008/9 season in a Merlot vineyard near Stellenbosch.

Both seasons showed a good correlation in pruning mass (Figure 32), with the exception of plot 5. Excluding plot 5 increase the fit to 70 % (y = 0.5687 + 0.2953*x; R = 0.8355, p = 0.01; r^2 = 0.70) In the warmer 2008/9 season plot 5 had a higher pruning mass. This can be ascribed to a greater degree of root distribution (Figure12 and Figure 13) due to excellent soil preparation. This enabled the grapevines in plot 5 greater buffer effects against the climate.

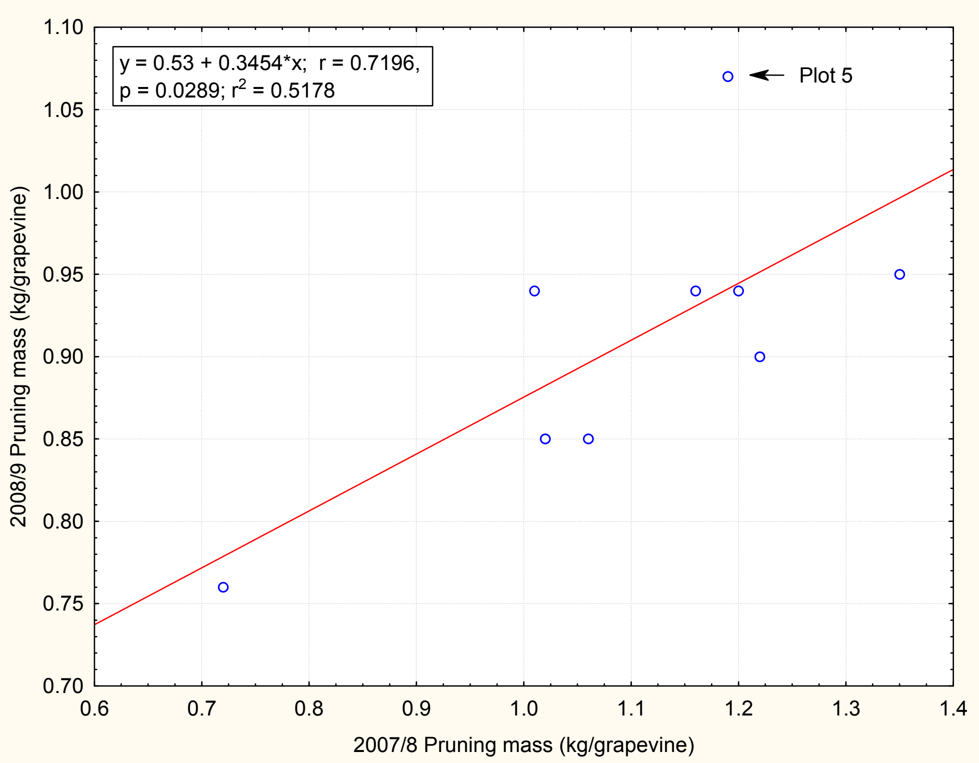

Figure 32 Relationship between pruning mass of Merlot/R110 measured in the 2007/8 and 2008/9 seasons, respectively, near Stellenbosch.

3.3.5.4 Grape ripening – treatment effects

Berry mass and volume were highly correlated ($R^2 = 0.96$; $p \leq 0.001$) (data not shown). In the beginning of the 2008/9 season (Figure 33) berry volume was higher for rain-fed plots. Rain-fed berry volumes reached a plateau quicker, and then lost volume as Ψ_{PD} became more negative. The volumes of irrigated berries stayed relatively constant, only converging at the end of the season with the berry volume of the rain-fed plots.

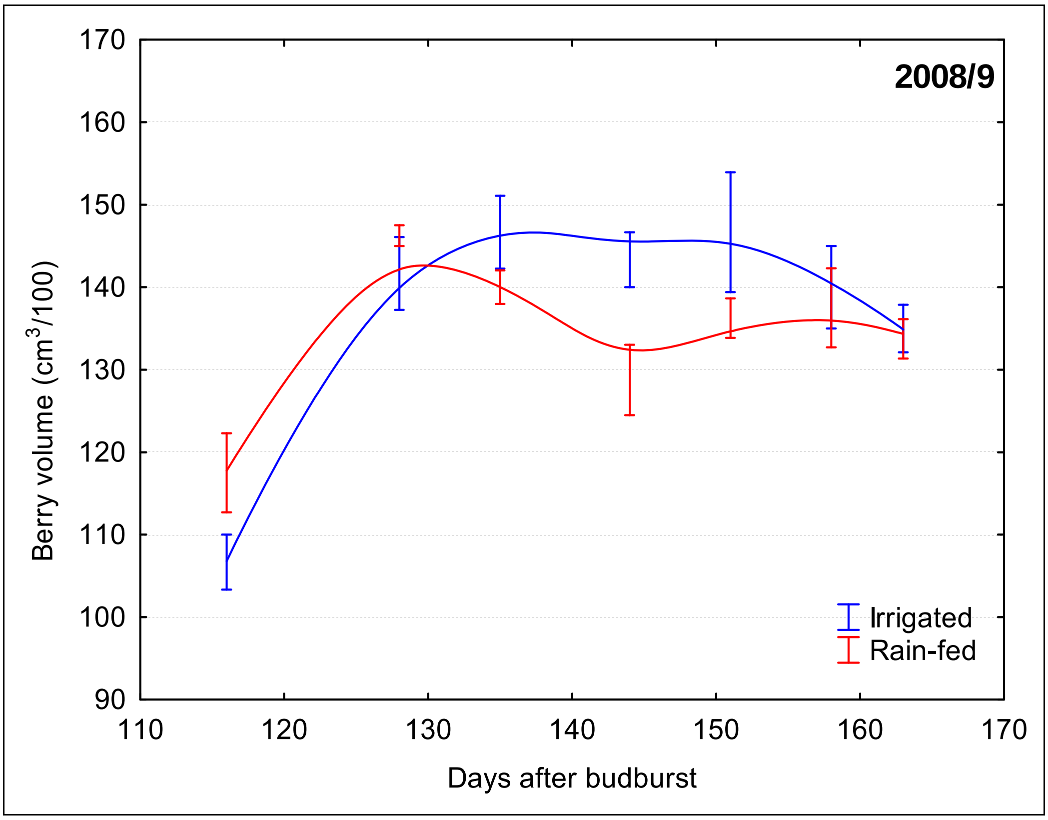

Figure 33 Berry volume for the respective treatments for the 2008/9 season in a Merlot vineyard near Stellenbosch. Whiskers show 95% confidence intervals.

In the 2008/9 season rain-fed plots showed almost constantly higher total soluble solids (°B) (Figure 34). This suggests that sugar loading may have commenced earlier in these plots.

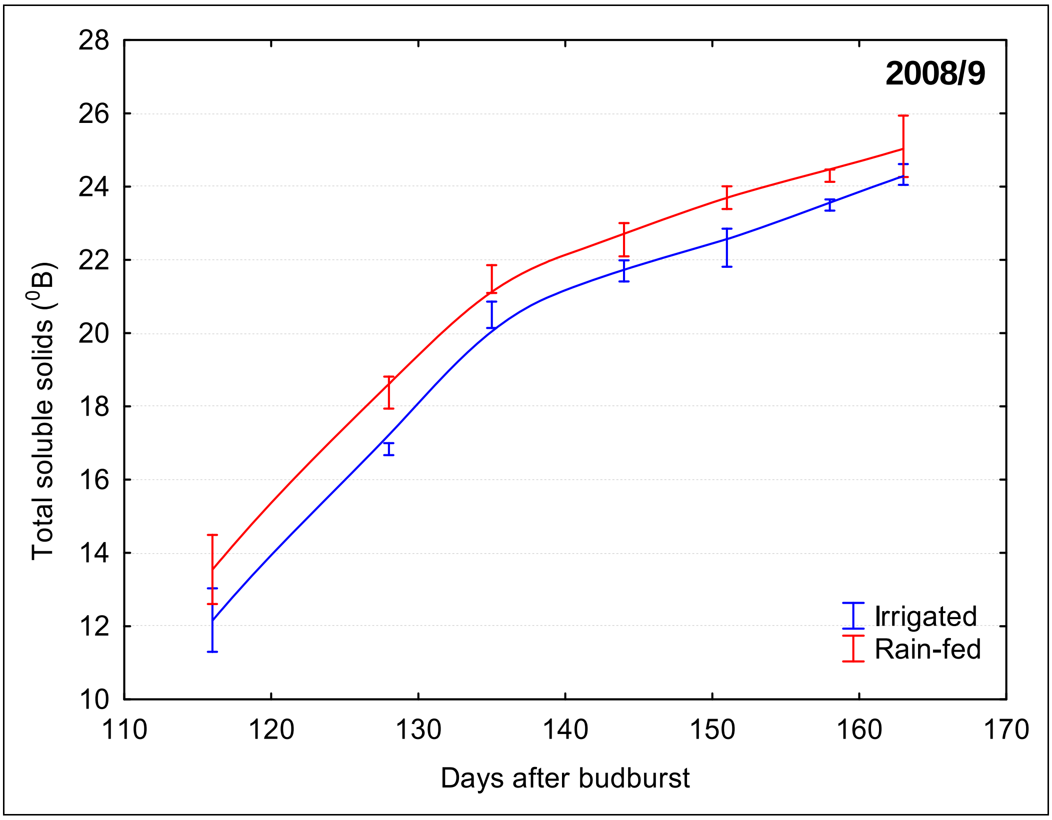

Figure 34 Total soluble solids for the respective treatments for the 2008/9 season in a Merlot vineyard near Stellenbosch. Whiskers show 95% confidence intervals.

Titratable acidity (g/l) seemed to show earlier degradation for rain-fed plots compared to irrigated plots in the 2008/9 season, with the difference diminishing at the end of ripening (Figure 35). This may be due to the observation that rain-fed plots were more advanced with regards to maturation, and this was also linked to earlier and more pronounced volume decreases after berry volume stabilised.

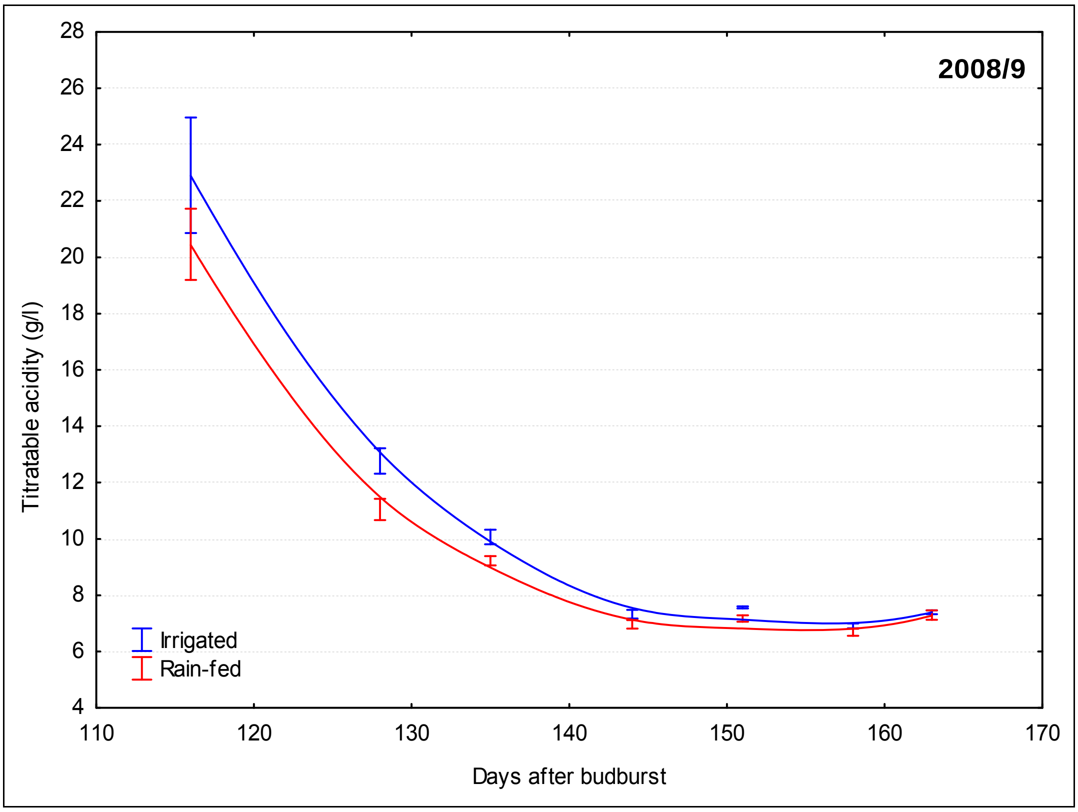

Figure 35 Titratable acidity for the respective treatments for the 2008/9 season in a Merlot vineyard near Stellenbosch. Whiskers show 95% confidence intervals.

In the 2008/9 season pH increased with the progression of berry maturation (Figure 36). The spike in the pH of rain-fed treatments' berries corresponds to a berry volume decrease, but apparently not a titratable acidity reduction. The tendency of the pH to "recover" afterwards is inexplicable.

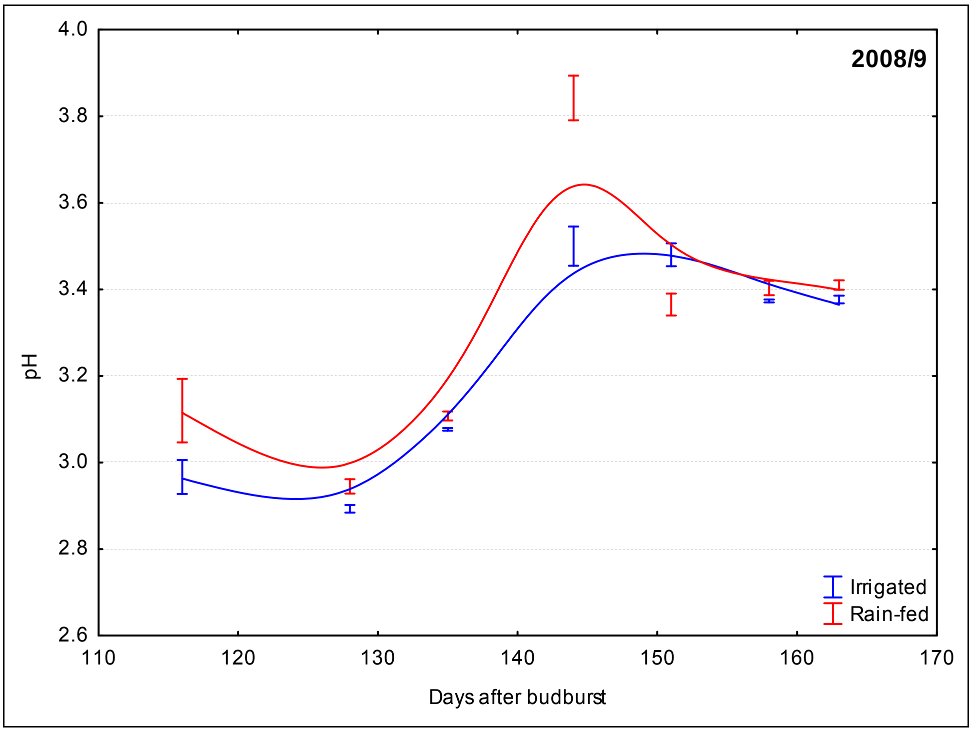

Figure 36 Juice pH for the respective treatments for the 2008/9 season in a Merlot vineyard near Stellenbosch. Whiskers show 95% confidence intervals.

In the 2008/9 season it seems like sugar loading commenced at an earlier stage for berries of rain-fed plots, showing a reduction after 130 DAB (linked to more negative Ψ_{PD}, as well as a decrease in berry volume), but recovering after about 144 DAB to about the same levels as the irrigated plots (Figure 37).

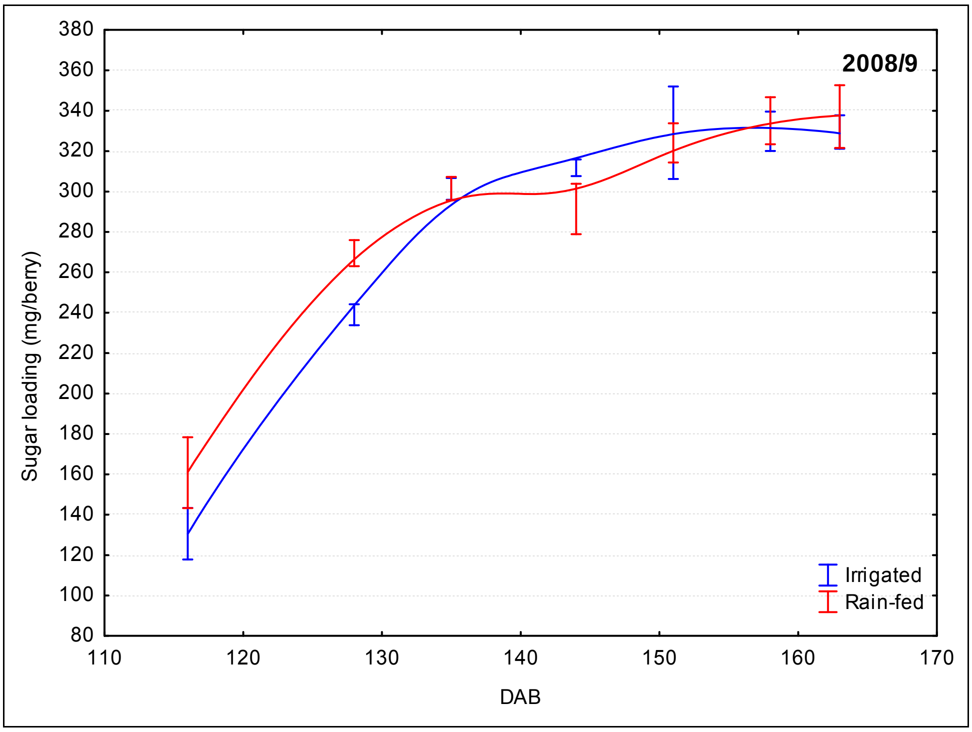

Figure 37 Sugar loading (mg/berry) for the respective treatments for the 2008/9 season in a Merlot vineyard near Stellenbosch. Whiskers show 95% confidence intervals.

3.3.5.5 Grape ripening – observations at specific plots

Plot 1 berry development initially seemed faster and more advanced (at DAB 116) than plot 6 and 9 (Figure 38), with 6 showing extreme fast volume increase until 135 DAB, probably due to high vigour. Plots 1 and 6 showed a decrease in volume from about the same time. This seemed to be independent of Ψ_{PD}. Plot 9 did not reduce in volume. The two decreases in berry volume for plot 1 seemed to correspond with two events where Ψ_{PD} became more negative.

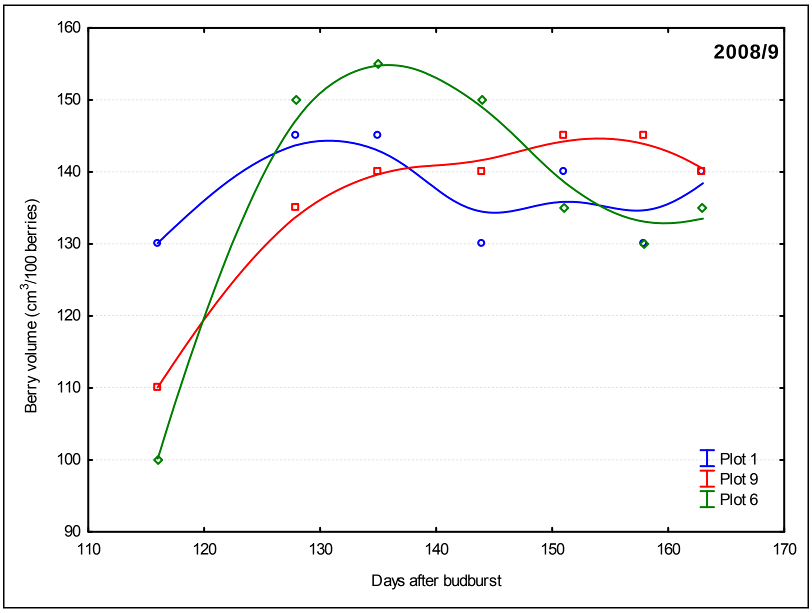

Figure 38 Berry volume for plots 1, 6 and 9 for the 2008/9 season in a Merlot vineyard near Stellenbosch.

Plot 2 total soluble solids (TSS) accumulation was at a more advanced level initially, and proceeded almost linear through the season (Figure 39), while the other two plots' TSS seemed to increase less after 135 DAB. Short term plant water status fluctuations seemed to have a less marked effect on TSS content, but decreases in berry volume at the end of ripening for 2 and A9 led to TSS concentration.

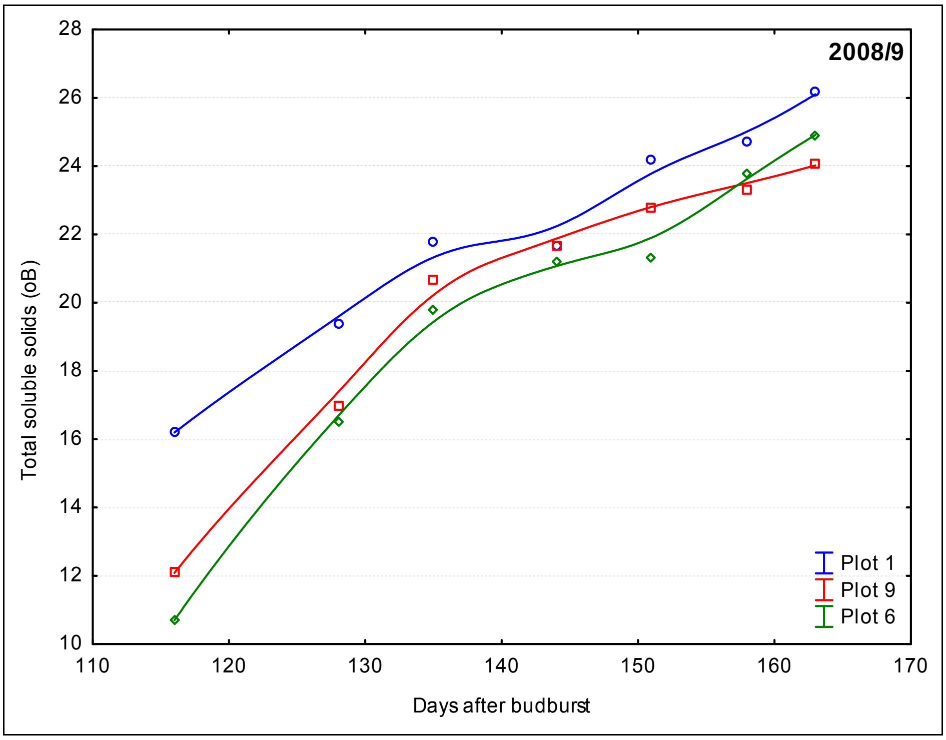

Figure 39 Total soluble solids for plots1, 6 and 9 for the 2008/9 season in a Merlot vineyard near Stellenbosch.

Plot 1 titratable acidity was initially at a lower concentration than plot 9, with plot 6 having the highest (Figure 40), with all plots showing convergence as the season progressed. This suggests that plot 1's berry maturation was more advanced, followed by 9 and 6.

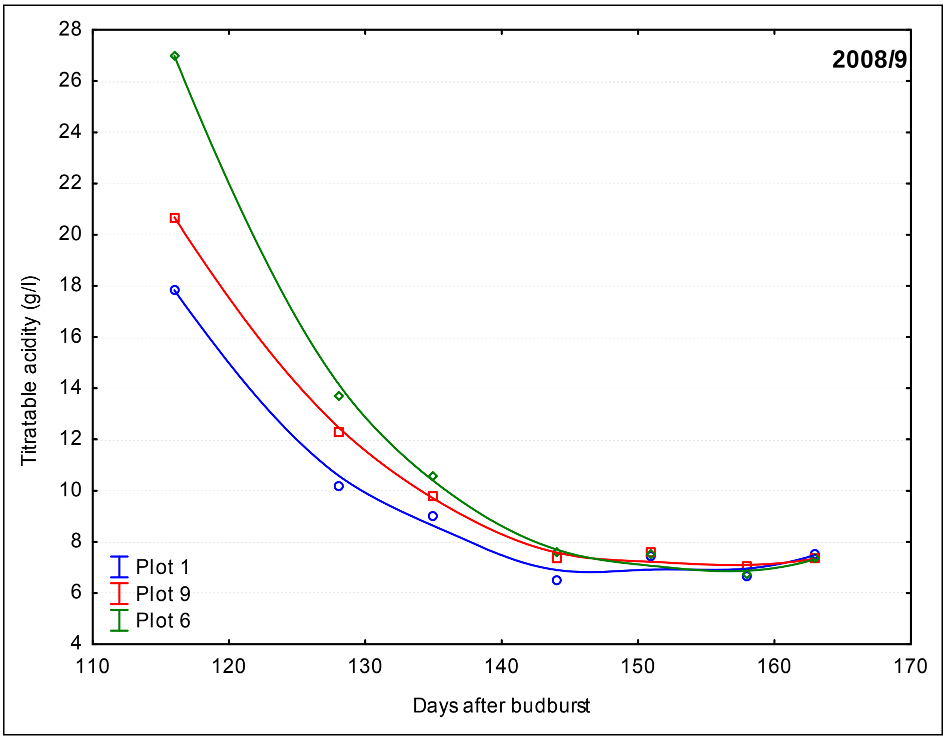

Figure 40 Titratable acidity for plots 1, 6 and 9 for the 2008/9 season in a Merlot vineyard near Stellenbosch.

Plot 1 sugar loading was initially more advanced than the other two plots. As the season progressed, plot 1 sugar loading were at a reduced rate than plot 6 and plot 9 (Figure 41). Although 6 started at a lower level, the tempo of sugar loading soon exceeded plot 9. At the end of ripening, plots 1 and 6 seemed to load sugar, with 9 staying stable, irrespective of more negative Ψ_{PD} in 1 and 9 at that stage.

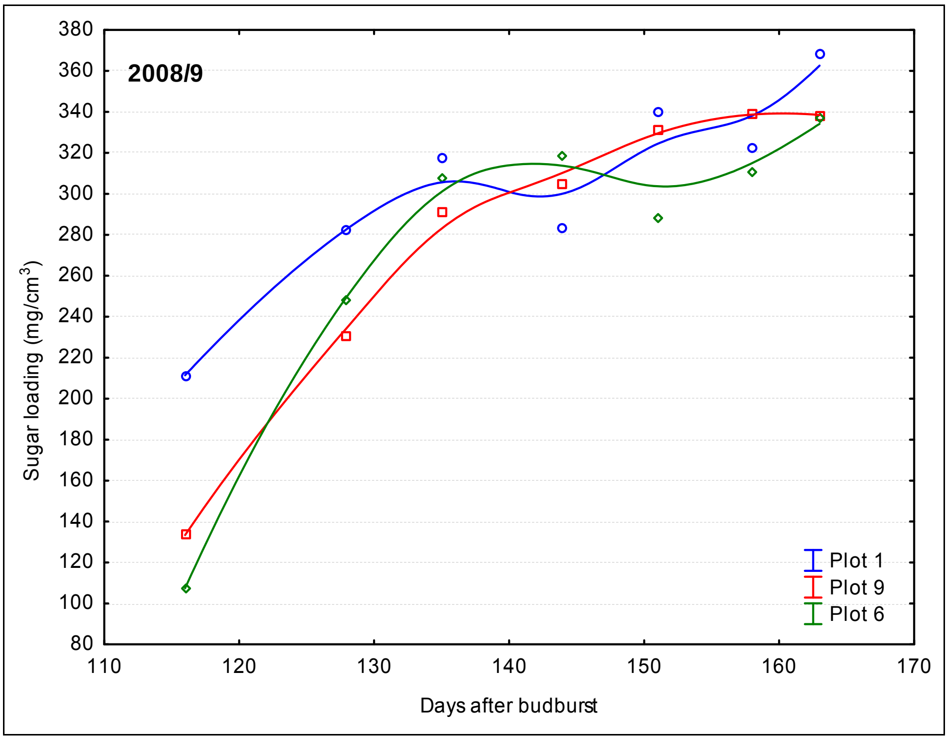

Figure 41 Sugar loading for plots 1, 6 and 9 for the 2008/9 season in a Merlot vineyard near Stellenbosch.

3.3.5.6 Bunch mass and yield

In the 2007/8 season the mean bunch and cane mass was higher for the rain-fed plots ($p < 0.05$) (Table 8). No statistical differences (according to a Student's T-test) could be found for any other parameter, or for any in the 2008/9 season.

Table 8 Means, standard deviation (SD) and Coefficient of variability (CV %) of reproductive and vegetative parameters for 2007/8 and 2008/9 for a Merlot vineyard near Stellenbosch.

	2007/8							
	Rain-fed			Irrigated				
Parameter	Mean	SD	CV %	Mean	SD	CV %	F	p-value
Shoots per vine	18.08	2.90	16.04	18.83	3.70	19.66	1.20	0.28
Water shoots per vine	2.68	1.46	54.46	3.60	1.95	54.19	5.97	0.02
Pruning mass (kg)	1.10	0.30	26.99	0.97	0.41	42.44	2.82	0.10
Mean cane mass (g)	61.38	16.47	26.83	52.54	21.66	41.23	5.02	0.03
Number of bunches per vine	23.21	6.54	28.16	24.60	6.77	27.52	1.03	0.31
Yield (ton/ha)	8.00	1.12	34.03	7.78	1.34	41.75	0.12	0.73
Mean Bunch mass (g)	141.10	28.48	20.19	127.39	29.04	22.80	5.40	0.02
Yield / Growth Ratio	3.20	1.22	37.99	3.60	1.62	44.98	1.86	0.18
Fertility	1.47	0.36	24.31	1.60	0.38	23.92	2.61	0.11
	2008/9							
	Rain-fed			Irrigated				
	Mean	SD	CV %	Mean	SD	CV %	F	p-value
Shoots per vine	16.41	3.63	22.12	15.79	3.06	19.41	0.78	0.38
Water shoots per vine	1.57	0.60	38.03	1.33	0.50	37.50	1.09	0.30
Pruning mass (kg)	0.91	0.22	24.37	0.88	0.22	24.52	0.35	0.56
Mean cane mass (g)	56.52	14.00	24.77	56.67	13.82	24.39	0.00	0.96
Number of bunches per vine	25.18	7.77	30.87	26.49	6.40	24.16	0.77	0.38
Yield (ton/ha)	8.00	1.24	37.20	8.80	1.12	30.89	1.52	0.22
Mean Bunch mass (g)	131.66	27.19	20.65	136.96	28.15	20.55	0.83	0.36
Yield / Growth Ratio	3.75	1.43	38.20	4.26	1.34	31.49	3.08	0.08
Fertility	1.61	0.37	23.26	1.71	0.27	15.51	2.32	0.13

3.3.6 Linking soil- and plant water status

Theoretically it would be possible for a direct correlation to exist between soil water content and plant water status. In some ways, the grapevine can be seen to act in the same way as a tensiometer. Like the tensiometer, the grapevine equilibrates with the soil water, dictated by the wettest soil layer, when only the osmotic component of water tension is in effect (Sellin, 1999).

In Figure 42, the whole profile (sum of all depths) soil water content was used to establish a link between SWS and PWS. This link was determined over time using nine plots, consisting of rain-fed and irrigated regimes. This was done specifically to incorporate all vigour and soil differences. A non-linear relationship was found between Ψ_{PD} and percentage extraction of PAW for rain-fed plots. As the amount of PAW in the soil profile diminished, Ψ_{PD} values became more negative, following a non-linear relationship (Figure 42). This corresponded with the trends of water retention curves (Lal & Shuckla, 2004), supporting the idea that the plant acts as a tensiometer. Similar non-linear equations was found for Merlot (Myburgh, 2011a) and Shiraz

(Pellegrino *et al.*, 2004). This correlation only held under rain-fed conditions, which was also the case in the study of Pellegrino *et al*. (2004). When irrigation was applied, no correlation could be found. This was to be expected, since the grapevines were irrigated to remain at constantly low Ψ_{PD} values. The Ψ_{PD} values fluctuated heavily, whether there was water in the soil profile or not. When irrigation is applied luxuriously (PWS was manipulated to remain constant), the grapevine seems to reduce its water use efficiency (Cifre *et al.*, 2005), and thus do not regulate its water use and therefore the water balance in the grapevine becomes disturbed, and no direct relation could be found between SWS and PWS.

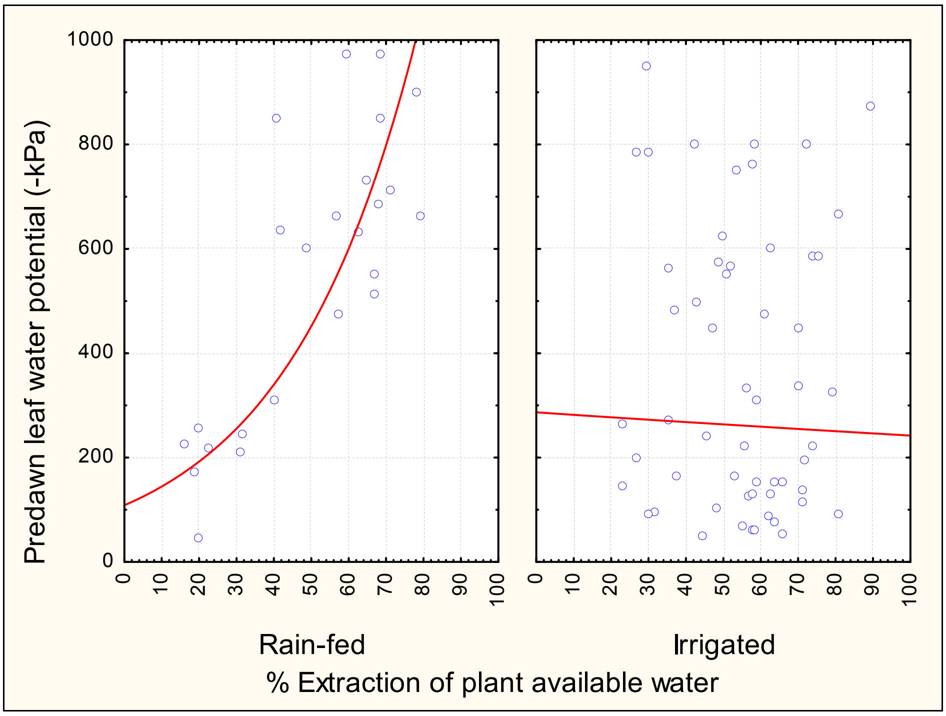

Figure 42 Relationship between pre-dawn leaf water potential and the % extraction of plant available water for the rain-fed (R = 0.81; $r^2 = 0.66$; $p \leq 0.001$) and irrigated (R = -0.03; $r^2 = 0$; $p \geq 0.05$) plots for both seasons

3.4 Conclusions

Vigour variability occurring at vineyard block level was readily identified through multispectral NDVI imaging. These variable vigour areas correspond to soil heterogeneous areas existing in the vineyard (Conradie *et al*., 2002). The highest vigour areas were associated with soils with high clay content and the lowest vigour with a soil with the highest sand content. Clay was the predominant contributing factor, which plays a large role in water distribution and acquisition in the soil profile (Rawls *et al.*, 1982; Saxton *et al.*, 1986; Reichert *et al.*, 2010). It provides a larger water and nutrient buffer capacity for the grapevines' growth (Foth, 1990). This is fairly apparent when the low (high sand content) and high (high clay content) vigour areas are compared to each other with regards to plant water status and the resulting vigour.

Irrigation did not seem to increase vigour in general, even though it was targeted at achieving relatively low water deficit levels in the irrigated plots.

There was a high variability in the inherent soil characteristics between vigour areas. Thus it is probable that the SWS of these vigour areas cannot be same, and therefore requires individual measurement. Not every option is viable to monitor the water status of either the soil or the plant. The neutron moisture probe has so far shown to be the quickest and easiest method available. Unfortunately it only measures the soil water, and cannot be automated (Jones, 2004). It also requires calibration (Dane & Topp, 2002). It is possible to use a general calibration for entire vineyard blocks with moderate accuracy ($R = 0.9$, $r^2 = 0.81$, $p \leq 0.001$). However, where quality grape production is the aim, more in-depth monitoring is necessary, since this generalised calibration can lead to over or under irrigation. By expanding the measuring depths and locations with individual calibration curves, the calibration fits was vastly enhanced. With the calibration, in conjunction with VWC, PPWP and retention curves, it is then possible to implement irrigation scheduling according to soil and vigour variability (Evett *et al.*, 2002).

If a single measurement, and/or a single calibration were to be used to determine the irrigation need of areas in a vineyard with variable soil and vigour, they would all be irrigated in the same manner. With the heterogeneity that occurs in even a single vineyard block, it would lead to over and under estimation, and therefore irrigation. Clearly the variable water application would lead to physiological effects on the grapevine. This effect could be seen between irrigated plots that received the same irrigation amount and interval. The plots differed in their PWS response to the irrigation supplied. This effect was more pronounced for the hotter and drier season.

To use soil-based methods to manage irrigation in the grapevine, it is necessary to link the soil and the plant water status. A strong link could be found between SWS and PWS for rain-fed vines.

3.5 References

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Chapter 4

General discussion and conclusions

CHAPTER IV: GENERAL DISCUSSION AND CONCLUSIONS

4.1 Introduction

Agricultural researchers have long understood that variability between zones within an experimental area, which is often caused by natural soil variability, or previous land use practices, can significantly reduce the ability to detect experimental treatment differences (Venter *et al.*, 2009).

Soil variability is almost inevitable in soils used for grape production in the Western Cape, South Africa (Conradie *et al.*, 2002). The most prominent natural causes for this variability are due to textural and chemical differences (Hillel, 1971; Lal & Shuckla, 2004). Soil preparation is used to alleviate problems that arise due to these discrepancies. If the soil preparation is not done properly, it can negatively impact soil quality. Soil heterogeneity spans a range of parameters that in the end influence the growth of the grapevine.

In the quest to understand how soil and plant water interacts, soil water needs to be quantified. This can be done with high accuracy by calibrating soil water monitoring methods like the neutron probe to a well-established mode of quantification, like gravimetric samples (Vachaud *et al.*, 1977). The calibration needs to take in regard soil heterogeneity that exists in the block. Heterogeneity is not only limited to locations in the vineyard, but also with depth. A good general calibration can be established per block level, but when premium quality aspects must be taken in regard, more in-depth precision is required. This significantly improves the calibration accuracy.

It is not only the inherent soil parameters that need to be taken in consideration. As important as the physical storage capability of the soil is, the grapevine still need to be able to extract the water from the soil. Physical and chemical limitations can reduce the root distribution and densities and thus confine the above-ground growth of the vine.

Irrigation also has an influence on root proliferation. As water supply decreases, more fine roots develop, and thus increase the root ratio between fine and thick roots. This increase soil utilization and enhance the grapevine’s ability to exploit the soil’s resources. A higher root ratio has been found to coincide with better wine quality (Archer & Hunter, 2005). The root system plays an integral part governing the link between soil and plant water status. It was interesting in the context of this study that root ratios seemingly could adapt under relative short time spans to altered irrigation regimes within a vineyard block.

4.2 General discussion

This study was conducted to evaluate the need for detailed calibrations of soil water measurements, in the context of soil heterogeneity, and to see how plant water status would react to the soil water status. The main aim was to investigate the relationship between soil- and grapevine water status in a heterogeneous vineyard in the Stellenbosch region, while evaluating the vegetative and reproductive response of the plant.

This was done by establishing the extent of variability in the study vineyard by using multispectral aerial photography, which was probably mostly caused by soil heterogeneity that exists within vineyards (Conradie *et al.*, 2002), such as differences in soil physical properties, with clay percentage (Foth, 1990; Lal & Shuckla, 2004; Lanyon *et al.*, 2004; Saxton & Rawls, 2006) and organic material content (Conradie *et al.*, 2002; Dexter, 2004; Lanyon *et al.*, 2004; Du Preez *et al.*, 2011) being possible main contributing factors. The performance of individual vines, and their root and shoot biomass distribution, can be strongly affected by the pattern of supply of soil-based resources (Hutchings & John, 2004).It was however difficult to see a clear relationship between individual plot vigour (as measured using pruning mass) and soil physical characteristics, except for more extreme examples. Plots with higher vigour exhibited higher clay contents, and would probably be able to sustain more vigorous growth in variable climate conditions due to the higher buffer capabilities of the soil (Foth, 1990).

The soil water status (SWS) of the plots were primarily affected by the texture(clay) and organic matter content (Dexter, 2004; Lal & Shuckla, 2004; Saxton & Rawls, 2006).The neutron scattering method proved the most accurate and reliable for continuous repeated measurements of soil water content (Dane & Topp, 2002). The effect of the noted soil variability on the calibration of soil water content was also mostly influenced by soil physical properties. Organic material and most clay contain significant amounts of hydrogen that may not always be in the form of water, but would still contribute to the soil water content measurement (Kramer & Boyer, 1995; Dane & Topp, 2002).Separate calibrations were performed for each soil heterogeneous area and depth, increasing the accuracy of neutron scattering measurements to a great extent (Evett *et al.*, 2002).

Predawn leaf water potential (Ψ_{PD}) measurements were used to determine the plant water status (PWS) of the grapevine. This was done to exclude external factors influencing the water balance in the plant. PWS plays a large role in determining vigour and yield of the plant (Dry & Loveys, 1998). The PWS levels are influenced by irrigation, but it is mostly affected by the season and grapevine location in the vineyard (Stevens *et al.*, 1995). Lower PWS levels may reduce vigour, but have a less notable effect on yield (Stevens *et al.*, 1995; Lebon *et al.*, 2006), which was also observed in this study.

The Ψ_{PD} indicates the soil water potential around the soil-root interface, since the PWS should equilibrate with the SWS (Sellin, 1999; Choné *et al.*, 2001; Jones, 2004). Plant water status changed in relation to SWS, and s non-linear relationship was suggested between PWS and SWS for rain-fed plots. As the amount of PAW in the soil profile diminished, Ψ_{PD} values became more negative, following a non-linear relationship. This corresponded with the trends of water retention curves (Lal & Shuckla, 2004), supporting the idea that the plant acts as a tensiometer. Similar non-linear equations was found for Merlot (Myburgh, 2011) and Shiraz (Pellegrino *et al.*, 2004).

4.3 General perspective

The high buffer capacity of the soils in the study area may have reduced the effects of SWS on PWS. The water deficits could probably have been not severe enough to fully illustrate the effect of vigour on vegetative and reproductive responses of the grapevine through PWS management. The interaction with the applied treatments, as well as differing plant vigour properties, was probably also strongly influenced by the characteristics of the pre-growing and growing seasons, as the first was a wetter season, reducing the irrigation effect that was observed between rain-fed and irrigated plots. Thus the relation between SWS and PWS effects was not distinctively clear, but it was still clear that considerable variability in grapevine vegetative and reproductive parameters could result from differing soil water holding capacities within the vineyard.

4.4 Perspectives for future research

Further research is needed to clarify the PWS response on soil water applications under a well-watered regime, since no clear relationship could be found between irrigated plots' PWS and SWS.

The need also exists to optimise the assessment as well as management of soil and plant water status in the variable conditions often found in local vineyards, which can be done with the help of new technologies such as thermal satellite remote sensing as well as aerial remote sensing. Further research need to be done on the use of these technologies in research, but also its application in practice.

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