The edaphic and climatic effects on production and wine quality of Cabernet Sauvignon in the Lower Olifants River region

by

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DECLARATION

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

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SUMMARY

Cabernet Sauvignon is the most planted red cultivar in South Africa and the second most planted red cultivar in the Olifants River region. The cultivar is prone to vigorous growth with low yields. Excessive irrigation could accentuate these cultivar characteristics. Considering the foregoing, the aim of the study was to describe how Cabernet Sauvignon will react to climate, soil type (texture) and irrigation within the Lower Olifants River wine region to enable growers to make the right decisions regarding long term as well as short term cultivation practices. This study is part of a project carried out by the ARC Infruitec-Nietvoorbij at Stellenbosch to determine the effects of soil type and atmospheric conditions on yield and wine quality of Cabernet Sauvignon in different grape growing regions of South Africa. Similar studies are being carried out in the Orange River, Stellenbosch and Swartland regions of South Africa.

The Lower Olifants River region could be divided into three climatic regions. Furthermore, two climatic regions is evident regarding the formation of grape wine colour and aromas. Proximity to the Atlantic Ocean would play an important role in a cultivar establishment policy.

The variation in stem water potential (Ψ_S) could be related to soil water status expressed in terms of matric potential (Ψ_M). In the case of sandy soils, Ψ_S decreased substantially more as the Ψ_M decreased compared to the sandy loam soils. The reason could be that the unsaturated hydraulic conductivity in sandy soils decreased more rapidly as the Ψ_M decreased compared to the heavier soils. Thus could explain why the grapevines in the sandy soils experienced more water stress than the ones in the sandy loam soils at a given Ψ_M.

Climate had a strong influence on grapevine water status with grapevines nearer to the ocean experiencing less water stress compared to the ones further inland. This was especially true for grapevines in the sandy soils.

Vegetative growth and yield of grapevines in the sandy soils were more sensitive to water deficits compared to the ones in the sandy loam soils. For deficit irrigated grapevines in the sandy soils, vegetative growth and yield decreased by ca. 30% when ca. 55% less water was applied from flowering to harvest. Yield reduction were ca. 15% with no or very little influence on vegetative growth with ca. 80% reduction in water applied from flowering to harvest for grapevines in the sandy loam soils.

The influence of soil texture on wine quality and style were evident under intensive irrigation as well as over different climatic regions. Overall sensorial potential wine quality of grapevines in sandy soils tended to be higher compared to the ones in the sandy loam soils. Deficit irrigation tended to increase wine colour intensity, irrespective of soil texture. Furthermore, deficit irrigation in sandy loam soils tended to increase wine fullness and the berry characteristics of the wine. Berry characteristics of wines from the sandy soils tended to be higher compared to the ones from the sandy loam soils. Too severe water deficits in sandy soils could be detrimental to wine quality. Climate tended

to have an influence on wine style of grapevines in the sandy soils with wines produced further away from the ocean tended to have higher berry characteristics.

Irrigation management could be a powerful tool to manipulate the grapevine in sandy soils. For grapevines the sandy loam soils in addition to regulated deficit irrigation, additional canopy management practices could be needed to improve wine quality.

OPSOMMING

Cabernet Sauvignon is die mees aangeplante rooidruif kultivar in die Suid-Afrikaanse wynbedryf. In die Olifantsriver streek is dit naas Shiraz, die tweede mees aangeplante rooidruif kultivar. Cabernet Sauvignon is bekend as 'n groeikragtige skaamdraer. Indien oorbesproei word, kan hierdie potensiële nadelige eienskappe nog meer na vore tree. Die doel van die studie is om die invloed van die klimaat, grond en besproeiing op Cabernet Sauvignon se vegetatiewe groei, produksie en wyngehalte in die Benede Olifantsrivier streek te bepaal. Hierdie inligting kan produsente help om ingeligte kort- sowel as langtermyn besluite te maak rakende die verbouing van Cabernet Sauvignon. Hierdie studie vorm deel van 'n breër studie in die Suid-Afrikaanse wynbedryf, gedryf deur die Landbou Navorsingsraad (LNR) Infruitec-Nietvoorbij, Stellenbosch om die invloed van atmosferiese toestande en grond op die produksie en wyngehalte van Cabernet Sauvignon te bepaal. Soortgelyke projekte word uitgevoer in die Oranjerivier, Stellenbosch en Swartland wynstreke.

Die Benede Olifantsrivier streek kan verdeel word in drie klimaatstreke op grond van temperatuurdata. In terme van die ontwikkeling van druifkleur en aromas, kan die streek verdeel word in twee klimaatstreke. Die afstand vanaf die Atlantiese Oseaan kan 'n belangrike rol speel in die ontwikkeling van 'n kultivarriglynplan vir die streek.

Grondwaterstatus, uitgedruk as die matrikspotensiaal (Ψ_M), kan aanleiding gee tot variasie in middag blaarwaterpotensiaal (Ψ_S) lesings. Die Ψ_S van die sand gronde verlaag vinniger soos die Ψ_M verlaag invergelyke met die sandleem gronde. Dit kan moontlik wees as gevolg van die verskil in die grond onversadigde hidroliese konduktiwiteit. Sand gronde se hidroliese konduktiwiteit verlaag vinniger soos die Ψ_M verlaag, invergelyke met sandleem gronde. Dit verklaar waarom wingerde in sand gronde by dieselfde Ψ_M, meer waterspanning ondervind as wingerde in sandleem gronde.

Klimaat het 'n invloed op die waterstatus van die wingerdstok. Wingerde nader aan die see het minder waterspanning ondervind invergelyke met wingerde wat verder in die binneland geleë is. Dit was veral die geval met wingerde in die sand gronde.

Vegetatiewe groei en produksie van wingerde in die sand gronde is meer sensitief vir waterspanning as wingerde in die sandleem gronde. Tekortbesproeiing in die sand gronde het die groei asook produksie met ongeveer 30% verlaag deur ongeveer 55% minder water toe te dien vanaf blom tot oes. In teenstelling daarmee is die produksie van wingerde in die sandleem gronde met ongeveer 15% verlaag met geen tot baie min verlaging in die groeikrag. Ongeveer 80% minder water is toegedien vanaf blom tot oes.

Grondtekstuur kan wyngehalte en -styl beïnvloed ten spyte van intensiewe besproeiing en klimaatsverskille. Sensoriese potensiële wyngehalte van wingerde in die sand gronde was beter invergelyke met dié van die sandleem gronde. Die wyne vanaf die sand gronde het ook geneig om oor meer bessie intensiteit te beskik as wyne vanaf die sandleem gronde. Tekortbesproeiing neig om die wynkleur intensiteit te verhoog, ongeag van grondtekstuur. Tekortbesproeiing in die sandleem gronde kan ook die volheid van die wyne verbeter, asook die bessie intensiteit van die wyn verhoog. Te hoë

waterspanning in die sand gronde kan wyngehalte nadelig beïnvloed. Klimaat kan ook die wynstyl vanaf sand gronde beïnvloed met wyne verder vanaf die see wat oor meer bessie intensiteit beskik as wyne nader aan die see.

Beheerde tekortbesproeiing kan as 'n kragtige hulpmiddel gebruik word om wingerde in die sand gronde te manipuleer. Vir wingerde in die sandleem gronde, addisioneel tot beheerde tekortbesproeiing en normale loofbestuurspraktyke, kan ekstra loofbestuurspraktyke bv. die verwydering van sylootlote, dalk nodig wees om wyngehalte te verbeter.

This thesis is dedicated to my parents, Wilman and Rina Bruwer for believing in me and always being there.

Hierdie tesis is opgedra aan my ouers, Wilman and Rina Bruwer vir hulle vertroue in my en hulle ondersteuning.

BIOGRAPHICAL SKETCH

Rachel Jacoba Bruwer (Marina) was born on 9 January 1980 and matriculated in 1998 from Calvinia High School.

She obtained her B.Sc. degree in 2002 from the University of Stellenbosch, majoring in Viticulture and Oenology. In 2003 she enrolled for her B.Sc. Agric. Honours degree in Viticulture at the same university and obtained it at the end of 2003.

In December 2003 Marina started working as a viticulturist at Namaqua Wines, Vredendal, where she is still employed to date.

In 2007 she enrolled for a Masters degree in Viticulture at the University of Stellenbosch.

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PREFACE

This thesis is presented as a compilation of 6 chapters. Each chapter is introduced separately and is written according to the style of the South African Journal of Oenology and Viticulture.

Chapter 1   **Introduction and Project Aims**

Chapter 2   **Literature Review**
The effect of grapevine water status on production and wine quality of Cabernet Sauvignon

Chapter 3   **Research Results**
The effect of climate, soil and irrigation on grapevine water status

Chapter 4   **Research Results**
The effect of climate, soil and irrigation on vegetative growth and yield components

Chapter 5   **Research Results**
The effect of climate, soil and irrigation on juice composition and wine quality

Chapter 6   **General Discussion and Conclusions**

<u>Abbreviations and symbols:</u>

abscissic acid - ABA

Agricultural Research Council - ARC

analysis of variance - ANOVA

and others - *et al.*

approximately - ca.

byvoorbeeld - bv.

calcium - Ca

canopy external leaf area perimeter - CELAP

carbon - C

carbon isotope composition - $\delta^{13}C$

centimetre per second – cm/s

coefficient of variability - CV

cool night index - CI

cubic metre per hectare - m^3/ha

deci Siemens per metre - dS/m

Degree Balling - ºB

Degree Celsius - ºC

dimethyl sulphide - DMS

equation - eq.

evapotranspiration - Etc

figure - Fig.

for example - e.g.

gibberellic acid - GA

gass chromatography-mass spectrometry - GC-MS

gram - g

gram per hectolitre - g/hL

gram per litre - g/L

growing degree days - GDD

heliotermal index - HI

high performance liquid chromatography - HPLC

hydrogen ion concentration (negative log) - pH

IBMP - 2-methoxy-3-isobutylpyrazine

leaf layer number - LLN

least significant difference - LSD

phosphorus - P

potassium - K

propyl methoxypyrazine - IPMP

kilopascal - kPa

kilometre - km

kilogram - kg

Landbou Navorsingsraad - LNR

leaf water potential - Ψ_L

Lower Olifants River Water User Association - LORWUA

malic acid - MA

manganese - Mg

matter other than grapes - MOG

mean February temperature - MFT

mean January temperature - MJT

Megapascal - MPa

methoxypyrazines - MP

metre - m

metre per second - m/s

milligram per litre - mg/L

millilitre - mL

millimetre - mm

nanogram per litre - ng/L

nanometer - nm

nitrogen - N

page - p

partial rootzone drying - PRD

percent/persentasie - %

phenylalanine ammonia lyase - PAL

predawn leaf water potential - Ψ_{PD}

primary bud necrosis - PBN

probability - p

reference evapotranspiration - ET_0

regulated deficit irrigation - RDI

relative humidity - RH

residual sugar – RS

roots per square metre – roots/m^2

sec-butyl methoxypyrazine - SBMP

sodium - Na

soil water matric potential/grond matrikspotensiaal - Ψ_M

South African Wine Industry Information and Systems - SAWIS

Standard error - se

stem water potential/middag blaarwaterpotensiaal - Ψ_S

sulphur dioxide - SO_2

that is - i.e.

tonnes per hectare - t/ha

total acid - TA

total diurnal leaf water potential - Ψ_{LT}

total soluble solids - TSS

1,1,6-trimethyl-1,2-dihydronaphthalene - TDN

volatile acidity - VA
water stress index - S_Ψ
water use efficiency - WUE
wilting point - WP

CONTENTS

Chapter 1

INTRODUCTION AND PROJECT AIMS

INTRODUCTION AND PROJECT AIMS

1.1   INTRODUCTION

The Olifants River Wine of Origin region is described as "The area under vineyard cultivation on 1 January 1973, situated in the divisional council regions of Clanwilliam and Van Rhynsdorp that includes the area that stretches until 20 km from the middle of the Olifants River on both sides of the current" (Anonymous, 1972; Anonymous, 1975) (Fig. 1.1). This region includes the Wine of Origin districts of Lutzville valley, Citrusdal mountain and Citrusdal valley (Fig. 1.2) as well as the Wine of Origin wards of Koekenaap, Piekenierskloof, Spruitdrift, Vredendal and Bamboes bay (Fig. 1.3) (F. van Niekerk, Personal communication, 2008). The Lower Olifants River area is situated within the above mentioned Wine of Origin region and consists of the Olifants- and Doorn River irrigation areas, respectively (L. van der Merwe, Personal communication, 2008). Viticulture is the most important agricultural industry in the Lower Olifants River irrigation area (M. du Randt, Personal communication, 2008).

Originally the soils of the Lower Olifants River region were used by nomadic farmers for grazing their livestock after the winter rains and subsequently by the more settled farmers who sowed grain and other crops. Outstanding grain crops were obtained in good years. In 1734 there were officially only three or four farms in the Lower Olifants River region. However, grapes were already grown along the river as long back as 225 years ago. Le Vaillant, the French traveller, tells of having bought "strong liquor" from the widow "Van Zeill" in 1783 near present day Vredendal (Rappoport, 1983).

Today Cabernet Sauvignon is the most planted red cultivar in South Africa with a total of 13 006 hectares, representing 28.7% of the total red grape plantings. The total area of Cabernet Sauvignon planted in the Olifants River region is 641 hectares, second only to the 968 hectares of Shiraz vineyards. Total wine grape plantings in the Olifants River region, i.e. excluding Sultana, amount to ca. 9 860 hectares (South African Wine Industry Information and Systems, 2007).

Cabernet Sauvignon originated in France and the Bordeaux region is considered as the home of Cabernet Sauvignon (Hands & Hughes, 2001). It is a hybrid crossing of Cabernet franc and Sauvignon blanc that most likely occurred in the 17th century. Since Cabernet Sauvignon was extensively planted in new and emerging wine regions at the expense of the local grape varieties, it is also known as the "colonizer" (Clarke & Rand, 2001). There is no record of Cabernet Sauvignon's first arrival in South Africa, but it is possible that this cultivar has been present for the past two centuries (Hands & Hughes, 2001).

Cabernet Sauvignon is a vigorous, late ripening cultivar, i.e after Pinotage and Merlot, with small berries and bunches, and known as a low yielding cultivar (De Villiers, 1986). Furthermore, the berry has a thick skin and a high seed to pulp ratio of 1:12 (Winter & Hand, 2003). The herbaceous, green bell pepper or earthy aroma is

unique to Cabernet Sauvignon and is due to the grape derived flavour compounds known as methoxypyrazines (MP). Methoxypyrazines, of which isobutylmethoxy-pyrazine (IBMP) is almost always dominant, have extremely low sensory detection thresholds, i.e. one ng/L to two ng/L in water and white wine and 10 ng/L to 15 ng/L in red wines. Other typical flavours in Cabernet Sauvignon wines are mint, eucalyptus and blackberries (Anonymous, 2000; Allen & Lacey, 2003).

Due to the cultivar's susceptibility to low yields it is important to find an optimum balance between wine quality and yield. In the light of the ongoing increases in production costs, it is becoming increasingly difficult for grape production to be economically viable with low yielding cultivars. However, the increasing and more competitive world markets demand high quality varietal wines. Considering the foregoing, it is important to know how Cabernet Sauvignon will react to climate, soil type (texture) and irrigation within a specific wine region. Such knowledge could enable grape growers to make the right decisions regarding long term as well as short term cultivation strategies.

1.1.1 CLIMATE

The Lower Olifants River region is an arid region with warm, dry summers and relatively low winter rainfall. The mean annual rainfall ranges from 216 mm at Klawer in the east to 146 mm at Ebenhaeser in the west (data obtained from the Agriculture Research Council (ARC) Institute for Soil, Climate and Water in Pretoria). Since rainfall occurs predominantly from May to August, successful cultivation of grapevines depends totally on irrigation during summer.

Temperature plays an important role in determining wine quality (Le Roux, 1974; de Villiers *et al.*, 1996; Marais & Fourie, 1997) and the mean February temperature (MFT) is used, amongst other climatic variables or indices, to demarcate the most suitable locality for a specific grape cultivar. It is estimated that the MFT increases by approximately 0.6ºC per 10 km increase in distance from the ocean (Myburgh, 2005 and references therein). A study carried out in the Western Cape Coastal region of South Africa showed that the Atlantic Ocean had a significant influence on MFT in excess of 60 km inland, and that the air flow or land-sea breeze circulation occurred in a westerly direction (Myburgh, 2005). These results suggested that the proximity of the Atlantic Ocean affects MFT over longer distances, compared to the 35 km reported for sea breezes around False Bay (Bonnardot *et al.*, 2003).

It was reported that the main effects of the sea breeze mechanism during February in the Stellenbosch region in South Africa consisted of (i) a change in wind direction and an increase in wind velocity in the early afternoon, (ii) higher relative humidity near the ocean which decreased rapidly inland, (iii) smaller temperature fluctuations near the coast than further inland and (iv) the maximum temperature was reached earlier in the day near the coast than further inland (Bonnardot *et al.*, 2001).

Based on the foregoing, it is expected that the macro climate in the Olifants River region will show a cooling effect from the east towards the coast in the west due to the

proximity to the cool water mass of the Atlantic Ocean caused by the cold Benguela current.

1.1.2 SOIL TYPE

"Edaphology" is the science that deals with the influence of soils on living things, particularly plants, including human use of land for plant growth" (Miller & Gardiner, 1998). The effect of soil type on wine quality is a widely debated subject. According to Seguin (1986) the main effect of soil type on wine quality is through its physical properties, specifically through regulation of the water supply to the grapevine. It was also suggested that the best terroirs in France are situated on soils that are well structured, highly permeable and well aerated, and that certain cultivars apparently produce better wines in certain geological parent material. Furthermore, the wine quality does not seem to be related to soil texture, but rather to soil structure and that the best "cru's" in France are those in which grapes ripen completely, but slowly, in spite of climatic variations. However, the soil would certainly intervene by limiting the climatic and hydric extreme conditions. According to Greenspan (2005), soil and rooting depths as well as soil texture, play an important part in soil water holding capacity. In this regard it was shown that soil water holding capacity, particularly under dry land (rain-fed) conditions, would exhibit a prominent influence on Cabernet Sauvignon wine style in South Africa (Conradie, 2002). The "drier" soils in the Durbanville area, give rise to the more grassy or green pepper characteristics in Cabernet Sauvignon wines. In contrast, fruity wines are associated with soils with low water holding capacity (Chapman *et al.*, 2005 and references therein). Conradie (2002) also showed that the sandier soils in Robertson area produced a light, atypical style Cabernet Sauvignon wine compared to the heavier soils.

Soils in the Lower Olifants River region can basically be classified into two categories namely, (i) the alluvial fertile soils close to the banks of the river, containing a high percentage of clay and (ii) the outlying "Karoo soils", which are sandier and sometimes contain free lime. Based on the inherent soil texture differences between these soil types, differences in eventual wine style and quality could be expected.

1.1.3 IRRIGATION

The effects of climate and soil on grapevine development and grape composition can to a large extent be explained via their influence on grapevine water status (Van Leeuwen *et al.*, 2004). As mentioned earlier, viticulture in the Lower Olifants River region depends largely on intensive irrigation. The only source of water is the Olifants River and grape growers receive water from the Olifants River irrigation scheme. The Olifants River, which was originally named the Tharakkama, raises high in the Koue Bokkeveld and Great Winterhoek Mountains near Ceres (Rappoport, 1983). The water is released inland at the Bulshoekdam and flows via 321 km of open man made cannels to Ebenhaeser near the Atlantic Ocean. Work on this scheme commenced in 1913 and was completed in 1923. A second storage dam was later built further

upstream near Clanwilliam, today known as the Clanwilliam dam, and was completed in 1932 (Broodryk, 1998). Today the Clanwilliam dam, with a capacity of 127 million m^3 is the main storage dam of the irrigation scheme, feeding the Bulshoek dam, with a capacity of 5.148 million m^3, which is used as a balance dam for the Lower Olifants River Water User Association (LORWUA) irrigation scheme (De Lange & Faysse, 2005). Approximately 9 212 ha agriculture land is enlisted for water out of the scheme and another 400 ha is administrated by the Matzikama municipality. Farm units enlisted in the irrigation scheme are theoretically allocated 12 200 m^3/ha water per annum. However, if the Clanwilliam dam is not full after the rain season in October/November the water allocations will be less than 12 200 m^3/ha. The canal operates for 40 weeks per year, with the maximum extraction rate equal to 325 m^3/ha/week for famers (De Lange & Faysse, 2005 and references therein).

It is well known that irrigation influences yield, must composition and eventual wine quality in other countries (Hardie & Considine, 1976; Prichard & Verdegaal, 1998; Chapman *et al.*, 2005), as well as in South Africa (Myburgh, 2006 and references therein). Vigorous vineyards are closely related to excessive irrigation, which can result in poor wine quality, even though the yields are low (Smart, 2006). The importance of good canopy management is well documented (Archer & Strauss, 1989; Hunter & Visser, 1990; Hunter, 1992). Shading caused by over irrigation can lead to reduced yield and colour, as well as an increase in pH and potassium concentrations that could eventually affect wine quality negatively. Detrimental effects due to water deficits include retarded sugar accumulation, decrease of total titratable acidity and delayed colour development of red grapes (Myburgh, 2005 and references therein).

Conradie (2002) showed that even under intensive irrigation of Cabernet Sauvignon in the Robertson area, different wine style and wine quality was obtained from various soil types. Irrigation did not eliminate soil-induced differences in aroma intensity, berry character and overall quality of Cabernet Sauvignon in the Breede River Valley (Olivier & Conradie, 2008).

From the foregoing it is evident that an oversupply as well as water deficits can negatively influence vineyards and wine quality. Consequently, irrigation in the Lower Olifants River region must be applied with discretion to achieve optimum grapevine balance. If irrigation water can be saved, it could be used to established more vineyards or for the cultivation of other crops as an extra income in the light of the increasingly difficult economic situation.

1.2 PROJECT AIMS

The Olifants River region study is part of a project carried out by the ARC Infruitec-Nietvoorbij at Stellenbosch to determine the effects of soil type and atmospheric conditions on grapevine water status, yield and wine quality of Cabernet Sauvignon in different grape growing regions of South Africa. The Orange River, Stellenbosch and Swartland regions were also included in the ARC project.

The formulated hypothesis is that soil type (texture) and climate have an effect on production and wine quality of irrigated Cabernet Sauvignon vineyards in the Lower Olifants River region.

The aim of the study will be to assess the integrated terroir influence on yield and wine quality of Cabernet Sauvignon vineyards in soils representative of the Lower Olifants River region by determining:
(i) macro- and meso-climatic conditions during the growing season.
(ii) root structure characteristics and soil water status.
(iii) grapevine water status.
(iv) grapevine canopy characteristics.
(v) bunch mass, berry mass and yield.
(vi) wine style and quality.

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Figure 1.1 The Olifants River Wine of Origin region (Source, *Wynboer*, January 1975).
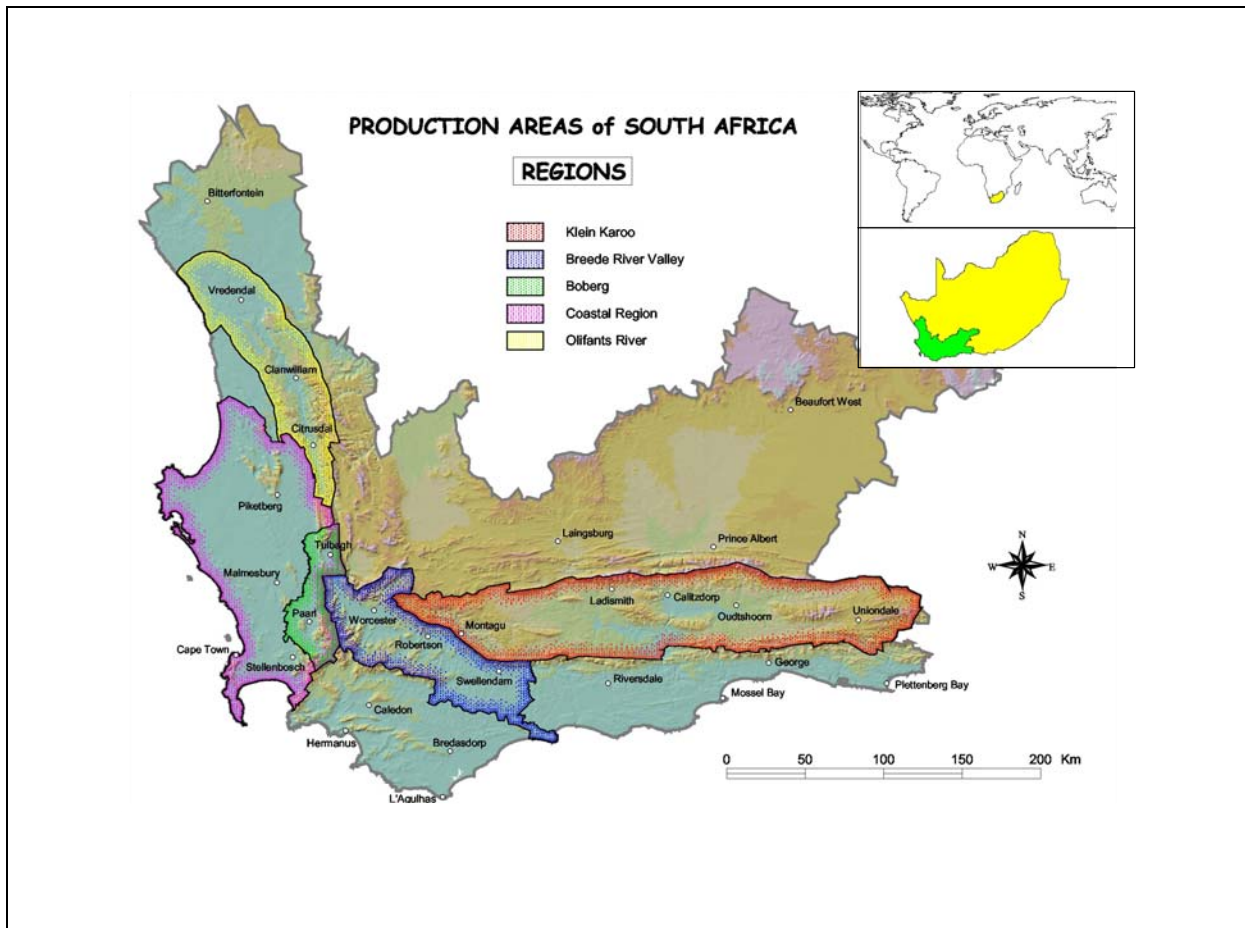
Figure 1.2 The Olifants River Wine of Origin region is situated in the Western Cape wine production area of South Africa. (http://www.sawis.co.za/cert/productionares.php)
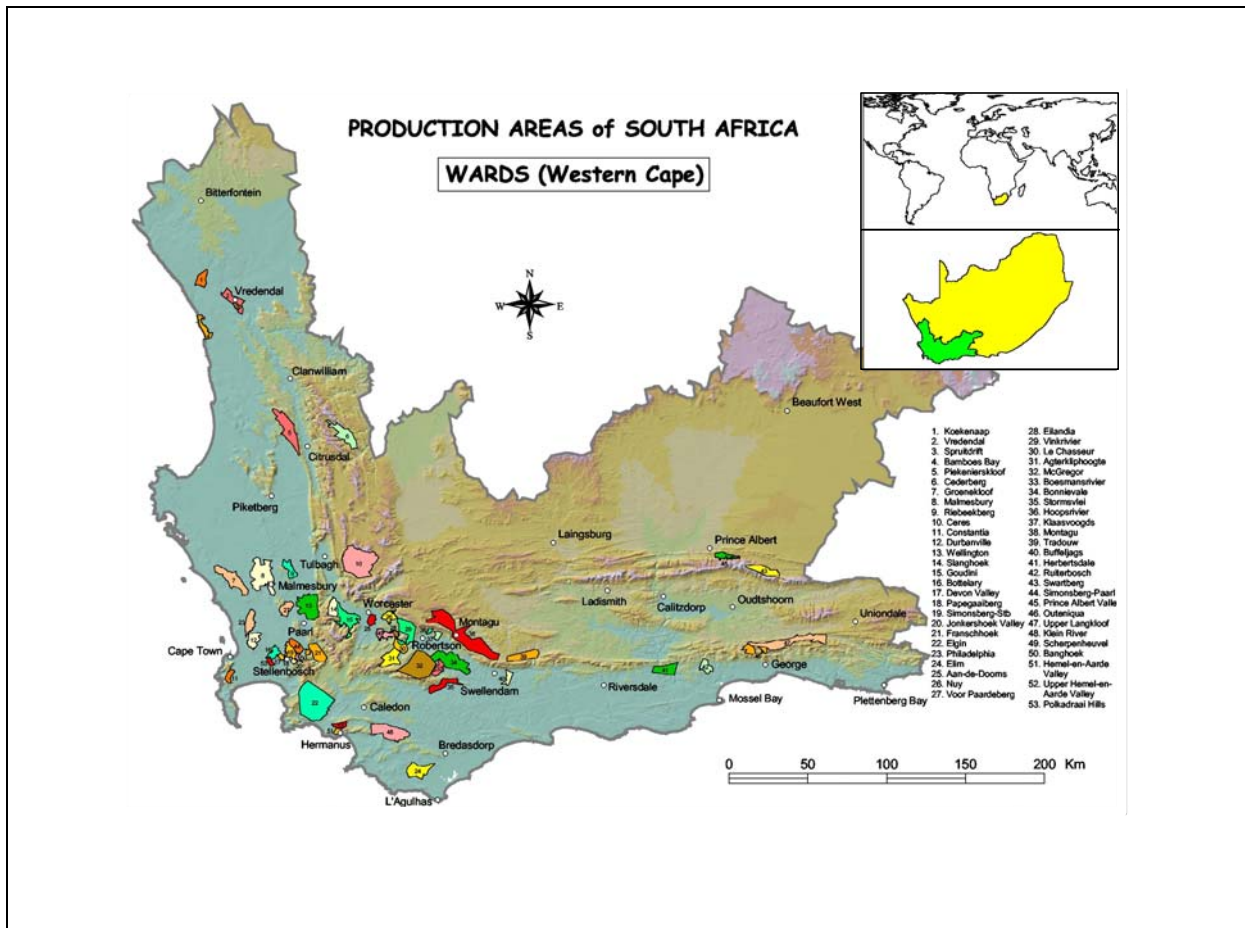
Figure 1.3 Wards of the Western Cape wine production area. The Olifants River Wine of Origin region includes wards one to six. (http://www.sawis.co.za/cert/productionares.php)

Chapter 2

LITERATURE REVIEW

The effect of grapevine water status on production and wine quality of Cabernet Sauvignon

CHAPTER 2

2.1 INTRODUCTION

In grape production the need always exists to find a balance between yield, which is important for economic viability of the grower and wine quality, which is important in the increasing competitive world markets.

Water stress could have positive and detrimental effects on grape production and wine quality. On the other extreme, over irrigation would nearly always be detrimental to wine quality.

The aim of this chapter is to discuss the effect of water stress on production and wine quality of Cabernet Sauvignon.

2.2 GRAPEVINE WATER STATUS

When water is sucked through the grapevine, suction arises in the leaves where liquid phase water evaporates. The water suction force is transferred throughout the grapevine that, in effect, has a continuous column of water through the xylem from the roots to the leaves. It gets more difficult to extract water as the soil becomes drier. Hence, there is a tug of war between the soil and the atmosphere and the grapevine is stuck in the middle. The drier the soil becomes and/or the higher the evaporative demand of the air becomes, the stronger the suction on the water column will be. This suction can be expressed in units of pressure (Greenspan, 2005). Diurnal patterns of water stress in well-watered grapevines appear when transpiration losses exceed water uptake (Hardie & Considine, 1976). However, when soil water potential becomes limiting, normal overnight recovery is not possible and prolonged periods of water stress occur.

Soil moisture monitoring is a traditional way to measure water status of agricultural systems. In drip irrigated vineyards, the wetted soil volume is usually discontinuous. Thus there is great potential for uncertainty, depending on location of the sensor with respect to emitter position, the variability in soil properties and whether the reading is done in the zone mostly occupied by the roots (Hunter & Myburgh; 2001 Greenspan, 2005).

In a study carried out in drip-irrigated Cabernet Sauvignon and Merlot vineyards, gravimetric and volumetric soil moisture content were determined with the goal to understand the distribution of soil moisture using regulated deficit irrigation (RDI). Soil moisture varied by depth, distance from the emitter and sampling time. The data suggested that collecting soil samples within a 200 mm to 400 mm radius, either diagonal or perpendicular to the drip line emitter position, would best reflect the amount of plant-available soil water. Monitoring should be conducted on both sides of the row around each emitter position and then averaged to avoid any patterns from hilling or disruption in water flow patterns (Davenport *et al.*, 2008). Soil moisture measurement

can be very useful early in the season, after winter rainfall has uniformly wetted the soil profile. Instruments that measure soil water content include the neutron probe, time-domain reflectometry and capacitance (dielectric) probes, soil-moisture blocks and tensiometers. These measurements are site-specific, because all of them have some associated error (Greenspan, 2005). According to Hunter & Myburgh (2001), gravimetric determination is still regarded as the most accurate way of determining the soil water content. According to Greenspan (2005) it is generally advantageous to monitor the grapevines rather the soil.

A decrease in soil moisture availability is known to reduce leaf water potential (Ψ_L), stomatal conductance and assimilation rate and to induce osmotic adjustment (Naor & Bravdo, 2000 and references therein). However, it is clearly shown that stomatal conductance is better correlated with soil water potential or soil water availability. This led to a concept which relates the control of stomatal conductance to soil water status, via root signals. This concept questions the importance of plant water potentials as indicators of plant water stress (Naor & Bravdo, 2000 & references therein). It seems that stomatal conductance responded to atmospheric water stress only when soil water availability was low, whereas Ψ_L responded to atmospheric stress regardless of soil water availability. Stomatal conductance is better correlated with soil and root water status than with Ψ_L. Stomatal conductance is highly correlated with both Ψ_L and stem water potential (Ψ_S) though the correlation with the Ψ_S was higher. Leaf water potential represents the water status in the vicinity of the stomatal guard cells while Ψ_S represents an integrated value of numerous plant organs (Naor & Bravdo, 2000). A decrease in root water potential is accompanied by an increase in intensity of root signal, which decreases stomatal conductance and thereby, transpiration rate (Naor & Bravdo, 2000 and references therein).

Roots are the primary organs sensing the onset of water stress (Loveys, 1984). There is strong evidence that abscissic acid (ABA) is the primary substance able to signal changes in root moisture (Wilkinson & Davies, 2002). Loveys *et al.* (2004b), has shown in Cabernet Sauvignon grapevines that ABA is the predominant regulator of stomatal conductance and that when part of the root system experience a reduction in available water, it is the changes in ABA that induce changes in stomatal conductance. Loveys (1984) have shown that grapevine leaves respond with a reduction in stomatal conductance when supplied with ABA at a 130 ng/mL concentration.

Cytokin are xylem-mobile and are also influenced by soil water deficit. In an experiment carried out in Cabernet Sauvignon grapevines with a Ramsey rootstock, part of the root system was allowed to dry, which subsequently reduced cytokinin content of the shoot tips, subtending buds and roots (Stoll *et al.*, 2000). Davies *et al.* (1986) also found that cytokinin activity is reduced under osmotic stress conditions. On the other hand, ABA accumulation may be stimulated under these conditions. Thus cytokinin and ABA are involved in responses to soil water deficits.

Grapevine water status can be manipulated by irrigation, but if the grapevine water status is not measured, there is no way of knowing what the effect is on the grapevine.

There is no better indicator of how the vineyard is doing than the grapevines themselves. The pressure chamber is by far the preferable method of monitoring grapevine water status (Scholander *et al.*, 1965; Greenspan, 2005). Leaf water potential has been used to monitor the water relations of grapevines and have been correlated with various aspects of grapevine physiology, vegetative growth and yield (Williams & Araujo, 2002 and references therein). Greenspan (2005) suggested that the irrigation season in California should start when Ψ_L reached -0.8 MPa for white cultivars and blocks prone to water stress or less vigorous blocks. For most red cultivars irrigation should start when Ψ_L reached -1.0 MPa. However, any water measurements must be carried out in conjunction with monitoring the visual water status of the grapevine. He gave some shoot tip ratings of grapevine water status, i.e. (i) Ψ_L > -0.8 MPa - active shoot growth when tendrils reach past the growing tip, (ii) Ψ_L = -0.9 MPa to -1.0 MPa - slowed shoot growth when tendrils are even with the growing tip and the basal tendrils are still turgid, (iii) Ψ_L = 1.2 MPa to -1.3 MPa - ceased shoot growth when leaves extend past the growing tip and the basal tendrils are turgid to slightly droopy and (iv) Ψ_L = 1.4 MPa to -1.5 MPa - dead or missing shoot tips, the basal tendrils are droopy or falling off and the leaf-petiole angle becomes smaller (Greenspan, 2005). As a general guideline Ψ_L measurements could be use as follow: Ψ_L > -1.0 MPa - No water stress; Ψ_L = -1.0 to -1.2 MPa - Mild water stress; Ψ_L = -1.2 to -1.4 MPa - Moderate water stress; Ψ_L = -1.4 to -1.6 MPa - High water stress; Ψ_L < -1.6 MPa - Severe water stress (Greenspan, 2005).

However, Hunter & Myburgh (2001) warned that Ψ_L is often found to be insensitive to soil water content and therefore should be used with care and along with soil water determination. Leaf water potential is a poor indicator of irrigation requirement because of the dependence on short term fluctuations in current stomatal conductance. Predawn leaf water potential (Ψ_{PD}) might be a more sensitive indicator of grapevine water status than Ψ_L (Loveys *et al.*, 2004a). When Ψ_{PD}, Ψ_L and Ψ_S was compared, it was shown that Ψ_S was the most discriminating indicator of moderate and severe water deficit (Choné *et al.*, 2000).

Stem water potential has been shown to be less variable than Ψ_L with improved ability to detect small, but significant differences among treatments. Furthermore Ψ_S has been shown to be a linear function of applied water and soil water availability (Williams & Araujo, 2002 and references therein). However, the time frame used to measure Ψ_S with limited resources on a daily basis, could limit the application of it, especially if a huge number of vineyards needs to be covered. Technicians must be well trained in the use of the pressure chamber as well as the choice of leaves to sample (Williams & Araujo, 2002 and references therein).

Measurements of Ψ_{PD} is used in grapevine studies, since it is assumed that before sunrise the grapevine is in equilibrium with the soil's water potential (Williams & Araujo, 2002 and references therein). Predawn leaf water potential better reflected soil water availability than Ψ_L and detected the onset of water stress in grapevines earlier and more accurately than Ψ_L and thus would provide a good estimate of the soil water status in the vineyard (Williams & Araujo, 2002 and references therein). Integrating Ψ_{PD} along

the season can be a valuable tool to quantify the degree of water stress experienced by the grapevine (Lopes *et al.*, 2001). According to Deloire *et al.* (2003) a moderate water level could be obtained maintaining the Ψ_{PD} of the grapevines between -0.2 MPa and -0.4 MPa during set to véraison and between -0.4 MPa and -0.6 MPa during véraison to harvest (Santalucia *et al.*, 2007 and references therein).

The only mechanisms by which plants achieve homeostasis in internal water status are changes in the conductance of their water pathways. There are two major cycles of temporal variations of plant water status, i.e. firstly, a daily cycle with maximum evaporative demand near solar noon, and secondly, annual cycles with maximum water stress occurring during the summer in temperate and Mediterranean climates. Plant responses to the constraints imposed by these cycles take place at two different levels (i) instantaneous control of transpirational flux via the stomata and (ii) the ability to survive drought periods of several weeks, which depends on the long term water relations between whole plant and the soil (Winkel & Rambal, 1993 and references therein).

It seems that grapevine water status could depend on the climate as well as on soil water status. In a study carried out in 25+ year-old un-irrigated Cabernet Sauvignon in Bordeaux, France it was shown that the water status of the soil could be influenced by the composition of the soil. Grapevines in soil A had a Ψ_L significantly more negative (more stressed) than all the other locations throughout the season, due to low water holding capacity of the soil, the high proportion of gravel and the shallow root zone. This was the only soil of the four soils, which were subject to mild water deficit in 1997 (Xoné *et al.*, 2001). In a dry season high berry and wine quality were strongly linked to a mild water potential. In a rainy season, mild water stress was less likely to occur, and other components of the soil, such as nitrogen (N) content could play more of a role. If the vineyard is not fertilized, grapevine N content would depend on soil organic matter, its mineralization rate and the carbon to nitrogen ratio. In summary it was found that two combinations of grapevine water status and soil N lead to the highest quality Cabernet Sauvignon wines, i.e. a low N status throughout the season, without water deficit and a medium N status coupled to a mild water status. The authors also find that low N status reduced vigour more than mild water deficit (Xoné *et al.*, 2001). According to Hunter & Myburgh (2001) the soil water regime was not only important because of direct effects of water relations on plant function, but also because of indirect implications via nutrient absorption. Conradie (1991) and Conradie (1992) concluded that autumn water stress will be detrimental for canopy and bunch development during the following spring, since autumn absorbed fertiliser-derived N is preferentially mobilised to new spring growth.

2.3 GRAPEVINE VEGETATIVE PARAMETERS

2.3.1 THE EFFECT OF GRAPEVINE WATER STATUS ON VEGETATIVE PARAMETERS

The grapevine begins growth in spring when the mean daily temperature reaches about 10⁰C. Growth is slow at first, but as temperature increases, overall growth increases. After three weeks to four weeks the period of most rapid growth is underway. At about the time of flowering, the rate of shoot growth declines rapidly and then continues at a slow rate until the end of the season (Kasimatis, 1967). Grapevines continue to grow as long as environmental conditions are favourable.

Kasimatis (1967) suggested using the rate of shoot elongation as a sensitive indicator of soil water availability. In a study carried out in Chenin blanc vineyards, it was shown that shoot elongation was most sensitive to water deficits and showed promise as a criterion for timing irrigations (Vaadia & Kasimatis, 1961). Shoot elongation ceased at Ψ_L of about -0.9 MPa to -1.1 MPa. Shoot tips would dry up at Ψ_L values lower than -1.4 MPa. Once shoot growth stopped, it would rarely restart unless excessive irrigation was applied. According to Greenspan (2005) shoot tips were the best indicator of water status, especially between flowering and véraison, however they were not useful after growth has ceased. Shoot growth would slow down and stop, usually before the shoot tip symptoms appear.

Other visual indicators of plant water stress include drooping of tendrils which is only useful before véraison, because afterwards it become tough and woody. Furthermore, leaf-blade petiole angles would change under water stress to avoid sun exposure. When no water stress occurs, leaves make a 90⁰ angle with the leaf blade. In severe water stress situations basal leaves would turn yellow, dry up and fall off (abscise). Yellowing is usually a sign of over stress (Greenspan, 2005). Some varieties, like Cabernet Sauvignon, do not express the change of the leaf-blade petiole angles readily, so it is not a very reliable indicator of water status.

According to Hardie & Considine (1976) the first visual water stress symptoms on container-grown Cabernet franc grapevines, appeared when Ψ_{PD} approached -0.4 MPa. The young leaves and tendrils wilted. As droughty conditions continued, young tendrils abscised and progressive defoliation began with older leaves. Stress induced defoliation could cause a reduction in the growth and sugar concentration of berries.

A severe or sudden reduction in the soil water availability would result in wilting of leaves and succulent shoots, followed by yellowing and shedding of basal leaves. This may happen with a sudden rise in temperature, e.g. during heat waves conditions or to grapevines growing in shallow soils where the wilting point (WP) is reached in all parts of the root zone at the same time. Wilting would occur infrequently on deep soils since only part of the soil is at the WP at the same time (Kasimatis, 1967 and references therein). Soils with low water holding capacity must be irrigated with lower volumes,

more frequently, than soils with a high water holding capacity, which could be irrigated with greater volumes, less often (Greenspan, 2005).

According to Smart (2003) leaf temperature would give an instantaneous measure of grapevine water stress, whereas shoot growth assessment would give an indication of water stress over the past two or so weeks. This is in agreement with Greenspan's (2005) opinion that all of the visual symptoms are "lagging indicators" since they are expressed only after the grapevine has experienced some stress.

Cabernet Sauvignon are known as a vigorous cultivar and could easily become over vigorous if irrigation is not applied judgemental. In a study carried out in Hawke's Bay, New Zealand, on Cabernet Sauvignon, it was shown that soil moisture had a significant positive impact on vegetative growth (Tesic *et al.*, 2001). As readily available soil water was depleted in successive parts of the soil, the grapevine adjusted to these conditions and made less shoot growth (Kasimatis, 1967 and references therein).

The distribution of photosynthetic products is regulated by the source to sink relationship (Johnson *et al.*, 1982). Under mild water deficits vegetative growth was not in competition with reproductive development as a sink of photosynthetic products and the fruits were the primary sinks (Choné *et al.*, 2001). Partitioning of assimilates between sites of production and sites of accumulation or utilisation ultimately determined yield and grape composition (Hunter & Myburgh, 2001).

Under over vigorous conditions, most of the photosynthate were distributed to the shoots and bunches were neglected. This would result in an increase in shoot length, leaf area, lateral shoots, water sprouts and the budding of buds at the base of spurs. Dense, shady conditions were formed inside of the canopy. Physiological reactions of these conditions included decrease in bud percentage and fertility of primary buds for next year's harvest, photosynthesis of the leaves decreased, sugar accumulation in the grapes were slowed down, sugar and tartaric acid concentrations in the grapes were decreased, pH of the juice increase, skins were poorly coloured, malic acid, N content and potassium (K) content of the grapes increased, yield was directly influenced by smaller and looser bunches and lastly root growth, and thus the uptake and transport of nutrients and water to the grapevine, was negatively affected (Hunter, 1992). Cytokinins are produced in the roots, thus its production would be affected by root growth and would eventually influence shoot physiology.

Sugar accumulation in berries during ripening was mainly dependent upon current leaf photosynthesis (Iland, 1989). The optimum temperature range for 90% to 100% photosynthetic efficiency was 18°C to 33°C. Over vigorous vineyards could hinder optimum photosynthesis of leaves (Hunter, 1992).

In a study carried out by McCarthy (2000), post-flowering water deficit reduced vegetative growth in some seasons and may have resulted in a greater proportion of older leaves with reduced photosynthetic capacity. Taken over four consecutive seasons, the combination of water stress and a reduction in photosynthetic capacity may have reduced bunch primordial development and subsequently berry weight as well as reducing berry growth during every season. Further studies needed to be done

on the cumulative effects of water stress on initiation and differentiation of bunch primordial. It was seen by Ferreyra *et al.* (2004) that floral induction was affected by water stress in the ongoing growing season. During an irrigation trial combined with a training system trial in Bordeaux, France in Cabernet Sauvignon vineyards, it was seen that there was two strong depressing effects on floral initiation. The first, a general depression, was probably due to a decline in capture of solar energy at the renewal-area level and the second, a specific depression on mostly the primary buds that could be inhibited during the floral-initiation period by a too great water flow in the tissues (Carbonneau & Casteran, 1979).

Pickering *et al.* (2007) found a strong positive relationship between vigour and bunch stem necrosis in Cabernet Sauvignon grapevines during the first season of applying management practices to manipulate vigour and the source to sink relationship. In the second season the relationship was not as strong, but still positive. The effectiveness of the practices would be influenced by the environmental conditions, especially near flowering.

Prichard & Verdegaal (1998) found on Cabernet Sauvignon that the total shoot length of grapevines that received adequate water (100%) during the season, were significant longer than the treatments that received less water. The pruning mass of the full potential treatment were also bigger than the other treatments. They also measured spur diameter and found that there exist a direct correlation between spur diameter and water consumption. However, the relation would vary according to the spring growing conditions and available soil moisture. Of more importance, it seemed that the practice of deficit irrigation at 70% and 50% of water use was sustainable over at least the seven year term of the trial and the two years of measuring the spur diameters. This was important because the long term effect of water stress on vegetative and reproductive structures could eventually affect the yield to quality relationship.

The production of plant biomass is not only a function of carbon metabolism, but was significantly determined by concurrent fluxes of water and nutrients and the process by which these resources are partitioned (Schulze, 1986). An increase in leaf growth and biomass directly influenced whole-plant production, because carbon assimilation was positively related to leaf area. But this simultaneously raised the transpiration rate and nutrient demand of the plant under conditions in which proportionately less carbohydrates were available for root growth and which in turn had an effect on water and nutrient uptake. The partitioning of carbon into leaves was one of the main processes which determine growth of individual plants subjected to drought (Schulze, 1986 and references therein). A depletion of the water storage would decrease leaf gas exchange and a reduction of available water for growth in the above-ground parts of the plants would modify carbon partitioning to favour growth of supporting organs. Similar effects occurred with nutrient deficiencies. Water stress caused premature aging of leaves and abscission, whereas nutrient deficiencies tended to prolong leaf age and promote a tendency to become evergreen (Schulze, 1986 and

references therein). Stomata may be regulated by the plant water status and by the functioning of the fine roots.

Plant carbon and water relations were inevitably linked by the diffusion pathway of carbon dioxide (CO_2) and water through the stomata. The difference between the magnitudes of transpiration and CO_2 uptake was primarily caused by the different atmospheric concentrations of these gases (Schulze, 1986 and references therein). Stomata closed when a plant or leaf exhausted the water available for transpiration and leaf cells reach zero turgor. Stomatal closure at the leaf wilting point was probably mediated by ABA released into the apoplast. It is apoplastic ABA, rather than total tissue ABA, that regulated stomatal function. ABA synthesis may be regarded as a form of stress integrator. During repeated episodes of low turgor, ABA accumulated in the chloroplasts and was then available for release to the apoplast in response to stress even at levels which may not be severe enough to induce ABA synthesis (Schulze, 1986 and references therein).

However, it was also found that the effect of ABA in the positive-turgor range depended on additional internal factors or upon pre-treatment. Furthermore, guard cells cease to be affected by ABA after a period of time. There was also evidence that stomata were not regulated by the water potential or turgor of a leaf in synchrony. Stomata may remain open even in wilted leaves and stomata may close in dry soil at positive turgor in a progressive rather than in a threshold manner (Schulze, 1986 and references therein). Leaf water potential and leaf turgor could be manipulated simply by changes in transpiration. Stomata closed when the soil dries, but at different levels of Ψ_L and leaf turgor depending on the transpiration rate of the leaf. When the water potential of an individual leaf was manipulated via changes in whole-plant transpiration rate, the lowest potential occur when transpiration was high, generally when the stomata were open. This effect was reversible. By contrast, when Ψ_L were manipulated by drying the soil, the response was no longer reversible and stomata closed progressively, irrespective of humidity or water potential (Schulze, 1986 and references therein). When plants were subjected to progressive soil drying while maintaining the leaf water potential near 0 MPa, stomata closed in dry soil even though the leaves of these plants were always fully turgid. This demonstrates a direct signal from the roots to stomata. It appeared likely that the root tip produced a signal which counteracted the effects of ABA and which kept stomata open.

Stomata were regulated by two "feed-forward" responses, i.e. air humidity and soil water status. There was an additional "emergency" reaction to avoid desiccation when ABA was released to the apoplast approaching or during wilting. The direct response to soil water status, however, appeared to close stomata prior to this event (regulate leaf conductance). It is possible that this signal also affected CO_2 assimilation, but the effect on photosynthesis appeared to be pre-treatment- and species-dependant (Schulze, 1986 and references therein).

According to Loveys *et al.* (2004a) and references therein, leaf responses such as reduced stomatal conductance, could be brought about by a slight shift in xylem sap pH.

Xylem sap became more alkaline as a result of water stress and the uptake of ABA into the cells was reduced when the pH of the solution bathing those cells was increased. Thus pH sap changed in xylem sap, originating in roots, might be a signal for leaf stomatal changes. Furthermore, ABA was added to the xylem stream by tissues in the canopy (Loveys *et al.*, 2004a). Soar *et al.* (2004) concluded that leaves have the ability to regulate stomatal conductance through changes in ABA independently of hydraulic or root-sourced signals, if non-stressful conditions occur.

In two year-old potted Chardonnay grapevines grown in a glasshouse, it was shown that continuous water limitation, from bud burst to leaf fall, reduced grapevine growth and more dry matter accumulated in the roots. Adaptive features in leaves were a high amount of epicuticular wax, increased prostrate hair density, small stomata, low average leaf area, preferential allocation of dry matter to the roots, few leaves on the lateral shoots and changes in the mean leaf inclination that resulted in a more upright leaf position. These changes increased water use efficiency (WUE) by 31% and increased the root to leaf area ratio by 93% (Palliotti *et al.*, 2001). These indicated an efficient water saving strategy which optimised water use.

Stomatal closure was the dominant factor changing WUE during water deficit and several studies have found differences in WUE between cultivars (Schultz, 2000 and references therein). Bravdo *et al.* (1972) and references therein found that WUE of Sultanina was less efficient than Queen of the Vineyards for grapevines with the same vigour. Water use efficiency is an indicator of the ratio of carbon acquired (or dry matter) per unit water lost (transpired water). Plant survival during drought would be closely coupled to efficient strategies for water use. The ideal cultivar would be one whose behaviour tended to maximise assimilation in relation to the amount of water available. A significant reduction in WUE was apparent below a Ψ_L threshold of -1.7 MPa. This latter reduction indicated a non-stomatal conductance, since a sole reduction in stomatal conductance must result in increased WUE due to its effects on transpiration only, whereas non-stomatal conductance affects assimilation rate rather than transpiration rate. Therefore, the reduction in WUE indicated an effect on the photosynthetic apparatus due to low water potential. This effect was reversible, as there were similar WUE in the two treatments in the morning (Naor & Bravdo, 2000). Both stomatal and non-stomatal limitations were involved under conditions of progressive water stress and stomatal conductance and CO_2 assimilation decrease. Other adaptive mechanisms which modified plant growth and productivity under drought conditions include changes in the pattern of dry weight allocation, respiratory loss, elasticity of leaf walls, hydraulic conductivity of the xylem, Calvin cycle activity, osmoregulation capacity and root signals which control the stomatal movement (Palliotti *et al.*, 2001 and references therein). In water-limited environments it is important to know and improve WUE, since it is an important component of drought adaptation and tolerance (Palliotti *et al.*, 2001 and references therein). There exists a positive correlation between WUE and vigour. It is likely that increasing leaf area improved the photosynthesis to

transpiration ratio, which was the water use efficiency (Bravdo *et al.*, 1972 and references therein).

In a study carried out in Grenache and Syrah grapevines near Montpellier, France, Grenache could be classified as drought avoiding or conservative, with a large range of physiological parameters changing in response to the water stress. All the changes in leaf water relation parameters observed acted to increase stomatal sensitivity, leading to a high intrinsic WUE. Stomatal closure in Grenache could be primarily hydraulically regulated and might not require a hormonal signal from the roots to close. In contrast, Syrah could be termed drought tolerant, exhibiting almost a complete absence of adaptive changes in any of the parameters tested, except the regulation of canopy morphology and total leaf area. Stomatal closure of Syrah could not be purely hydraulic, since after excision, stomata remained partially open even at low Ψ_L and complete turgor loss. However, the cultivar which did not "adapt" to the stress achieved crop maturation, yet almost completely exploited the soil water and the cultivar which "adapted" to the stress failed to mature the crop, yet conserved water.

2.4   REPRODUCTIVE PARAMETERS

2.4.1 GRAPE BERRY DEVELOPMENT

The berry is an independent biochemical factory with the ability to synthesize berry components like flavour and aroma compounds (Kennedy, 2002 and references therein). The grape berry has three major types of tissue, i.e. flesh, skin and seed. Wines made from smaller berries would have a higher proportion of skin- and seed-derived compounds and the number of seeds in the berry could influence the proportion of seed-derived components in wine. The berry is supplied by xylem of water, minerals, growth regulators and nutrients from the roots and is functional in grape berries up to véraison, but afterward its function is reduced or eliminated. Phloem is involved in photosynthate (sucrose) transport from the canopy to the grapevine and has a reduced function early in berry development, but becomes the primary source of ingress after véraison. For some varieties like Shiraz, the vasculature between the grapevine and berries has reduced function during late season fruit ripening (Kennedy, 2002 and references therein).

Berry development consisted of two successive sigmoidal growth periods separated by a lag phase. The first period of growth lasted from flowering to ca. 60 days afterwards (Kennedy, 2002 and references therein). During this phase fruit grow by cell division and cell enlargement (Hardie & Considine, 1976 and references therein). The berry was formed, seed embryos were produced, rapid cell division occured and at the end of this period the total number of cells within the berry had established. Cell division has an influence on the eventual berry size. The berry expanded in volume due to the accumulation of solutes which would reach an apparent maximum at véraison. Solutes that accumulated include tartaric acid, with the highest distribution to the outside of the

berry and malic acid (MA), being the highest in the flesh. Tartaric acid appeared to accumulate during the initial stages of berry development, and MA accumulated just prior to véraison (Kennedy, 2002 and references therein). According to Conde *et al.* and references therein (2007), tartaric acid biosynthesis in grape berries was limited from post-anthesis until véraison. Both leaves and immature green berries were able to form tartaric acid and MA and photosynthesis in the green berry were responsible for 50% of the accumulating acids (Conde *et al.*, 2007 & and references therein).

Other solutes that accumulated include hydroxycinnamic acids, which were distributed in the flesh and skin of the berry. Hydroxycinnamic acids are involved in browning reactions and are precursors to volatile phenols and tannins that are present in seed and skin tissue of the berry and are responsible for the bitter and astringent properties of red wine and are important in red wine colour stabilisation, minerals, amino acids, micronutrients and aroma compounds such as MP (Kennedy, 2002 and references therein).

In most cultivars the first growth phase is followed by a lag phase. The duration of this phase is specific to the cultivar and its end corresponds to the end of the herbaceous phase of the fruit. During this stage no growth takes place (Conde *et al.*, 2007).

The beginning of the second phase of berry growth was characterized by softening and colouring of the berry (véraison). The berry approximately doubles in size during this stage (Kennedy, 2002 and references therein). During this phase cell enlargement alone accounted for the increase in fruit size (Hardie & Considine, 1976 & references therein). Many of the solutes that accumulated in the grape berry during the first stage of growth remained at harvest, but due to the increase in berry volume, their concentration is reduced. However, some compounds produced during the first period of growth were reduced on a per-berry basis and not simply by dilution. Among these was MA, which concentration could roughly be correlated with climate as well as seed tannins, due to oxidation as the tannins became fixed to the seed coat. Skin tannins declined or remain constant and also became modified and aroma compounds that declined were MP. On the other hand, at the beginning of véraison, sucrose that was produced from photosynthesis was imported into the berry and once inside the berry sucrose was hydrolyzed into glucose and fructose. Anthocyanins were also produced during the second growth stage and most of the volatile flavour components were produced late in the ripening and were called "engustment". Some of the compounds produced were precursors and not volatile until after the wine has been produced and aged for some time. These precursors were present in the grape berry as glycosides and the period of time when they were produced are called "gustation" (Kennedy, 2002 and references therein).

The first steps of berry development, from fecundation to nouaison (fruit set) were under the control of developmental hormones, e.g. auxins, cytokinins and gibberellins. These hormones promoted cell division and cell expansion. Although they could be imported into the berry, these hormones were mostly produced by the seeds or by

maternal tissues, in the case of seedless cultivars. Cytokinin production by seeds is not completely established for all plant species. The final size of the berry would upon other things, depend on the number of seeds it contain (Conde *et al.*, 2007 and references therein). Hormonal control of grape berry ripening from véraison to harvest is still not very clear and may result from a combination of signals rather than being under the control of a single hormone. Abscissic acid, ethylene and brassinosteroids may associate to regulate the grape berry maturation processes (Conde *et al.*, 2007 and references therein).

Potassium (K) was absorbed by the roots and distributed to all parts of the grapevine. Early in the season, when the growth rate was high, much of the K accumulated in the leaves. After véraison a sharp increase in berry K was observed as a result of K redistribution from leaves to the berries. Potassium uptake of Cabenet Sauvignon berries was slow before véraison and strongly increases when ripening started in the same proportion as sink strength and phloem water flux (Conde *et al.*, 2007 and references therein). The K concentration was generally higher in berry skins than in the pulp. Calcium (Ca) concentration was at its maximum at véraison and remains stable or decreased during maturation.

It is important to have knowledge of berry morphology and when various components accumulate in the berry. This knowledge could aid in the adjustment of viticultural practices for modification of wine quality and style.

2.4.2 THE EFFECT OF GRAPEVINE WATER STATUS ON REPRODUCTIVE PARAMETERS

In warm irrigated areas, one of the major constraints to berry growth could be the availability of water. Irrigation could have direct and indirect effects on reproductive parameters and eventual wine quality and style.

Direct effects were mainly due to the response of berry growth to water stress. Yield losses may occur if water deficit was applied to either of the two major growth phases. Water deficit led to smaller berries since it inhibited both cell division and especially, cell expansion. The implicit mechanism of this concept was that the surface area to volume ratio of the berries decreased with an increase in berry size. Anthocyanins and other phenolic compounds accumulated in the skin and thus smaller berries would have a relative greater solute to solvent ratio than larger berries. However, independently of the resultant differences in fruit size, the effect of grapevine water status on the concentration of skin tannins and anthocyanins was greater than the effect of fruit size per se on those same variables (Conde *et al.*, 2007 and references therein). The main reason for that was the differential growth response of skin and inner mesocarp tissue to water deficit, although there may also be a direct stimulation of phenolic biosynthesis.

It was seen on Shiraz that berry weight was most sensitive to water stress during the post-flowering period and depending on methodology, less sensitive on other stages. The berries had a reduced sensitivity to water stress in the period following the post-flowering stage (McCarthy, 2000). Alexander (1965) suggested that grape berries

were extremely sensitive to water stress for approximately four weeks after flowering and then it was followed by a more resistant period. Insufficient water during the early period of rapid berry enlargement prevented the attainment of normal berry size. Applying water after this period would not enable undersized berries to become normal (Kasimatis, 1967 and references therein). Berry size was further decreased where severe water deficits occured in several successive years (Vaadia & Kasimatis, 1961).

In an irrigation trial carried out in Cabernet Sauvignon grapevines in Somontano, Spain, a reduction in berry size due to pre-véraison irrigation cut-off (PRE) was observed at harvest, as well as at the onset of véraison. This indicated that berry growth of field grown grapevines was sensitive to grapevine water deficits one to two weeks before véraison. Non-irrigated grapevines (control) had lower berry weight than the PRE grapevines, which show that the reduction in berry growth due to water deficits before véraison depended upon both the severity and the duration of the deficits (Sipiora & Gutiérrez Granda, 1998 and references therein). Yield in the PRE treatment was reduced by more than 1 kg per grapevine.

When water stress treatments were applied to Cabernet Sauvignon grapevines in Santiago, it was shown that stressed treatments significantly reduced berry weight and berry size (Ferreyra *et al.*, 2004) and that the yield was mainly reduced when no water was applied between budburst and véraison. This agreed with an experiment in Chile on seven year-old Cabernet Sauvignon grapevines which showed that the berry size and yield was reduced by water stress, especially if water deficit was applied during pre-véraison (Acevedo *et al.*, 2004). A study carried out near Lodi, California in Cabernet Sauvignon grapes resulted in a yield reduction between different irrigation treatments. Treatment 1 was supplied with adequate water (100%) to maintain favourable grapevine water status during the season and produced the highest yield of 37.3 lbs per grapevine or 24.3 tonne per ha (t/ha). The 70% potential water use treatments averaged 29.6 lbs per grapevine and the 50% of full water treatments resulted in the lowest yield of 24.5 lbs per grapevine or 66% of the full water treatment (Prichard & Verdegaal, 1998). This was in agreement with Chapman *et al.* (2005) which found that minimally irrigated treatment yielded 15.0 t/ha Cabernet Sauvignon grapes versus the double irrigated treatment which yielded 21.7t/ha. In a trial in seven year-old irrigated Cabernet Sauvignon grapevines located in the Pencahue valley, Chile, water stress reduced the total yield and berry size, especially in grapevines under pre-véraison water deficit (Acevedo *et al.*, 2004). In the Priorat region, Spain it was shown that Cabernet Sauvignon yield per hectare increased by 37% in the irrigated grapevines compared to the non-irrigated grapevines. Yield per grapevine was 26% higher when irrigated. However, there was no difference in the yield to pruning weight ratio, indication a positive effect of the water supply to the grapevine's vigour. A decrease in berry size and drought symptoms was observed in the non-irrigated grapevines. This "positive" effect of irrigation on yield was also seen in other non-irrigated grapevines trials. In a study carried out in Requena, Spain on Tempranillo, irrigation increased the yield with an average of 31%, primarily because of increased berry weight (Intrigliolo & Castel,

2008). In a study on non-irrigated Cabernet Sauvignon grapevines in Sicily, Italy, grapevines growing under moderate water stress conditions showed higher yield and dry matter per shoot compared to grapevines growing under dry, non-irrigated conditions (Santalucia *et al.*, 2007). Under non-irrigated conditions, irrigation could be seen as a tool to increase yield without a detrimental impact on wine composition.

In a Cabernet Sauvignon trial in Santiago, Chile, a relationship between water deficit and yield decrease was observed. Differences in yield during the first season was not related to the number of clusters, but rather to the individual cluster weight as well as berry weight, since a similar number of clusters were recorded for all the treatments (Ferreyra *et al.*, 2004). A relationship between water deficit and return flowering was observed, where a significant decrease in clusters per plant and berries per cluster were observed. Effects on floral induction could be the main reason of the yield decrease where no irrigation was applied until véraison and thereafter 100% of crop evapotranspiration (Etc) being applied throughout the rest of the season. In other reports it was found, that even after véraison, water stress decreased the bunch numbers in the next season (Intrigliolo & Castel, 2008).

During a study on Cabernet franc grapevines the yield effects could be ascribed to a lack of photosynthesis and loss of turgor in fruit together with complete fruit desiccation and interference with cell division (Hardie & Considine, 1976). Photosynthesis in grapevines was directly related to stomatal aperture. Photosynthesis decreased as Ψ_L approaches -0.5 MPa and ceased at a critical Ψ_L of ca. -1.2 MPa (Hardie & Considine, 1976 and references therein). It was also reported that a five day lag in photosynthesis recovery exist after rewatering of droughted grapevines, despite rapid recovery of leaf water status. Reference in Hardie & Considine (1976) cited that reduced carbohydrate availability caused by defoliation and a low leaf area per unit of fruit caused poor colouration in a number of varieties. According to Hardie & Considine (1976), stress during the normal colouration period caused a decrease in colour on the basis of both unit skin area and berry volume. The effect could probably be attributed to reduced carbohydrate availability.

During a trial in the warm regions of the Murray-Darling Basin, Australia it was found that Cabernet Sauvignon grape colour was strongly negatively correlated with berry weight, but poorly with yield (Stevens *et al.*, 2004). Reducing berry size by applying deficit irrigation did not increased colour. It also showed that the management practices that improve Shiraz fruit colour, like reducing berry size by applying deficit irrigation, did not translate directly to improve Cabernet Sauvignon fruit colour (Stevens *et al.*, 2004). However, analysis of winery data sets showed good evidence that Cabernet Sauvignon colour intensity declined concomitantly with an increase in the duration that fruit was left to hang after 1 January and increased with fruit exposure, but only weak evidence that colour intensity declined with increase in yield. Cabernet Sauvignon management strategies which improve the rate of ripening might lead to improvements in fruit quality quantified as colour intensity. Smaller berries had higher anthocyanin concentration (Stevens *et al.*, 2004).

When day temperatures reach above the maximum temperature range of 15ºC to 25ºC for optimum red grape colouring (Kliewer, 1977; Iland, 1989), berry size is an important potential quality parameter because of the increase in pulp to skin ratio and greater extractability obtained by smaller berries (Hunter & Myburgh, 2001). Efforts should be done to manage water availability during the berry cell division stage to reduce berry size, without negative effects on canopy capacity and other processes such as sugar accumulation, acid production, berry colouring and flavour production.

The incidence of bunch rot in grape cultivars which have compact clusters, had increased with irrigation regimes that is favourable for the development of large berries (Vaadia & Kasimatis, 1961). Just before harvest excess water should be avoided since it could increase berry size and cause a dilution of solutes, e.g. sugars, acids, anthocyanins and tannins, or cracking of berries (Conde *et al.*, 2007 and references therein).

Fruit stress symptoms before véraison include flaccid or shrivelled berries in the afternoon, but if the berries retain turgidity in the evening, the grapevines were not necessarily over-stressed. This condition could lead to small berries that would make a more highly structured wine. After véraison, puckering or shrivelling of berries indicate an over-stressed condition. During ripening, flaccid or shrivelled berries would never recover their turgidity and could result in loss of both yield and wine quality. Shrivelling of berries due to water stress, would be seen on fruit all over the grapevine, but the rachis would remain green (Greenspan, 2005). According to Hardie & Considine (1976) water stress caused shrivelling of berries at all stages of development, but would be first observed in the most immature berries on any cluster and usually disappeared upon watering. Complete desiccation was generally confined to those berries less than 4 mm in diameter. Water deficits could also have an effect on the timing of colouring as well as the simultaneously colouring of berries (Hardie & Considine, 1976). Berries exceeding about 4 mm in diameter acquired some resistance to complete desiccation. Delayed colouration was probably associated with those berries which barely exceeded the critical size when stress was applied.

Irrigation could have an indirect effect on reproductive development due to increased and prolonged vegetative growth. Water availability in luxurious amounts would result in excessive grapevine growth (Kasimatis, 1967). Active shoot growth in the pre-véraison stage may compete for carbohydrates available for fruit ripening. Increased vegetative growth may also impair cluster microclimate, particularly fruit light exposure. Excessive irrigation could also lead to a delay in accumulation of sugar. Van Leeuwen *et al.* (2004) found in Bordeaux, France from 1996 to 2000, that the good vintages in term of grape quality, was in 1998, when grapevine water uptake was limited early in the season (pre-véraison), but still moderate. Pre-véraison grape quality was affected indirectly by provoking early shoot growth cessation and reduced berry size. When vigorous varieties tend to grow into fall, irrigation should be withheld after midsummer to promote ripening of the wood (Kasimatis, 1967).

High shoot vigour, excessive irrigation, shade, high gibberellic acid (GA) levels and a reduction in bud carbohydrates have all been associated with primary bud necrosis (PBN) of Shiraz (Collins & Rawnsley, 2008 and references therein). Endogenous GA levels were greater in buds from vigorous grapevines than buds from grapevines that were not vigorous. A level of PBN of greater than 20% could have a significant impact on fruitfulness and therefore final yield (Collins & Rawnsley, 2008 and references therein). The processes involved in floral initiation appeared to coincide with the commencement of PBN. High GA levels have been associated with excessive cell elongation and the imbalances of hormones and changes in cell development may lead to an increase in necrosis of the primary bud. Gibberellin produced in seeds could influence the development of uncommitted primordial into tendrils and subsequently inhibit floral development. The inhibition of flowering by GA was normally associated with stimulation of vegetative growth. In this study on Shiraz in the Barossa Valley, Australia, it was found that the incidence of PBN was related to shoot vigour, which was closely associated with changes in GA concentration (Collins & Rawnsley, 2008). Dry & Coombe (1994) also found that PBN was the highest in the most vigorous vineyards. Primary bud necrosis was positive correlated with indices of shoot vigour (cane diameter, total number of lateral shoots per cane and percent nodes with lateral shoots). Thick shoots had a higher incidence of PBN than thin shoots at all node positions and the incidence of PBN was higher at basal nodes than more distal nodes. This phenomenon was magnified as shoot diameter increased. Increased severity of shoot thinning resulted in increased vigour of the remaining shoots and an increased incidence of PBN that further confirm the correlation between shoot vigour and PBN. In Shiraz for any node with PBN, there was a two to four times greater chance of that node having a lateral shoot than not. The authors believe that shading is not a major cause of PBN. Any association between shading and PBN incidence was an indirect consequence of the poor light environment within the canopies of vigorous grapevines. They also proposed that the reduction in bunches associated with high vigour, was due to an increased incidence of PBN which resulted in a change in the ratio of secondary to primary shoots, particularly at basal nodes. Average fruitfulness (bunches per shoot) was decreased by the replacement of the relatively fruitful primary shoots by less fruitful secondary shoots. High grapevine shoot vigour, high levels of soil N, canopy shading and exogenous application of GA as well as climatic and cultural conditions that favour excessive shoot vigour and induce low bud fruitfulness had been shown to correlate with high levels of PBN (Dry & Coombe, 1994 and references therein). Bud sectioning showed that PBN developed after flowering and reached maximal levels at one to three months post-flowering and that it was the highest in the basal nodes one to eight.

During a study carried out by Archer & Strauss (1989) in the Stellenbosch region, South Africa, it was seen that Cabernet Sauvignon bunch mass, berry mass and yield decreased due to shading. The yield of the "control" was 4.62 kg per grapevine compared to the "double shading" experiment which yielded 2.44 kg per grapevine.

Unfavourable microclimatic conditions during full flowering and subsequently fruit set probably caused this morphological degeneration.

During a study carried out on Cabernet Sauvignon grapevines in Oakville, California the effects of leaf shading was compared to the effects of cluster shading under conditions of identical grapevine vigour and viticultural practices. The rates of berry growth were slower in fruit from grapevines with shaded leaves (Morrison & Noble, 1990). The larger size of shaded fruit under conditions where leaves were well exposed may be due to lower temperatures and reduced transpiration in the shaded fruit zone. The smaller fruit size in the shaded leaf treatments was likely due to a decrease in photosynthesis and carbohydrate transport from the shaded leaves. Fruit size directly affected the concentration of all soluble components in the fruit. The effects of leaf and cluster shade on fruit composition were probably a combination of the direct effects of light and the indirect effects of temperature. In field conditions it was difficult to separate the two (Morrison & Noble, 1990).

On the other hand, severe water stress could also be indirectly detrimental to fruit quality because of poor canopy development and reduced leaf assimilation rate and thus an inadequate grapevine capacity to ripen the fruit (Intrigliolo & Castel, 2008 and references therein).

2.5   WINE QUALITY

What is the objective: "To make the best wine possible, or to focus on what sells, in other words, what the consumer wants?" Although it is possible to chemically measure odour active chemicals in wine, it is difficult to create a model that would predict the interactions of the chemicals that lead to flavour perception (Norris *et al.*, date unknown). Wine flavour is the result of complex interactions of non-volatile and volatile compounds as perceived in the mouth (Norris & Lee, date unknown).

Wine quality has traditionally been defined by the perception of flavour by experts or by simple analytical measurements, such as volatile acidity (VA) and alcohol. Not everyone has the same wine preferences, so it becomes advantageous to define quality as the flavour perceived by the targeted consumer population. Thus quality is based on "fit for purpose", that is the development of wine styles for a targeted population (Norris & Lee, date unknown). It has been seen by research carried out in Australia that consumers preferred the taste of highly coloured wines, even when they were not aware of the colour. There seems to be a high correlation between colour and perceived wine quality by the consumer (Warner, G., date unknown).

In an article by Richard Thomas (2002) on "What defines quality?" he asks "Is availability of fruit the real tail that wags the quality dog?" He suggested that the moral is that growers should be paid based on the quality of fruit delivered to the winery and that should be based upon the quality of the wine that it makes.

According to Guinnard *et al.* (1999) quality could be measured by expert ratings, trueness to type, absence of defect, or consumer acceptance. Different results may be obtained depending on which definition of quality was chosen in a study.

Optimal grape maturity is essential for wine quality, but it is difficult to assess because it is under multifactor control, involving the specific cultivar and environmental parameters such as soil, temperature, exposure to sun and hormonal regulation.

2.5.1 CABERNET SAUVIGNON AROMA

2.5.1.1 The "green" character

Cabernet Sauvignon has a stronger tendency than other red cultivars to produce strong capsicum and herbaceous characters (Winter & Hand, 2003). These characters could be attributed to the grape derived flavour compounds, methoxypyrazines (MP) (Allen & Lacey, 2003). Pyrazines are nitrogen heterocyclic molecules (Allen & Lacey, 2003). The potential of 2-methoxy-3-isobutylpyrazine (IBMP) to contribute a vegetative or herbaceous aroma to Cabernet Sauvignon wine flavour was first reported by Bayonove *et al.* in 1975. Later work by Augustyn *et al.* (1982) implicated that this compound is also found in Sauvignon blanc flavour. Concentrations of IBMP, the dominant MP, is perceptible at 0.5 ng/L to 2 ng/L in water, synthetic and white wine and at 10 ng/L to 16 ng/L in red wine (references in Sala *et al.*, 2005). The next most abundant MP is propyl methoxypyrazine (IPMP) with characteristics of cooked asparagus, peas, beans, potato and earthy (Seifert *et al.*, 1970). The sensory detection threshold of IPMP in water is 2 ng/L (Sala *et al.*, 2005 and references therein). Concentration levels of the third MP, sec-butyl methoxypyrazine (SBMP), are very low and are of academic, rather than practical, interest (Allen *et al.*, 1990). Sec-butyl methoxypyrazine could be detected by the human nose at 1 ng/L in water (Sala *et al.*, 2005 and references therein). These three components could occur in berries and wine at levels higher than their sensory detection threshold and have an important impact on wine quality (Sala *et al.*, 2005 and references therein).

At low levels, vegetative aromas such as bell pepper or asparagus contribute to the distinctive varietal aromas of Cabernet Sauvignon, Merlot and Sauvignon blanc wines. The general term "vegetal" could be applied to a wide range of aroma notes. Many sulphur-containing compounds elicit related aromas such as asparagus, cooked corn, cassis, boxwood and rubber (Preston *et al.*, 2008 and references therein). The norisoprenoids could also contribute to the vegetal-related aromas of wines, including the aroma of green, cut grass associated with a norisoprenoid-related compound, 1-buta-1,3-diene (Preston *et al.*, 2008 and references therein). The use of the term "vegetal" is complex, consisting of many related aromas, and precise terminology for vegetal-related characteristics is necessary when communicating about wine sensory properties. At high levels, these vegetal aromas may be considered undesirable or suggest possible defect (Preston *et al.*, 2008 and references therein). Methoxypyrazines are the most influential contributor to herbaceous flavours in wine. "Green" becomes a

problem when it is overpowering and out of place. According to Dr. Patrick Iland, the green character of Cabernet Sauvignon could be described as "herbaceous, vegetative and/or capsicum, the mouthfeel as drying, thin, hard, harsh, grippy and/or aggressive and the taste as acidic and bitter". Seeds were a major source of these phenolic compounds that contributed to the bitterness, astringency and drying mouthfeel sensations (Winter & Hand, 2003). Bogart, K (2006) stated that grapes with vegetal characteristics were most often physiologically immature that often led to a lack of colour development and harsh tannic quality in the wines produced of these grapes. Some other contributors to green flavours are C6-, C9-aldehydes/alcohols, phenols, thiols/mercaptans, terpenoids, MP, dimethyl sulphide (DMS), ladybirds, locusts, matter other than grapes (MOG) during crushing and eucalyptus trees within a range of 50 m to vineyards (Mckay, 2009). Furthermore, because of Cabernet Sauvignon's higher number of seeds and also a high skin to pulp ration, it is important to pay attention to skin and seed maturation (Winter, 2004). Phenolic compounds could impart bitter tasting herbaceous flavours to grapes and wine. Berry sensory analysis before harvest could reveal a lack of seed ripeness. Seed ripening seems to need continuous warmth on bunches, but not excessive heat loads. Maintaining bunches at less than $35^{\circ}C$ and optimal soil moisture is important. The optimum range for enzyme activity is $15^{\circ}C$ to $35^{\circ}C$. Little is known about viticultural practices that could influence the formation of grape lipids, precursors of herbaceous aromas. Lipids are produced in green tissue, such as stems and unripe berries. Formation of these herbaceous flavours involved the activity of lipoxygenases and hydrolases before and during fermentation. The quantity of these enzymes depended on the amount of green matter at harvest, enzyme inhibition by sulphur dioxide (SO_2) after harvest, and contact of the berries with oxygen. Post-harvest grape handling that reduced oxygen contact is a preventative measure against hay-type green characters (Winter, 2004).

The IBMP is assayed in wine using stable isotope dilution gas chromatography-mass spectrometry (GC-MS) (De Boubee *et al.*, 2002 and references therein). These compounds exist in a free state in grapes and no precursors have been identified. Methoxypyrazines are produced by the metabolism of amino acids (Conde *et al.*, 2007 and references therein).

The analysis of pyrazine concentrations alone may give an incomplete picture of factors that could impact vegetal aromas. This is particular important to consider, given that many aroma compounds are present in grapes and produced during winemaking. Therefore, even when viticultural practices were optimized to result in low IBMP levels, vegetal wines may still result (Preston *et al.*, 2008). In a study carried out by Preston *et al.* (2008) on 16 Cabernet Sauvignon wines of California, no significant relationship were obtained between the vegetal aroma perception as determined by descriptive analysis, and the pyrazine concentrations. The qualitative differences in vegetal aromas could be defined and quantified, and it appeared that the major factor distinguishing these wines was the contrast between combined vegetal characteristics and the non-vegetal or fruity characteristics (Preston *et al.* 2008).

Methoxypyrazine formation occured between fruit set and ca. two to three weeks prior to véraison (Allen & Lacey, 2003). Ryona *et al.* (2008) found in Cabernet franc grapevines that the earliest observations to date of IBMP at quantifiable levels (2 to 7 ppt) were observed at five days post-flowering. The majority of IBMP accumulation was observed three to six weeks post-flowering, and IBMP degradation began two weeks before véraison. Thus the total amount could be reduced by achieving water stress during this period. Pyrazines compounds were gradually destroyed by sunlight as the grape ripens. It was shown that initial pyrazine concentrations were less in the drier years in France (Bogart, 2006). However, it was also showed that it is weather conditions just prior to and during véraison that has the most impact on MP concentrations in grapes, rather than the period between véraison and harvest. The decrease in MP concentrations in berries from about three weeks before véraison, through to harvest, was independent of the dilution that occured during berry enlargement. Thus unlike tartaric acid, MP was actually broken down as the berry swelled and ripened (Bogart, 2006). High water content before and after véraison seemed to delay the offset of MP degradation (Winter, 2004).

Methoxypyrazines follow nearly the exactly same curve as the decline of MA concentration (Winter & Hand, 2003; Allen & Lacey, 2003), but were differently affected by cluster exposure pre- and post-véraison (Ryona *et al.*, 2008). Significant higher levels of IBMP were detectable at all pre-véraison time points in shaded clusters. The un-shaded clusters had 21% to 44% lower IBMP and these differences did not increase post-véraison, indicating that cluster exposure reduced accumulation of IBMP and did not increase IBMP degradation post-véraison (Ryona *et al.*, 2008). In contrast to MP, MA could be more readily measured in a laboratory. Since MA was decomposed faster as night temperatures increase, warm nights may also assisted in reducing MP levels (Winter, 2004).

Regardless of ripeness, IBMP is mainly located in stems, then in skins and seeds, while the flesh contained very little (De Bouree *et al.*, 2002). According to Bogard (2006) regardless of the phenological stage, the pulp contains very little MP, while stems and older leaves contain a lot. In Cabernet Sauvignon grape bunches at harvest 53.4% of IBMP were located in the stem. The proportion of IBMP decreased in the stem and increased in the skin between véraison and full ripeness (de Bouree *et al.*, 2002). According to Winter & Hand (2003), after véraison most of the MP was located in the grape skin. In the grapevine MP content could also be very high in stems and leaves. A large proportion of leaves in must or exposing stems to significant extraction could lead to higher levels of MP (Winter, 2004). Thus the amount of MOG in mechanical harvested loads transported to the wineries could have an influence on the MP levels of the final juice or wine. During this period of MP formation early in berry development, much of it was transported and redistributed from the leaves (source) to the fruit (sink). Thus more vegetative growth equals more MP. Early removal of leaves and laterals reduced MP concentrations in fruit, by increasing light intensity, but also by decreasing

the source of MP. It appeared that MP synthesis was related to vegetative growth (Anonymous, 2006b).

Allen *et al.* (1990) found that climate had a strong influence on the levels of MP in grapes, with higher levels under cooler conditions. A higher humidity in the pre-véraison month would result in higher IBMP contents in the grapes at harvest. On the other hand, a sunnier and less humid year led to lower IBMP amounts. The levels of IBMP were again higher in the year with frequent rainfall. The reconstitution of soil water reserves favoured the growth of the grapevine until harvest, which, in turn, increased the production and retention of IBMP, and was given as the explanation (Sala *et al.*, 2005 and references therein). It was also found that the concentrations of IBMP, the dominant MP, decrease with an increase in grape exposure to sunlight (Marais, 1996).

Analyses of a range of Australian and New Zealand Cabernet Sauvignon based wines showed that the IBMP concentration correlated well with the mean January temperature (MJT) of the growing region, confirming that after grape selection, the most important factor for MP production was the growing temperature (Allen, 2001). According to Allen & Lacey (2003) IBMP concentrations typically present in Bordeaux Cabernet Sauvignon wines were ca. 10 ng/L. This level was attained in Australian wines produced from grapes of regions with a mean January temperature (MJT) of ca. 20ºC, such as McLaren Vale (South Australia), Seymour (Victoria) and Frankland (Western Australia).

Cabernet Sauvignon press wine contained higher IBMP contents than free-run wines. The IBMP content of the wine depended mainly on the composition of the grapes. Focussing on the vineyard and vineyards practices were thus important (Anonymous, 2006b).

2-methoxy-3-isobutylpyrazine is highly extractable in wines (de Bouree *et al.*, 2002). Termovinification was the most documented method for reducing MP concentrations (Anonymous, 2006; Bogart, 2006) and it appeared that there are little cellar practices that are going to alter the amount of MP in the wine. Methoxypyrazines was found to be volatized and dissipate into the headspace after heating above 50ºC. Using termovinification conservatively could lead in certain cases to more highly coloured, fruity and less vegetal wines (Bogart, 2006).

During vinification of Cabernet Sauvignon grapes it was found that the must had a similar IBMP content 24 hour after it was put into vat to that of the wine at the end of the vatting period. Most of the IBMP of the free-run wine was extracted in aqueous phase before alcoholic fermentation started. Under micro-vinification, extraction of the IBMP from grapes into must was even faster and the concentrations did not increase when the cap was punched down during fermentation or when the wine was left on the skins after fermentation (de Bouree *et al.*, 2002). It was also shown that IBMP was easily extractable in an aqueous medium and that the concentration in free-run wine was principally determined by that in the grapes, while it was relatively unaffected by vatting conditions. However, the IBMP content of press wine may be higher than that of free-run wine. Part of the IBMP associated with grape solids may be extracted as a result of mechanical pressing operations (de Bouree *et al.*, 2002). In Cabernet Sauvignon it was

found that the amount of pyrazine found in wine after racking, have been extracted from the grapes within 24 hours of crushing, before alcoholic fermentation began. Methoxypyrazines were highly extractable in grape must, however it has been shown that press juice contain higher levels of MP. Thus a fraction of MP may remain in the skins and was extracted during rigorous pressing. Furthermore, there was no significant change in the amount of MP in Cabernet Sauvignon wine that was aged for three years in a dark cellar which showed that ageing was not an effective method to decrease vegetal character (Allen & Lacey, 2003).

It was shown during vinification of Sauvignon blanc grapes that IBMP was easily extractable from grape as soon as they were crushed and in the early part of the pressing cycle. Thus IBMP was easily extractable at the beginning of the winemaking process and the final concentration in the wine was relatively unaffected by the methods used. The IBMP concentration of the first free-run juice and the final blend were quite similar. Furthermore, clarified must (200 NTU) contained approximately half as much MP as untreated must. Some of the IBMP seemed to be associated with the lees and was therefore eliminated when the must was clarified. Thus settling had more impact than pressing on the IBMP content of white must (de Bouree *et al.*, 2002). According to Bogart (2006) it has been shown that settling of white wines for example, Sauvignon blanc, may reduce grassy characters.

2.5.1.2 Fruity aromas

The fruity aromas in Cabernet Sauvignon are due to esters, acetate esters, fatty acids and norisoprenoids (Chapman *et al.*, 2005). Factors such as increased light exposure and temperature have been shown to decrease IBMP and bell pepper aromas. This may also increase norisoprenoid concentrations, although effects on sensory properties in the latter studies are unknown (Preston *et al.*, 2008 and references therein). References in Marais (1996), reported that the norisoprenoid concentrations in Cabernet Sauvignon sun-exposed grapes were higher than those of shaded grapes. A recent study indicated that fruity aromas may significantly decrease perception on bell pepper aromas in wine, even when the concentration of the bell pepper aroma compounds did not change (Preston *et al.*, 2008 and references therein).

In grapes, norisoprenoids occur mainly as glycosidically bound precursors which when extracted into wine, could contribute to the aroma (Asimon & Ebeler, 2002).

1,8-Cineole has been reported as one of the major constituents responsible for the characteristic aroma of black currant in various cultivars (Bitteur *et al.*, 1990).

Cabernet Sauvignon is one of the more neutral cultivars not dependent upon monoterpenes for the varietal flavour (Conde *et al.*, 2007 and references therein).

Fruit-derived C_{13}-norisoprenoids were thought to originate from carotenoid precursors in grapes. The induction of the specific carotenoid cleavage dioxygenase gene occured at véraison which coincided with the characteristic sharp decrease in total carotenoid content and concomitant increase in the formation of C_{13}-norisoprenoid precursors (references in Bindon *et al.*, 2007). Increased incidence of sunlight on

developing grape bunches mediated the accelerated decrease of carotenoids after véraison. C_{13}-norisoprenoids concentration could be increased by full sunlight compared with shaded conditions. This accumulation of certain C_{13}-norisoprenoids was more strongly affected by sunlight than others. For instance ß-damascenone concentration was unaffected by sun exposure whereas 1,1,6-trimethyl-1,2-dihydronaphthalene (TDN) concentrations could be increased by up to 52% by sun exposure (Bindon *et al.*, 2007 and references therein). Water stress could indirectly affect the light environment of developing fruit through a reduction in shoot growth rate and grapevine leaf area and thus influence the metabolism of carotenoids and the precursors of C_{13}-norisoprenoids. However, due to the close relationship of the metabolic pathways for carotenoids and stress-related plant hormones such as ABA it was possible that there may also be a direct effect of water stress on the metabolism of carotenoids and C_{13}-norisoprenoids (references in Bindon *et al.*, 2007). The most abundant carotenoids in Cabernet Sauvignon fruit was ß-carotene and lutein.

During a study carried out on Cabernet Sauvignon in Langhorne Creek, South Australia it was seen that the partial rootzone drying (PRD) treatment increased the hydrolytically released ß-damascenone and TDN concentrations in the PRD-treated fruit in both the 2001/02 and 2002/03 seasons. ß-ionone concentrations were only significantly higher in PRD-treated fruit the 2002/03 season. TDN was the compound most significantly affected by PRD treatment. In the 2001/02 season it was speculated that the relative increase in concentration of ß-damascenone and TDN in response to PRD was mainly due to a reduction in berry size. However, there were a more significant increase in the concentration of ß-damascenone and TDN per gram of fruit in 2002/03 compared to 2001/02. This was also reflected by a significant increase in the content of these components per berry, despite the fruit weight reduction with PRD. It was therefore more likely that biochemical changes induced by PRD caused the changes in C_{13}-norisoprenoid concentration, rather than a change in berry weight alone (Bindon *et al.*, 2007). From their study it was evident that the effect of sunlight on developing bunches could not have operated in isolation to bring about the observed changes in C_{13}-norisoprenoid concentration. The findings of the study suggested that irrigation strategy could induce changes in the glycosylated precursors to volatile C_{13}-norisoprenoids in grapes, which could potentially be recovered in wines during crushing and fermentation (Bindon *et al.*, 2007). The reported levels in this study represent hydrolytically released C_{13}-norisoprenoids, which gave an estimate of the maximum amount of precursor available for hydrolytic release during the aging process of wines. It gave an indication of the potential of irrigation management to influence the volatile profile of fruit and resultant wines. To conclude it was found that deficit irrigation could be associated with an increased in the fruity characteristics in Cabernet Sauvignon wines. A chemical candidate for this response could in part be ß-damascenone, which has a complex fragrance of flowers, tropical fruit or stewed apple. It could be detected by human senses at low concentration, with perception thresholds of 2ng/L in water and 45ng/L in dilute alcohol solution (Bindon *et al.*, 2007 and references therein). However

TDN may impact negatively on wine sensory characteristics with a kerosene-like odour at high concentrations. This compound is an important varietal character to the aroma of Riesling wines.

2.5.2 THE EFFECT OF GRAPEVINE WATER STATUS ON WINE STYLE AND QUALITY

2.5.2.1 Juice and wine chemical analyses

Prichard & Verdegaal (1998) found that when grapes were harvested at the same total soluble solids (TSS), pre-véraison water stress enhanced soluble solids in Cabernet Sauvignon grapevines. It also appeared that pH was reduced more if deficit was imposed pre-véraison. The pH, tartaric acid, MA and K concentration of the juice was higher for grapevines which received adequate water (100%) during the season, compared to treatments of 70% en 50% of full water potential. However, post-véraison water stress had adverse effects. Furthermore, the best results were obtained with a 30% reduction in water use and when early (pre-véraison) deficit was applied compared to grapevines that received adequate water for the whole season. It resulted in reduced wine pH and K concentration and an increase in colour density (420 nm + 520 nm). This increase in quality was achieved by a 19% reduction in yield, still producing a yield of ca. 19.75 t/ha (Prichard & Verdegaal, 1998). Cabernet Sauvignon grapevines growing under moderate water stress, compared to non-irrigated, in Sicily, Italy showed an increase in sugar and phenols in a semi-arid climate with a loamy sand soil (Santalucia *et al.*, 2007). The grapes also had less acidity with higher total anthocyanins as milligram per berry but less total antocyanins and flavonoids as milligram per kilogram of grape because of the smaller berry weight of non-irrigated grapevines.

In an irrigation trial in Cabernet Sauvignon in Somontano, Spain it was shown that when irrigation was cut-off before véraison (PRE), i.e. discontinued at the end of July, ca. two weeks before véraison, and when no irrigation was applied (control), TSS of fruit at harvest was significantly lower compared to when irrigation was cut-off after véraison (POST), i.e. when irrigation was applied from April and discontinued at the end of August. Fruit from the PRE treatment had higher acid and lower K concentration compared to the fruit from the POST treatment. No significant difference was observed between the MA concentrations. There were no significant differences in sugar concentration, pH and K concentration between fruit from the PRE and the non-irrigated control. Severe grapevine water deficit before véraison retarded sugar accumulation and delayed fruit maturity. A reduction in sugar concentration was already seen at véraison, where irrigation was cut-off two weeks earlier. This suggested that the period of rapid sugar accumulation at the onset of véraison was sensitive to grapevine water deficits. The PRE treatment did not result in an increase in concentration of anthocyanins or total phenols in the finished wines, although the berry size was smaller compared to the POST treatment. Therefore the benefits of a smaller berry were outweighed by a 22% yield reduction. It was shown in this particular study that skin

contact time had a larger influence on total phenol and anthocyanin concentration of the finished wines, than irrigation. Based upon the results, oenological practices, such as extended skin contact, must acidification, control of fermentation temperature or adjustment of skin to juice ratio during fermentation, were recommended more than irrigation management of berry size for manipulation of the anthocyanin and total phenol content, anthocyanin equilibriums and wine colour of finished wines (Sipiora & Gutiérrez Granda, 1998). The irrigation treatments had a significant influence on the classical parameters of wine composition, i.e. ethanol, pH and acidity, while skin contact time did not influence these parameters. The main objective of the PRE treatment, to increase the extraction of anthocyanins was accomplished. The skin contact was only imposed five days after harvest. However, the PRE treatment also favoured the loss of anthocyanins at the end of fermentation. It was shown that PRE wines had lower pH, higher acidity, lower K concentration, lower etanol content and a higher colour hue (A420/A520) than wines from the POST treatment. These differences in wine composition due to irrigation were the same at both skin contact times. The concentration of total anthocyanins in the finished wines was significantly lower in the PRE wines than in the POST wines at both skin contact times. Grapevine water deficits during the first two weeks after the onset of véraison, where there was rapid increase in the concentration of anthocyanins in the skin, have been shown to have the greatest influence on final concentration of anthocyanins in fruit (Sipiora & Gutiérrez Granda, 1998).

Although water deficit had a less pronounced effect on sugar accumulation compared to berry growth, when it occurred at post-véraison, fruit sugar was often reduced rather than improved. Malate concentration decreased primarily due to water deficit pre-véraison (Conde *et al.*, 2007 and references therein). Hardie & Considine (1976) also found in their trial that ripening was delayed by all stress treatments and that berries stressed after véraison did not ripen completely. Delay in ripening was directly proportional to crop load remaining after stress. Berries appeared to be most sensitive during the lag phase to the ripening delay induced by stress. At least part of the delay in ripening appeared attributable to diversion of available carbohydrate into the development of lateral shoots after stress periods. The commencement of pigment accumulation at véraison was directly related to carbohydrate metabolism and could depend on attainment of a threshold sugar level. Induction of a high sugar concentration through temporary shrivelling of berries may explain early colouration of berries (Hardie & Considine, 1976 and references therein). The work of Nadal & Arola (1995) on Cabernet Sauvignon grapevines in the Priorat region, Spain showed that during ripening the increase of sugar and the decrease of acids were delayed in non-irrigated grapevines. The irrigated grapevines were harvested one week before the non-irrigated grapevines. In berries of irrigated grapevines acidity decreased progressively until the middle of September to ca. 6.3 g/L tartaric acid, whereas in the non-irrigated grapevines the acidity hardly varied until the end of September when it decreased to 6.5 g/L. They

showed that moderate irrigation during July and August, when water stress was more severe, could be beneficial for grapevine growth and wine quality.

According to Choné *et al.* (2001) early water deficits and lower N status throughout the growing season had beneficial effects on total berry phenolic contents and wine quality of Cabernet Sauvignon in Bordeaux, France. This was probably due to the limiting effect on the grapevine vigour by both of these factors. In a study carried out in Cabernet Sauvignon grapevines in the Maipo Valley, Chile, it was seen that vigour alters the concentration of all phenolic compounds in skins and seeds of grapes during ripening. Furthermore, at the end of harvest, samples from low vigour grapevines were different in their flavanol concentration when compared with the other vigour groups. The concentration of the most important flavonols, i.e. (+)-catechin and (-)-epicatechin, and the majority of the procyanidins, were higher in seeds but lower in skins of low vigour grapevines compared to medium and high vigour samples (Neira-Pena *et al.*, 2004). The vegetative parameters used to classify the vigour according to "low", "medium" and "high" was, diameter of shoots (mm), number of clusters, number of shoots, length of internodes (cm) and length of shoots (cm). Statistical analyses showed that the vegetative parameters were all different. In another study it was found that when pre-véraison water stress increased the total polyphenolic index and colour density of Cabernet Sauvignon wines increased (Acevedo *et al.*, 2004). The total polyphenols and anthocyanins of must increased as berry size decreased (Acevedo *et al.*, 2004). This was also seen by Stevens *et al.* (2004) in the warm regions of the Murray-Darling Basin, Australia that smaller Cabernet Sauvignon berries contained higher anthocyanin concentrations. In contrast, in a study carried out in Oakville, California, USA in Cabernet Sauvignon grapevines, it was shown that the skin tannin was relatively insensitive to berry size and the concentration of seed tannin generally increased with berry size. Sugar and anthocyanin concentrations decreased with increase berry size (Roby *et al*, 2004). The study showed that the composition of mature berries was not dependant in a simple way on the final size attained by the berry. The lower concentrations of soluble solids in berries from "high irrigated" grapevines of any size clearly showed that water deficit caused increased sugar accumulation. However the sugar concentration of the lowest irrigated grapevines was not the highest and that may indicate that the severity of the water deficit was sufficient to inhibit photosynthesis and translocation to the fruit. This suggested an optimum Ψ_L for sugar accumulation in Cabernet Sauvignon grapevines of between -1.2 MPa and -1.4 MPa. There was no berry shrivelling in this experiment, thus it was not likely that that could cause an increase in sugar or other solutes, but altered allocation patterns, may have been (Roby *et al.*, 2004). In the same experiment it was also shown that when berries of the same size were subjected to different irrigation treatments, both skin tannin and anthocyanin contents and concentrations, were greater in the "low irrigated" than in the "control" and "high irrigated" treatments. Thus the concentrations of skin tannins and anthocyanins were increased by grapevine water status that was independent in the role of water status in berry size, because the berries were of the

same size (Roby *et al.*, 2004). Although there maybe a direct stimulation of biosythesis, the primary way in which water deficits increased the concentrations of skin tannins and anthocyanins was probably the differential growth responses of skin and inner mesocarp tissue to water deficit (Roby *et al.*, 2003). Treatment differences largely disappeared when the concentrations of skin tannins and anthocyanins were evaluated on the basis of relative skin mass per berry. The similar skin mass of large berries from the "low" and "high" irrigated treatments suggested, that when growth was not restricted a similar skin mass developed. These observations imply little effect of grapevine water status on synthesis of tannins, or anthocyanins in berry skin when water status was altered after véraison (Roby *et al.*, 2004).

Wine colour intensity, phenols and anthocyanin concentration were higher, in stressed Cabernet Sauvignon grapevines in Santiago. The acidity increased when water stress was applied between véraison and harvest. It was also seen that the overall wine quality increased when grapevines were irrigated at 100% of the Etc from budburst to véraison and no irrigation was given from véraison until harvest (Ferreyra *et al.*, date unknown).

In a study carried out in Requena, Spain on Tempranillo, it was found that on average, irrigation had some negative effects on wine composition. It altered the balance between malic and tartaric acid, by increasing malic acid and decreasing tartaric acid. This led to an increase in wine pH that, together with a slight decrease in anthocyanin concentration, reduced the colour intensity. These effects might be attributed to a dilution effect. The higher vigour of the irrigated grapevines could also impair the cluster microclimate, reducing fruit light exposure (Intrigliolo & Castel, 2008). The larger canopy of the irrigated grapevines probably reduced cluster exposure to direct solar radiation and therefore cluster temperature. These conditions were favourable for the retention of MA and counteract the dilution effect by irrigation because of larger berries. Tartaric acid decreased in the wines probably due to the dilution effect. Malic acid is a weaker acid than tartaric acud, thus the overall effect is an increase of wine pH. Furthermore, wine colour also decreased by 18%, probably due to the increase in wine pH and decrease in anthocyanin concentration. An increase in wine pH would lead to a lower fraction of pigments in the coloured form. However, overall wine phenolic content and anthocyanin concentration were not clearly affected by irrigation (Intrigliolo & Castel, 2008 and references therein). Increasing yield linearly decreased wine alcohol content, but irrigation was able to mitigate, in part, the negative effects of increasing crop level.

In a study on drip irrigated Cabernet franc grapevines in Napa Valley, California, it was shown that the sugar concentration, acidity and K were slightly higher before véraison in early deficit (ED) grapevines, where water was withheld before véraison compared to the continual treatment (C) where water was supplied throughout the season or late deficit (LD) grapevines where water was withheld after véraison. This may be due to the moderate pre-véraison water deficit having a greater effect on fruit growth than on fruit metabolism. The acidity was slightly lower in ED grapevines at

harvest and thus the rate of acid loss was probably greater in the ED grapevines compared to the other treatments and most of the acid loss was probably due to the loss in MA. The MA at harvest of the full treatment where water was applied twice before véraison and twice after véraison (FD) juice was also low, which indicated that the pre-véraison water deficit decreased the final MA independent of grapevine water status during fruit ripening. The pattern of decline in tartaric acid after véraison suggests that the difference in MA may have been due to differences in catabolism after véraison rather than to the MA level at véraison. The large effect on MA and the relatively small effect on tartaric acid suggested that early season water deficits resulted in an increased tartrate to malate ratios (Matthews & Anderson, 1998). The responses of juice pH and K to seasonal deficits were similar since no difference between treatments were observed at harvest, although early deficit caused a slightly decrease in acidity. This study suggests that under those conditions, there appears to be limited potential to manipulate juice pH status with irrigation scheduling. The general sensitivity of juice pH to grapevine water status is not high and may be site- and variety specific (Matthews & Anderson, 1988 and references therein).

The concentration phenolics in the juice were dependant upon grapevine water status. Both the early- and late-season water deficits resulted in phenolic concentrations in the juice and dermal extracts which were more than 30% and 15% greater, respectively, than in the grapevines maintained at a higher water status throughout the season. The increase in phenolic concentration in the juice was similar to the decrease in fruit volume caused by low water status. However, the phenolic concentration in dermal extracts also increased when expressed on a surface area basis and is important due to the role phenolics play in determining the colour, bitterness and astringency of wines (Matthews & Anderson, 1988 and references therein). Colour development was more sensitive to grapevine water status in the early than in the late stages of the ripening process. The proline concentration, the primary free amino acid in juice, at harvest was higher in grapevines which were at low water status compared to grapevines at high water status. Amino nitrogen plays an important role in yeast growth during fermentation and proline levels had been correlated positively with summed amino acid concentration in ripening grapes (Matthews & Anderson, 1988 and references therein).

During a Cabernet Sauvignon study on sandy loam soil in Santiago, Chile it was found that when no irrigation was applied after véraison, maturity was reached before the other treatments. No differences in pH were found, but acidity was significantly greater for the wine when irrigation was suppressed after véraison. Phenolic compounds and anthocyanins concentration of wine significantly increased in treatments with water stress. The greatest increase in phenolic concentration was found when no irrigation was applied until véraison and then 100% of Etc (evapotranspiration) was applied throughout the rest of the season. The highest level of anthocyanins was found with irrigation of 100% Etc from budburst until véraison, and no irrigation throughout the rest of the season (Ferreyra *et al.*, 2004).

In seven year-old irrigated Cabernet Sauvignon grapevines in the Pencahue valley, Chile, pre-véraison water stress determined an enhancement of solid solids, but post-véraison water stress had an adverse affect on it. Total polyphenols and anthocyanins in the must increased as berry size decreased. In wines, the pre-véraison water stress led to a significant increase in the total polyphenol index and colour density that could be associated with a pre-véraison water stress and reduction of the berry size (Acevedo *et al.*, 2004). Research of Iland (1989) suggested that berries at harvest with higher concentrations of seed tannins and/or lower ratios of skin colour to seed tannins were more likely to produce wines with unpleasant mouth feel characteristics

In 25+ year-old un-irrigated Cabernet Sauvignon grapevines on an estate in Bordeaux, France it was shown that berry total nitrogen followed soil organic content rather closely (Xoné *et al.*, 2001).

Lopes *et al.* (2001) found on Tempranillo in southern Portugal that the water stress index (S_Ψ) in the period flowering to véraison, had a higher contribution to explain variation in berry weight, anthocyanins and phenolics concentration than the Ψ_{PD} in the period véraison to harvest. Negative dependence of berry weight and yield from S_Ψ in the period flowering to véraison showed the importance of early water deficit. The positive relationship between S_Ψ and the anthocyanins and phenolics concentrations appeared to be a consequence of the indirect effects of water stress on cluster exposure by leaf senescence, and in the skin to pulp ratio by berry growth. The higher contribution of the S_Ψ in the period flowering to véraison explained the variation in anthocyanins and phenolics concentrations and indicated that the degree of water stress experienced before véraison had an important role on the development of berry colour (Lopes *et al.*, 2001).

Due to shading the skin colour of Cabernet Sauvignon grapes were reduced (Archer & Strauss, 1989). The formation of anthocyanins is promoted by light and mainly light in the shorter wavelengths. Sugar concentration decreased while pH and K concentration increased with and increase in shading. These increases could be due to the inhibition of phytochrome driven enzyme reactions. The acidity increased mainly due to the increase in MA. However, the concentration of tartaric acid decreased with an increase in the level of shading. Eventual lower wine quality was achieved. It was seen that management practices that would increase canopy quality would increase grape and wine quality (Archer & Pienaar, 1993). During a study carried out in Cabernet Sauvignon grapevines in Oakville, California the effects of leaf shading was compared to the effects of cluster shading under conditions of identical grapevine vigour and viticultural practices. The rates of berry growth and sugar accumulation were slower in fruit from grapevines with shaded leaves. Leaf shading also decreased both the rate of pre-véraison malate accumulation and the rate of post-véraison malate decline. Malate, K and pH were higher in fruit from the leaf shading treatments at harvest. Shading clusters did not affect sugar, acid or K accumulation, but anthocyanins and total soluble phenols were lower in fruit that developed in shade. This data indicated that Cabernet Sauvignon was a cultivar in which phenylalanine ammonia lyase (PAL) activity in the

fruit was responsive to light exposure (Morrison & Noble, 1990). The larger size of shaded fruit under conditions where leaves were well exposed may be due to lower temperatures and reduced transpiration in the shaded fruit zone. The smaller fruit size in the shaded leaf treatments was likely due to a decrease in photosynthesis and carbohydrate transport from the shaded leaves. These fruit also had lower soluble solids content. Fruit size directly affected the concentration of all soluble components in the fruit. The effects of leaf and cluster shade on fruit composition were probably a combination of the direct effects of light and the indirect effects of temperature. In field conditions the two cannot be separated (Morrison & Noble, 1990). However, the authors were confident that in this situation the changes in berry composition were closely related to differences in light interception rather to temperature differences. Shading produced significant differences in the aromas of both fruit and wine. The largest differences were between the un-shaded control and the leaf shade or total shade treatments. However, these differences were not sufficiently pronounced for judges to consistently describe the differences (Morrison & Noble, 1990).

2.5.2.2 Wine sensorial attributes

It is difficult, but essential for sensorial evaluation of vineyard experiments if the ultimate objective was to manipulate wine sensory attributes through vineyard management. Sugar concentration, pH and acidity are the most commonly measured components of fruit composition, but the information about the sensory attributes of the resultant wines that could be expected from the values of these parameters are limited (Chapman *et al.*, 2005).

The beginning of aroma development from precursors in the berries seemed to be regulated by the ripening hormone ABA. These ABA either came from water stressed roots or imported from leaves. A low leaf to fruit ratio after véraison may not only be supplying not enough sugar, but also perhaps not enough ripening hormone and thus could influence aroma formation (Winter & Hand, 2003).

In a study carried out by Chapman *et al.* (2005) in the Napa Valley, California, USA in Cabernet Sauvignon it was shown that the minimally irrigated (MI) grapevines which was only irrigated when Ψ_L reaches -1.6 MPa with 32 L per grapevine, led to the most fruity and least vegetal wines. Fresh cherry, red or black berry, jam or cooked berry, dried fruit or raisin aromas, as well as acidic and fruity by mouth was rated the highest in these wines. On the other hand, the grapevines that received a standard irrigation (SI) of 32 L per grapevine per week led to the most vegetal and least fruity wines and received the highest ratings in vegetal and bell pepper aroma and astringency and bitterness. The SI wines were also highest in tannin concentration, which match with the sensory astringency ratings. The double irrigation (DI) of 64 L per grapevine per week led to wines that were moderate in both fruity and vegetal aromas and low in bitterness and astringency. These wines behaved for most attributes as though they were diluted. According to Chapman *et al.* (2005) the MI treatment may have led to a greater flux of carbon through alternative pathways for example the biosynthesis of amino acids and

carotenoids, which produced aroma compounds giving the MI wines a more fruity sensory profile. It was seen by Oliviera *et al.* (2003) that water deficits increased the concentration of the carotenoid precursors to norisprenoids. Low grapevine water status produced significant sensory aroma and flavour differences in the resultant wines, including reduced astringency and vegetal (bell pepper and vegetal) aroma.

Cabernet Sauvignon trials carried out in Oakville, California reported that wines produced from grapevines with low irrigation regimes were rated highest in dried fruit or raisin, jam, red and black berry aromas, fruity by mouth and lowest in brown colour. Low irrigation wines received slightly higher quality ratings, but the difference was not significant. Medium irrigation wines received highest scores in veggie aroma, astringency, brown, dark, body, ethanol and bitterness and were ranked lowest in cherry aroma. The high irrigation treatment was ranked lowest in bitterness, ethanol, body and darkness (Ahlgren *et al.*, 2002).

In a Cabernet Sauvignon study in Santiago, Chile it was seen that better overall sensation was observed in treatments with restricted water supply compared to when irrigation was applied at 100% of Etc throughout the whole season. The wine with the best overall sensation came from the treatment where irrigation was applied at 100% Etc from budburst until véraison and no irrigation throughout the rest of the season. Differences in colour intensity were also detected sensorial. A better colour was found in the wine with water deficit and the less-coloured wine was obtained when no water deficit occurred during the season. Attributes and overall quality of wine were favoured by a decrease of water supply, particularly after véraison and the authors suggested that deficit irrigation in a controlled way should start from this phenological stage to improve Cabernet Sauvignon wine quality (Ferreyra *et al.*, 2004).

It was found in Bordeaux that better drained soils had a faster decline in MP levels than less well drained soils. In the year with higher rainfall before and after véraison, the MP levels were higher at harvest. Thus the wetness in the soil could have played a role since it could have an influence on cytokinine hormones. It seemed that high water levels during véraison prevented MP degradation. Unripe seeds had high MP levels and seed ripening needs warmth (< 35°C) on bunches and thus shading would prevent that (Winter & Hand, 2003).

It had been noted by Noble *et al.* (1995) that there had been an association between the vegetative notes of wines and the deep clay-rich soils that are nutrient-rich and have a high water-holding capacity. Fruitier wines, rich in berry aromas, had been linked to shallow, sandy soils that were nutrient-poor and had a lower water-holding capacity. The deep clay-rich soils produced more vigorous canopies, which limited the sunlight exposure to the berry. The grapevines grown on the sandy soils produced a wide, open canopy and the fruits were better exposed to sunlight.

Water stress could have an indirect effect on Cabernet Sauvignon wine sensory quality through regulation of the yield. Ahlgren *et al.* (2002) reported that lower crop yields had the tendency to produce wines with high bell pepper and black pepper aromas, high in astringency, bitterness, ethanol, tannin concentrations and veggie by

mouth. On the other hand grapevines with higher yields resulted in wines with higher red or black berry, jam and cherry aromas, red colour, fruit by mouth and acidic characters. It was further shown that when yield reduction took place via water deficits, particularly in the pre-véraison period, the wines became less vegetative and fruitier (Anonymous, 2006a). According to Chapman *et al.* (2005) the viticultural practices that were use to control yield were more important than the yield values per se to determine the sensory characteristics of the eventual wines, because it was seen that the relationships of irrigation-adjusted yield to sensory attributes were the inverse of the relationships for pruning-adjusted yields. Cabernet Sauvignon wines made in Napa Valley pruned to low bud numbers were higher in vegetal aroma and flavour, bell pepper aroma, bitterness and astringency than "high-yield" wines. The wines made from high bud numbers were higher in red or black berry aroma, jam aroma, fresh fruit aroma, and fruity flavour than "low-yield" wines. In general, vegetal attributes decreased in intensity and fruity attributes increased in intensity as bud number and yield increased. Minimum and maximum yield ranged between 6.1 t/ha and 22.2 t/ha. Cabernet Sauvignon aromas and flavour responded to yield manipulation, but did so significantly only when yield was altered early in fruit development, e.g. with winter pruning. Cluster-thinning had little effect on wine aroma and created no significant regressions with particular aroma attributes (Chapman *et al.*, 2004).

It was shown in an irrigated Cabernet Sauvignon trial, Tarragona that wines from the irrigated treatment were significant higher in IBMP content. The concentration on SBMP and IPMP was higher in grapes from the irrigated treatment, compared to the non-irrigated treatment (Sala *et al.*, 2005). None of the SBMP and IPMP contents were detected in the final wines. Therefore in terms of sensory impact, IBMP was the MP more likely to influence the flavour of wine. The decrease in IBMP contents decreased mainly at the first stage of the ripening process. This meant that the MP contents in the final wines could be determined by the harvest date. Methoxypyrazines passed to the juice during the winemaking process because they were partly located at the skins, seeds and stems of the fruits (Sala *et al.*, 2005 and references therein). The observed delay in the drop of IBMP levels of the grapes belonging to the irrigated plants could be due to the fact that these fruits ripened at a slightly slower rhythm, although they reached harvest with the same sugar level (Sala *et al.*, 2005).

2.6 SUMMARY

Grapevine water status could have direct and/or indirect effects on wine composition and style via its influence on vegetative and reproductive growth. Through grapevine water status, the yield, canopy microclimate, fruit metabolism and the biosynthesis or degradation of flavour compounds could be manipulated.

In the traditional Old World wine countries, irrigation is still somewhat restricted or even prohibited, based on the idea that irrigation is detrimental for wine quality. There lies merit in this believes, but the positive effects of applied irrigation at the right time,

could out way the negative effects. The increase of production (tha), increase in berry sugar accumulation and an increase in wine quality in very dry years and when high crop yields are attained, could be some of the positive effects. However, there is no doubt that excessive irrigation would negatively impact on wine quality.

In Europe irrigation are reduced after véraison and in Australia deficit irrigation is generally applied between fruit set and véraison. The different strategies followed could be ascribed to different vineyard management styles and climatic conditions. With high crop yields, reducing irrigation after véraison could be detrimental to wine quality. On the other hand, with lower crop yields, reducing irrigation after véraison could help to reduce berry water accumulation and the competition between vegetative and reproductive growth (Intriglio & Castel, 2008 and references therein). In South Africa, with its diverse climate and soils there are endless ways to manipulate irrigation with the objective to aid in obtaining a specific wine style for a specific market. Also due to increased scarcity of water and rising electricity costs, irrigation management strategies could be of great help in saving water and production costs.

It is important to remember that fruit quality depends on various environmental and endogenous factors (Jackson & Lombard, 1993), therefore in conjunction; the overall effect of irrigation might be obscured or accentuated. Thus, irrigation should be made custom fit for the specific environment and situation based on scientific research. Furthermore, vinification practices could also play an important role in accentuating these differences obtained by irrigation management. It is important that with the increase economic pressure on wineries, chemical correction within the cellar should be kept to the minimum. The objective of every viticulturist should be to deliver the best possible grapes to the winemaker in an attempt to save as much intervention as possible in the winemaking process. Irrigation management is a powerful tool to obtain this goal.

Data in the literature on the effect of irrigation on fruit growth, fruit ripening, must and wine composition and wine style are sometimes contradictory, possibly due to different climate, soils and irrigation management strategies. Thus, although there are basic guidelines, research is important for understanding how a specific cultivar will react in a region to optimise irrigation management strategies. Measurement of grapevine water status is necessary to make informed choices about irrigation with eventual wine goal in mind.

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Chapter 3

RESEARCH RESULTS

The effect of climate, soil and irrigation on grapevine water status

THE EFFECT OF CLIMATE, SOIL AND IRRIGATION ON GRAPEVINE WATER STATUS

3.1 INTRODUCTION

Climate, and in particular temperature, plays an important role in determining wine quality (Le Roux, 1974; de Villiers *et al.*, 1996; Marais *et al.*, 1997). Long term weather data, e.g. mean February temperature (MFT), is used as criteria to determine wine quality potential of a region (De Villiers *et al.*, 1996). It was shown that the proximity of the Atlantic Ocean has an effect on the MFT in the Western Cape Coastal Region over distances up to 60 km inland (Myburgh, 2005b). The Western Cape wine region was classified according to the mean temperature in February, which is the warmest month in many parts of the Western Cape, as follows (De Villiers *et al.*, 1996; adapted from Smart and Dry, 1980):

Temperature (ºC)	Region	Cultivation potential
17 - 18.9	Cold	High quality white table wine
19 - 20.9	Cool	High quality white and red table wine
21 - 22.9	Moderate	High quality red table wine
23 - 24.9	Warm	Low acid, high pH
> 25	Very warm	Low acid, high pH

Another climatic index that describes the potential for viticulture is the Amerine & Winkler index (1944) which was adapted for the Western Cape wine producing regions Le Roux (1974). The latter is calculated as the summation of the daily mean temperature above 10ºC through the seven months of the growing season, i.e. September to March. The adapted climatic criteria for the Western Cape wine producing regions are as follows (Le Roux, 1974):

Growing degree days (GDD)	Region	Cultivation potential
< 1 389	I	Quality red and white table wine
1389 - 1666	II	Good quality red and white table wine
1667 - 1943	III	Red and white wine and port
1944 - 2220	IV	Desert wine, sherry and standard wine
> 2220	V	Desert wine and brandy

The heliothermal index (HI) is extensively used worldwide to describe the potential for viticulture (Huglin, 1987). This index is based on the mean and maximum monthly temperatures prevailing from October to March (Huglin, 1987; Tonietto & Carbonneau, 2004). This calculation also includes a coefficient to allow for the greater photosynthetic

active radiation that occurs with longer days at higher altitudes, i.e. higher than 40º. A value of one is given for latitudes lower than 40º. The classes and class intervals of the HI are as follows:

Class of viticultural climate	Acronym	Class interval (ºC)
Very cool	HI$_{-3}$	$\leq$ 1 500
Cool	HI$_{-2}$	> 1 500 $\leq$ 1 800
Temperate	HI$_{-1}$	> 1 800 $\leq$ 2 100
Temperate warm	HI$_{+1}$	> 2 100 $\leq$ 2 400
Warm	HI$_{+2}$	> 2 400 $\leq$ 3 000
Very warm	HI$_{+3}$	> 3 000

The cool night index (CI) is a night coolness variable which takes the minimum mean night temperatures during the month preceding harvest into account (Tonietto & Carbonneau, 2004). The objective of the index is to improve the assessment of the qualitative potential of wine growing regions regarding wine colour and aromas. This index is based on the minimum daily temperature during March. The CI classes and class intervals are as follows:

Class of viticultural climate	Acronym	Class interval (ºC)
Warm nights	CI$_{-2}$	> 18
Temperate nights	CI$_{-1}$	> 14 $\leq$ 18
Cool nights	CI$_{+1}$	> 12 $\leq$ 14
Very cool nights	CI$_{+2}$	$\leq$ 12

In terms of the South African wine industry, the Lower Olifants River region is regarded as a warm and hot region. It is described as a Winkler Class V region, i.e. more than 2 220 GDD, with the potential to produce dessert wine and brandy (Le Roux, 1974; De Villiers, 1996). This could be due to the fact that mean long term weather data is used without considering differences at different localities within the region.

The Lower Olifants River region has a mean annual rainfall of approximately 211 mm, i.e. the mean recorded at the Klawer weather station from 1973 to 2006 (data obtained from the Agriculture Research Council (ARC) Institute for Soil, Climate and Water in Pretoria). Due to the low summer rainfall, irrigation is necessary for the growing of grapevines in this region. Irrigation can have positive or detrimental effects on growth, yield and wine quality (Kasimatis, 1967 and references therein; Tesic *et al.*, 2001; Acevedo *et al.*, 2004; Chapman *et al.*, 2005; Santalucia *et al.*, 2007). These effects could be the result of direct or indirect effects on the grapevine physiological processes or morphology.

Atmospheric conditions can have a direct effect on micro organisms by influencing their disease cycle and infection intensity, e.g. downy mildew and Botrytis (Dalla Marta

et al., 2008 and references therein). Solar radiation plays a role in the production of phenolic compounds which affect the degree of infection by *Plasmopara viticola* (downy mildew). The production of polyphenolic compounds are directly linked to the intensity of solar radiation and have a significant influence on the process responsible for greater resistance to downy mildew in vineyards (Dalla Marta *et al.*, 2008). Since differences in temperature and relative humidity were less than 1ºC and 3%, respectively, high light intensity in the cluster zone near the spurs of field grown Chardonnay and Cabernet Sauvignon in the Golan region of Israel was considered as the primary factor which limits powdery mildew growth (Zahavi *et al.*, 2001).

The effects of climate and soil on grapevine development and grape composition can to a large extent be explained via their influence on grapevine water status (Van Leeuwen *et al.*, 2004). Soils with a low water holding capacity produced fruity Cabernet Sauvignon wines whereas those with higher water holding capacities produced wines with a more vegetative character (Chapman *et al.*, 2005). The soil water storage capacity, and thus plant available water, is determined by soil and/or root depth, soil texture and to a lesser extent by soil structure (Van Zyl, 1981). Soil water contents which are either near the upper or the lower limits of plant available water for prolonged periods during the growing season is unfavourable for achieving the desired balance between yield and wine quality (Seguin, 1983).

It is assumed that the grapevine's stomata are closed before sunrise and that the plant is in equilibrium with the soil water potential or the most humid layer of soil (Bogart, 2006). Hence, predawn leaf water potential (Ψ_{PD}) is considered to be a sensitive indicator of the soil water availability. However, Ψ_{PD} can underestimate grapevine water deficits experienced by the grapevines during the day when soil water content is heterogeneous, but Ψ_{PD} can still be used to determine plant water status where the available soil water is not easily measured by means of neutron probes or time domain reflectometry (TDR) probes (Deloire *et al.*, 2005).

The effect of soil on eventual wine quality is well documented, and is even evident under intensive irrigation (Conradie 2002). However, Fregoni (1977) stated that the influence of soil on wine quality is often confusing, particularly in warmer climates, where climate dominates all other factors.

The aim of this study was to determine the effect of climate, soil and irrigation on grapevine water status in Cabernet Sauvignon vineyards in the Lower Olifants River region of the Western Cape.

3.2 MATERIALS AND METHODS

3.2.1 EXPERIMENT LAYOUT

The field trial was carried out during the 2006/07 and 2007/08 seasons in Cabernet Sauvignon vineyards in the Lower Olifants River region. Based on the experience of

viticulturists working at the co-operative wineries in the region, eight commercially cultivated Cabernet Sauvignon vineyard blocks were selected to represent macro climate and soil variation. The inland areas in the east tend to be warmer compared to those in the west near the cold Atlantic Ocean. Soils on the banks of the Olifants River differ considerably from those further away. The vineyards were at four localities at different distances from the Atlantic Ocean, ranging between approximately 34 km at Kapel and 12 km at Koekenaap (Fig. 3.1). At each locality, vineyard blocks in two different soil textures, i.e. in the lower lying alluvial soils and in the sandy "Karoo" soils further away, respectively, were selected to obtain eight main plots.

Each of these eight main plots were further divided into two plots consisting of one plot where the grapevines were irrigated according to the growers' schedule ("Normal" irrigation) and one where grapevines were subjected to water deficits ("Deficit" irrigation). Hence, a total of 16 experiment plots were used in the study (Table 3.1). Each plot comprised two rows of six experiment grapevines. Experiment grapevines were bordered by a buffer row on each side and two buffer grapevines at each end (Fig. 3.2). Deficit irrigation was applied when shoot length reached approximately 300 mm to 400 mm, i.e. approximately three to four weeks after bud break. Bourdon type tensiometers were used to measure the soil water matric potential (Ψ_M). Grapevines were irrigated when Ψ_M reached approximately -0.06 MPa in the root zone of the sandy soils. However, no visual water stress symptoms, e.g. drooping of tendrils and/or inactive shoot tip growth had occurred when Ψ_M in the loamy alluvial soils reached approximately -0.08 MPa, i.e. the maximum range of the tensiometers (Greenspan, 2005). Consequently, grapevines in sandy loam soils were irrigated when water stress symptoms became visual. Irrigation amounts were recorded by means of water meters in each plot.

All vineyards included in the study were drip irrigated. The cultivation practices applied in the selected vineyards were representative of the Lower Olifants River region. In all the blocks grapevines were split-trained. Canopy management practices included spur pruning to two buds per bearer, 10 to 14 bearers per meter, suckering before flowering and tipping of shoots where necessary. Green bunches (second crop), were removed at véraison. Fertilization, as well as pest and disease control was carried out according to the growers' practices.

3.2.2 CLIMATE

The climate in the region was described according to long term air temperature, relative humidity (RH), rainfall, wind speed, incoming solar radiation (insolation) and reference evapotranspiration (ET_0) data for the weather stations near Klawer, Vredendal, Lutzville and Ebenhaeser (Fig. 3.1). The prevailing weather conditions during the study period, i.e. August 2006 until July 2008, were determined by means of automatic weather stations (MC Systems, Cape Town) near Klawer, Vredendal, Lutzville and Ebenhaeser. All the atmospheric variables mentioned above were recorded hourly. All weather data

were obtained from the Soil, Climate and Water Institute of the ARC in Pretoria. The GDD of the region was calculated using the means of the four weather stations, i.e. Klawer, Vredendal, Lutzville and Ebenhaeser.

3.2.3 QUANTIFICATION OF SOIL CONDITIONS

3.2.3.1 Soil classification and analyses

The soils were classified and described according to the South African Soil Classification System (Soil Classification Working Group, 1991). Soil samples were collected in 300 mm increments to a depth of 900 mm by means of a soil auger at the beginning of the study in August 2006. Due to stony subsoils, the 600 mm to 900 mm increments could not be sampled in P1, P2, P7, P8, P13 and P14.

3.2.3.1.1 Chemical properties

Soil pH, electrical conductivity of the saturated soil extract (EC_e), phosphorus, potassium, exchangeable cations (sodium, potassium, calcium & magnesium), micro nutrients (copper, zinc, manganese & boron) and organic carbon content were determined. The soils were analysed by a commercial laboratory (BEMLAB, Strand) according to their standard methods.

3.2.3.1.2 Physical properties

Soil particle analyses were determined according to the standard methods used by BEMLAB. Soil texture was classified according to a texture chart (Soil Classification Working Group, 1991). Soil bulk density was determined in the 0 mm to 300 mm, 300 mm to 600 mm and 600 mm to 900 mm layers. In each layer two 28×10^{-5} m^3 undisturbed soil cores were extracted and dried in an oven until constant mass was attained. The cores were weighed to obtain the dry mass.

3.2.3.2. Measurement of soil water status

Soil water status was measured at 200 mm, 300 mm, 600 mm and 900 mm depths by means of the neutron scattering technique. Two access tubes were installed in the grapevine row ca. 500 mm from a grapevine in each plot. The neutron probe (HYDROPROBE 305DR, CPN, California) was calibrated against soil water matric potential (Ψ_M). For this purpose, two sets of tensiometers were installed at 150 mm, 300 mm and 600 mm in each of the deficit irrigation plots in the shallower sandy soils and at 300 mm, 600 mm and 900 mm depths in the other soils. The relationship between neutron probe count ratio and Ψ_M was determined for each depth. These "soil water characteristic curves" were used to convert neutron probe count ratios to Ψ_M. The equations developed to convert neutron probe count ratio to Ψ_M are presented in Table

3.2. Examples of soil water characteristic curves representing the different soil textural classes are presented in Figure 3.3 and Figure 3.4.

Soil water status was measured once a week from bud break until harvest and every fortnight after harvest. However, in some soils, rapid drying limited the number of Ψ_M measurements that could be obtained by weekly measurements. During the second season soil water status measurements were carried out more frequently as soon as the soils began to dry out.

Bud burst, flowering and véraison dates were noted when 80% of the buds, flowers or berries reached the specific phenological stage. These dates were used to determine the mean Ψ_M and amount of water applied during the different stages, i.e. bud burst to flowering, (E-L 4 to E-L 25), flowering to véraison (E-L 25 to E-L 35) and véraison to harvest (E-L 35 to E-L 38) (Coombe, 1995).

3.2.4 ROOT STUDIES

Root structure was characterised in each of the two soils at the four localities in the Cabernet Sauvignon vineyards during May 2007. The profile wall method of Böhm (1979) was used to qualify and quantify root distribution within the constraints imposed by this method. Trenches were dug across the grapevine row between two experiment grapevines, with the trench sides 0.15 m from each grapevine. To allow comparison of root systems between the different plots, the vertical sections in all plots were 1.0 m deep and 2.4 m wide, which was the row width in most plots. Exposed roots were mapped with the aid of a portable steel grid, divided into 100 mm squares. Roots were mapped in vertical sections perpendicular to the grapevine rows. Roots were classified into four classes, i.e. fine (< 0.5 mm diameter), medium (0.5 mm to 2.0 mm diameter), coarse (2.0 mm to 5.0 mm diameter) and thick (> 5.0 mm diameter).

3.2.5 PLANT WATER STATUS

The best indicator of the water supply to the grapevine is to measure the water status in the grapevine itself (Hardie & Hinckley, 1975; Greenspan, 2005). Water potential in the grapevines was measured by means of the pressure chamber technique (Scholander *et al.*, 1965). This is considered to be an easy, repeatable and reliable method.

3.2.5.1 Water potential during berry ripening

Midday leaf water potential (Ψ_L) and stem water potential (Ψ_S) were measured three times during berry ripening, i.e. in January and February, during both seasons (2006/07 and 2007/08). Three teams were used to complete measurements in all plots between 12:00 and 13:00. Three mature, intact grape leaves were used per plot for Ψ_L and Ψ_S, respectively. In the case of Ψ_L, leaves that were fully exposed to the sun were used. The Ψ_S was measured in leaves that were covered with an aluminium foil sachet at least one hour before measurements were made. This effectively stops the natural

transpiration of the leaf, allowing the Ψ_L to come into equilibrium with the Ψ_S (Bogart, 2006). To allow Ψ_L measurements on all plots, grapes were left on four grapevines on the plots that were harvested before 22 February during the 2006/07 season.

3.2.5.2 Diurnal changes in water potential

To quantify grapevine water status in response to soil and atmospheric conditions, hourly changes in diurnal leaf water potential were measured during the 2006/07 season in eight plots, i.e. Kapel (P1, P2, P3 & P4) and Lutzville (P9, P10, P11 & P12). These measurements were carried out at three stages during the growing season, i.e. at pea size (beginning of November 2006), pre-véraison (middle of December 2006) and during ripening (end of January 2007). Three mature, intact, fully exposed to the sun leaves were picked from three different grapevines per plot. Leaf water potential values at 04:00 were considered as the predawn leaf water potential (Ψ_{PD}) values. Total diurnal leaf water potential (Ψ_{LT}) was calculated for each cycle using the trapezoidal rule as follows (Larson *et al.*, 1994):

$$\Psi_{LT} = [(0.5 \times \Psi_0) + \Psi_1 + \Psi_2 + ….. + \Psi_{n-1} + (0.5 \times \Psi_n)] \times \Delta t \qquad \text{(Eq. 3.1)}$$

where, Ψ_{LT} is accumulated leaf water potential (MPa^2), Ψ_0 and Ψ_n are the leaf water potentials (MPa) measured at the beginning and end of the period, respectively, and Δt is the time interval (h) between measurements.

3.2.6 STATISTICAL ANALYSES

The diurnal leaf water potential values were subjected to an analysis of variance (ANOVA) using Statgraphics[®]. Turkey's least significant difference (LSD) was calculated to facilitate comparison between mean values. Means which differed at $p \leq 0.05$ were considered to be significantly different. Analysis of variance was also used to test the effects of locality, soil texture and irrigation strategy on grapevine water status during berry ripening. Fisher's least significant difference was calculated at the 95% confidence level to compare treatments. Version 9 of Statistica[®] was used. Excell 2000[®] was used to determine relationships between variables by means of general linear regression at the 95% confidence level and Statgraphics[®] was used to calculate multiple linear regressions.

3.3 RESULTS AND DISCUSSION

3.3.1 CLIMATE

3.3.1.1 Long term weather conditions and prevailing atmospheric conditions during the study period

Climatic indices: Macroclimate in the Lower Olifants River region shows a cooling effect as distance to the Atlantic Ocean decreases, i.e. from Klawer to Ebenhaeser which are ca. 34 km and ca. 12 km from the ocean, respectively (Table 3.1). According to the MFT (De Villiers *et al.*, 1996), Klawer is described as a very warm area with the potential to produce wines with low acidity and high pH, similar to Upington in the Lower Orange River region (Fig. 3.5). Lutzville and Vredendal have the potential to produce high quality red table wine, the same as Stellenbosch. It is interesting to note that the MFT in Paarl (Nederburg) and Robertson (Vinkrivier) are higher than MFT in Lutzville and Vredendal. Considering the MFT, Ebenhaeser is a cool area with the potential to produce high quality red and white table wines.

It is important to note that within a wine producing region there will be fluctuations in temperature due to variations in altitude and topography (Carey *et al.*, 2008 and references therein). According to the Winkler index (Le Roux, 1974), the Lower Olifants River region could be sub-divided into three climatic regions (Fig. 3.6). Similarly, the region's climate could be divided into three HI classes and two CI classes, respectively (Fig. 3.7 & Fig. 3.8). The different climatic regions in the Lower Olifants River region result from the proximity of the Atlantic Ocean. It was shown that the proximity of the Atlantic Ocean and altitude has an effect on the MFT in the Western Cape Coastal Region over distances as far as 60 km inland (Myburgh, 2005b). The sea breeze effect from False Bay also had a significant effect on mean maximum temperatures in the Stellenbosch wine producing area (Bonnardot *et al.*, 2001). Although the sea breeze penetrates up to ca. 100 km inland, the effect on relative humidity and temperature decreased rapidly with distance from the coast. The temperature at weather stations within 50 km from the coast differed by ca. 4ºC. The mean GDD of the four weather stations, i.e. Klawer, Vredendal, Lutzville and Ebenhaeser, were ca. 2 267 and 2 521 for the 2006/07 and 2007/08 seasons, respectively (Table 3.3). These GDD values are within a Winkler class V. However, considering the above mentioned variation in GDD, HI and CI as the distance to the ocean decreases, it is misleading to describe the Lower Olifants River region as being warm and hot. In addition to the different climatic classes within the region, the climate also varied between seasons. The Winkler index, HI and CI showed that the 2007/08 season tended to be warmer compared to the 2006/07 season (Table 3.3).

Maximum temperature: Highest daily mean maximum temperatures in the Lower Olifants River region are usually recorded during February (Table 3.4). Within the

region, the highest mean daily maximum temperature was 33ºC at Klawer, i.e. the furthest away from the Atlantic Ocean, and the lowest was 27ºC at Ebenhaeser, which is nearest to the ocean. At Klawer, the maximum February temperature falls outside the optimum range for photosynthesis which is between 25ºC and 30ºC (Fontana, date unknown; Ferrini *et al.*, 1995 and references therein). The lowest net photosynthesis values were recorded for grapevines grown at 35ºC and were closely related to chlorophyll content. Photosynthesis in plants grown at 35ºC does not depend on stomatal opening, but on biochemical factors of an enzymatic nature (Ferrini *et al.*, 1995).

During the 2006/07 and 2007/08 seasons, maximum daily temperatures were comparable to the long term means (Fig. 3.9). However, maximum daily temperatures during November 2007 as well as February 2007 were cooler compared to the long term mean for the region (Fig. 3.9). Considering hourly recorded temperatures in February 2007, the number of hours above 35ºC was 20 hours at Kapel and two hours and Koekenaap, respectively (J. Joubert, Personal communication, 2009). During February 2008 the number of hours was 232 hours at Kapel and 18 hours at Koekenaap, respectively. This confirmed that temperatures not only vary considerably between localities, but also from season to season. Furthermore, these results indicated that there were more days in February 2008 during which photosynthesis would have stopped compared to February 2007 (Ferrini *et al.*, 1995). The higher temperature in February, i.e. when most cultivars ripen, could have affected grapevine phenology.

Hourly temperatures recorded at Kapel and Koekenaap in February 2007 and February 2008 showed that maximum daily temperatures were reached between 13:00 and 16:00 (J. Joubert, Personal communication, 2009). However, on some days maximum temperature at Kapel occurred approximately one hour later compared to Koekenaap. This delay in maximum temperature with an increase in distance from the ocean also occurs in the Stellenbosch wine producing region (Bonnardot *et al.,* 2001). It seemed that on days when heat waves occurred, commonly known as "east wind days", this trend did not exist in the Lower Olifants River region. At this stage there is no explanation for this phenomenon, since analyses of hourly temperature data was beyond the scope of the study.

Minimum temperature: During the 2006/07 and 2007/08 seasons, minimum daily temperatures were comparable to the mean long term values (Fig. 3.10). However, the daily mean minimum temperature was higher in May 2008 than the long term mean. According to Archer & Goussard (1988), the main cause of delayed bud break is high minimum temperatures in early winter, particularly in May. Within the study area, Klawer is the only locality where the long term mean daily minimum temperature exceeds 10ºC during May, which apparently causes this problem (Table 3.4). Hourly temperature recorded at Kapel and Koekenaap during February 2007 and February 2008 showed that the minimum daily temperatures at these localities normally occurred between 05:00 and 07:00 (J. Joubert, Personal communication, 2009). However, this does not

necessarily mean the grapes were the coolest at these times. Due to the heat capacity of the fruit which tends to resist cooling, fruit temperature lags ambient temperature in time (Greenspan, 2008).

Fluctuations in the long term mean daily maximum and daily minimum temperatures were higher at Klawer compared to Ebenhaeser which is closer to the ocean (Table 3.4). During the ripening period, i.e. January to March, the daily fluctuation in temperature at Klawer was ca. 16ºC compared to ca. 13ºC at Ebenhaeser. Previous research also showed that smaller temperature fluctuations occurred in the coastal areas compared to further inland in the Stellenbosch-Drakenstein winegrowing area due to the sea breeze mechanism (Planchon *et al.*, 2000).

Relative humidity: The long term mean monthly relative RH varies between approximately 52% at Klawer and 69% at Ebenhaeser (Table 3.5). Higher RH near the coast compared to further inland was also observed in the Stellenbosch wine producing area (Bonnardot *et al.*, 2001). During ripening, i.e. January to March, mean monthly RH varies around approximately 60%, except for 70% RH at Ebenhaeser which is closest to the ocean. High RH could favour disease pressure, e.g. powdery mildew (Wilcox, 2003). Due to the effect of RH on evapotranspiration (Williams, 2000), it would be expected that evapotranspiration in vineyards at Klawer will be higher than in ones at Ebenhaeser. During the 2006/07 and 2007/08 seasons, mean monthly RH compared reasonably well with the mean long term values most of the time (Fig. 3.11). However, during October 2006, January 2007, February 2007 and April 2007 RH was higher than the long term means.

Rainfall: Long term mean annual rainfall ranges between 216 mm at Klawer and 146 mm at Ebenhaeser (Table 3.5). Since 69% of the rainfall occurs from May to August, the Lower Olifants River is classified as a winter rainfall region. Due to the low annual rainfall, the Lower Olifants River region is described as an arid region (Anonymous, 2001) where irrigation is necessary for viticulture. During the 2006/07 and 2007/08 seasons, total monthly rainfall differed substantially from the long term mean values (Fig. 3.12). According to Dent *et al.* (1988), the coefficient of variability (CV) of the mean annual rainfall in the Lower Olifants River region is moderate, i.e. between 11% and 20%. Zones with a high CV, i.e. more than 20%, are primarily in the mountainous regions of the Western Cape, Lesotho, the Eastern Transvaal Drakensberg and the Soutpansberg.

Wind speed: The highest mean daily wind speeds usually occur during November, December and January (Table 3.6). The lowest wind speeds tend to occur at Klawer and the highest at Ebenhaeser. It was shown that wind speeds above 4 m/s reduce grapevine transpiration (Campbell-Clause, 1998). Furthermore, wind speeds above 5 m/s will induce stomatal closure in grapevine leaves (Greenspan, 2008). Apparently stomatal closure is stimulated by rapid leaf movement. During October to February mean daily wind speed at Ebenhaeser exceeds the threshold value of 4 m/s (Table 3.6). Thus in addition to lower RH at Ebenhaeser, the wind speed would further decrease

vineyard evapotranspiration at Ebenhaeser compared to Klawer. With the exception of high wind speeds during October 2007, mean daily wind speed were comparable to the long term values (Fig. 3.13).

Solar radiation: Although there is a substantial difference in the long term mean daily maximum temperatures between the localities (Table 3.4), the total daily solar radiation does not differ correspondingly (Table 3.6). During the 2006/07 and 2007/08 seasons, mean daily radiation was comparable to the long term values (Fig. 3.14). However, total daily radiation was lower during November 2007 and May 2008 compared to the long term mean. This effect could have contributed to the lower than average daily maximum temperatures in November 2007 as discussed above. Solar radiation plays an important role on meteorological elements, such as air temperature and RH (Dalla Marta *et al.*, 2008 and references therein). In addition to the low mean daily maximum temperatures during November 2007 (Fig. 3.9) and high wind speed during October 2007, low mean daily radiation during November 2007 (Fig. 3.14), could also have had negative effects on berry set in the 2007/08 season and reduced bud fruitfulness in the following season (Sánchez *et al.*, 2005).

Reference evapotranspiration: The highest long term mean daily ET_0 rates are normally recorded during January (Table 3.6). Since ET_0 is an integration of many atmospheric elements, it is expected that the highest ET_0 (8.90 mm/day) would occur at Klawer and the lowest (6.93 mm/day) at Ebenhaeser. Hence, this trend is also a result of the proximity of the ocean. The ET_0 at Ebenhaeser is comparable to 7.05 mm/day at Upington in the semi-arid Northern Cape, but the ET_0 at Klawer is considerably higher (Myburgh, 2003a). With the exception of November 2007, mean daily ET_0 during the 2006/07 and 2007/08 seasons were comparable to the long term values (Fig. 3.15). The lower ET_0 during November 2007 was probably caused by the lower maximum temperatures and solar radiation.

3.3.2 SOIL CHEMICAL AND PHYSICAL CONDITIONS

3.3.2.1   Chemical properties

With the exception of experimental plots P7 and P8 near Vredendal, soil $pH_{(KCl)}$ was higher than 6.0 which indicated that there were no severe acidity problems in any of the soils (Table 3.7). The only signs of salinity occurred in the sub soil of P15 and P16 at Koekenaap. However, it is unlikely that salinity levels of lower than ca. 0.87 dS/m would have had any significant negative effect on grapevine growth and yield (Ayers & Westcott, 1985; Moolman *et al.*, 1999; Volschenk & Myburgh, 2006). The phosphorus (P) level as well as other nutrient element levels in all the plots indicated that the grapevines were not subjected to nutrient deficiencies.

Organic carbon content of the soils was low, i.e. lower than 0.50%, compared to similar soil forms in the Robertston area (Roux, 2005). However, similarly low values, i.e. 0.12% organic carbon, were reported for a sandy soil at the Lutzville Experiment

farm (Conradie & Myburgh, 2000). The sandy loam alluvial soils tended to contain more organic carbon than the sandy soils further away from the river.

3.3.2.2 Physical properties

Clay contents varied between ca. 2% in the sandy soils and ca. 12% in the sandy loam soils (Table 3.8). Silt contents varied between ca. 3% in the sandy soils and ca. 12% in the sandy loam soils. The fine sand fraction in the soils tended to increase with an increase in distance from the Atlantic Ocean, whereas the medium sand fraction tended to decrease further away from the ocean. The fine sand content also seemed to be a function of altitude. Approximately 90% of the variation in the fine sand content in the top soil could be explained at the hand of altitude (A) and distance from the ocean (D) in the following multiple linear regression equation:

Fine sand = $18.96 + 0.423*A + 0.96*D$ ($R^2 = 0.8914$; se = 6.1; p < 0.05)   (Eq. 3.2)

This model basically quantifies the effect of wind blowing in a westerly direction from the Atlantic Ocean on the distribution of fine sand in the study area. This distribution suggested that the prevailing winds carried the fine sand particles further and higher inland. Theoretically, the fine sand fraction should be ca. 19% in soils near the ocean, i.e. when D = 0.

Soil bulk densities were relatively high, i.e. more than 1.5 Mg/m^3 (Table 3.8). Soil texture can influence bulk density, which in turn can influence root depth (Pool, 2000). Viticulture cultivation practices, such as compaction by wheel traffic, could possibility have contributed to the high bulk densities. The bulk densities in the Dundee soil form (P5 & P6 and P11 & P12) were comparable to the bulk densities in a similar soil form in the Robertson area (Roux, 2005). However, the bulk density in the Valsrivier soil form (P3 & P4) was lower in the Lower Olifants River region compared to a similar form in the Robertson area.

3.3.3 SOIL WATER STATUS

The irrigation amounts were summed for each of the different phenological stages (Table 3.9). The irrigation amounts applied by the growers ("normal" irrigation) varied between 200 mm and 682 mm in the sandy soils from bud break until harvest (Table 3.10). In the heavier soils the irrigation amounts varied between 0 mm (no water applied) and 547 mm. The amount of water applied in the deficit irrigation strategy is expressed as a percentage of the normal irrigation (Table 3.11).

Seasonal soil water matric potential (Ψ_M) varied considerably between the plots (Fig. 3.16 to Fig. 3.31). Mean Ψ_M was calculated for each of the different phenological stages (Table 3.12). In general, almost no water deficits occurred in any of the soils from bud break to flowering, i.e. mean Ψ_M of lower than - 0.015 MPa (Table 3.12). During the 2007/08 season irrigation of the deficit irrigated grapevines in the heavier soils (P5 and P11) were cut off early in the season, i.e. just after bud break. Consequently, a mean Ψ_M value of approximately -0.020 MPa was obtained (Table

3.12). This strategy was adopted because the heavy soils did not dry out as quickly as the sandy ones after the soil profile was saturated. When irrigation was cut of after fruit set, the soils were still wet during the early stages, i.e. phase I of berry development. Inadequate water supply during flowering is one of the main reasons for poor fruit set, after fruit set deficit irrigation could be applied to obtain beneficial effects for red wine production (Van der Westhuizen, 1972). Water deficits between flowering and véraison does not modify cell division, but rather cell enlargement in an irreversible manner, depending on the intensity of the constraint (Deloire *et al.*, 2005 and references therein). Hence, any possible beneficial effects of smaller berries on wine quality were probably lost in the case of P5 and P11 during the 2006/07 season.

In some plots, e.g. in the sandy soil at Koekenaap (P14) where mean Ψ_M was -0.005 MPa from bud break to harvest (Table 3.12), no water deficits occurred during both seasons (Fig. 3.22 & Fig. 3.30). In the sandy soil at Kapel (P2) no water deficits occurred from bud break to véraison (Fig. 3.16 & Fig. 3.24), but from véraison to harvest mild water deficits, i.e. mean Ψ_M of -0.015 MPa to -0.020 MPa, occurred (Table 3.12). Although Ψ_M at 600 mm in P2 was lower than -0.020 MPa, Ψ_M at 150 mm and 300 mm was never lower than -0.020 MPa. The grapevine roots system will absorb water where the least energy is required, i.e. where Ψ_M is the highest. In the deficit irrigation plots in alluvial soils, e.g. at Vredendal P5 (Fig. 3.18 & Fig. 3.26), Lutzville P11 (Fig. 3.21 & Fig. 3.29) and Koekenaap P15 (Fig. 3.23 & Fig. 3.31), mean Ψ_M was as low as -0.080 MPa (Table 3.12). Similarly, Ψ_M reached values of -0.075 MPa when irrigation of a Cabernet Sauvignon vineyard in a sandy loam soil in Santiago, Chile was suspended (Ferreyra *et al.*, 2002). When grapevines received irrigation at 100% ET, Ψ_M remained between -0.010 MPa to -0.015 MPa. Similar high Ψ_M values prevailed in the loamy sand soil at Lutzville (P12) (Table 3.12). Previous studies showed that water stress in field grown grapevines sets in when Ψ_M reach -0.064 MPa (Van Zyl, 1987). In coarse sandy soil plant physiological parameters showed that the onset of water stress in Barlinka table grapes occurred at Ψ_M of -0.030 MPa and -0.035 MPa (Fourie, 1989). These findings suggested that the onset of water stress in grapevines in sandy soil might occur at higher Ψ_M than in heavier soils. Mesophyl conductance in potted Cabernet Sauvignon grapevines was 42% and 70% lower at Ψ_M of -0.050 MPa and -0.060 MPa, respectively, compared to Ψ_M of -0.020 MPa (Pellegrino *et al.*, 1987).

Extensive floods during winter are common in the Lower Olifants River region. However, not all vineyards are flooded. Vineyards in alluvial soils closer to the main course of the river are more frequently under water in winter compared to those further away. The possibility exists that the flooding can create water tables in soils closer to the river. Furthermore, it could be possible that the water tables are still present in the deeper soil layers during summer. Although the water tables might be deeper than the root systems, it could be a source of water for grapevines via capillary rise during the entire growing season. The alluvial soils at Vredendal (P5 & P6) and Lutzville (P11 & P12) were relatively close to the river banks compared to those at Kapel (P3 & P4) and

Koekenaap (P15 & P16) as indicated in Figure 3.32. During the study period the vineyards at Vredendal and Lutzville were flooded numerous times, but the ones at Kapel and Koekenaap were too far away from the main course of the river.

3.3.4 ROOT DISTRIBUTION AND DENSITY

Root numbers and density varied considerably between plots (Table 3.13). Furthermore, there was no consistency in the depth distribution of the root systems. With the exception of P13 and P14 the highest root concentrations occurred either in the 300 mm to 600 mm or the 600 mm to 900 mm layers. Root densities tended to be higher in the sandy soils compared to the heavier ones, except in P13 and P14 at Koekenaap. With the exception of P15 and P16, root density increased as the fine sand fraction of the soil increased (R^2 = 0.7765; se = 35.4; $p \leq 0.001$). In the loamy sand soil, i.e. P11 and P12 at Lutzville, root densities tended to be lower compared to the sandy loam soils.

Visual observation indicated that the roots were primarily concentrated underneath the drippers in the sandy soils (Fig. 3.33 to Fig. 3.40). In the heavier sandy loam soils grapevines tended to have deeper and wider root systems. In most of the sandy soils the root systems were restricted to ca. 800 mm to 900 mm depth by the presence of a "dorbank". The root system was deeper in the sandy soil at Lutzville (P9 & P10) where there were no physical restrictions (Fig. 3.37). The deep root system also indicated that the neo-carbonate layer did not limit root depth.

3.3.5 PLANT WATER STATUS

3.3.5.1 Diurnal leaf water potential changes

The Ψ_L followed a typical diurnal pattern that was similar to previous findings (Hardie & Considine, 1976; Myburgh, 2003b). Maximum Ψ_L occurred at predawn followed by a fairly rapid decrease during the morning and a steady increase during the late afternoon and night (Table 3.14, Table 3.15 & Table 3.16). During November the lowest Ψ_L occurred at 16:00, but in December and January the lowest Ψ_L were recorded at 12:00. Due to the warmer and drier atmospheric conditions in December and January, Ψ_L decreased more rapidly during the morning. Consequently, the daily minimum occurred earlier than in November.

The diurnal Ψ_L patterns tended to show a phase shift as the season progressed, i.e. from November (pea size) to January (ripening). In the sandy loam soils, Ψ_L tended to be lower in the morning (08:00) and higher during the evening (20:00) in November than in January (Table 3.14, Table 3.15 & Table 3.16). Leaf water potential in grapevines in the sandy soils showed a similar trend. These results indicated that the water status of the grapevines recovered more rapidly in November compared to January. Furthermore, it also seemed that Ψ_L in the grapevines recovered to higher levels during

November than in January. This was probably caused by warmer and drier atmospheric conditions as the season progressed.

When the diurnal cycles were measured shortly before the next irrigations were due, Ψ_{PD} in grapevines in the deficit irrigated sandy soils at both localities (P1 & P9) exceeded the threshold value for severe water stress, i.e. -0.6 MPa (Carbonneau, 1998) (Table 3.14, Table 3.15 & Table 3.16). The low Ψ_{PD} indicated that grapevines were subjected to water stress that could have inhibited vegetative growth and reduced or inhibited berry growth, photosynthesis and berry maturation (Deloire *et al.*, 2005). However, it is important to remember that the physiological consequences of water stress also depend on the duration of the period that the grapevines were subjected to these low Ψ_{PD} values. Grapevines in the normal irrigated sandy soil at Kapel (P2) were subjected to moderate to severe water stress that could have been favourable to wine quality, i.e. Ψ_{PD} values of ca. -0.40 MPa from pea size to harvest (Carbonneau, 1998). Expected consequences include reduced vigour, possible stimulation of anthocyanin biosynthesis, slow ripening without major inhibition, concentration of metabolites and increase in the skin to flesh ratio (Deloire *et al.*, 2004). On the other hand, Ψ_{PD} values of ca. -0.20 MPa in normal irrigated grapevines in the loamy sand at Lutzville (P12) indicated that they did not experience any water stress from pea size to ripening (Carbonneau, 1998). This low level of water stress could have caused excessive vigour and dilution of berry metabolites (Deloire *et al.*, 2004).

During November (pea size) normal irrigated grapevines in the sandy soils at Kapel experience more water stress from noon onwards compared to the ones that were closer to the ocean at Lutzville (Table 3.14). However, in January (ripening) normal irrigated grapevines in the sandy soils at Kapel experienced more water stress throughout the course of the day compared to the ones at Lutzville (Table 3.16). This suggested that grapevines at Lutzville, i.e. nearest to the ocean, tended to experience less water stress compared to the ones at Kapel. The effect of the climate on grapevine water status became more pronounced as the season progressed from November to January. In the heavier sandy loam soils this effect appeared to be less prominent.

With the exception of the deficit irrigated grapevines in the sandy soil (P9), total diurnal leaf water potential (Ψ_{LT}) tended to be higher at Kapel compared to Lutzville which is closer to the ocean (Table 3.17). This indicated that deficit irrigation could induce water stress in grapevines in sandy soils to comparable levels, irrespective of the locality. This suggested that the effects of water deficits in sandy soils could dominate the effects of proximity to the ocean on grapevine water status under the given conditions. During pea size, Ψ_{LT} in grapevines in the sandy and sandy loam soils at Kapel as well as the deficit irrigated ones in the sandy soil at Lutzville, was higher compared to ca. 15 MPa^2 measured at pea size in Sauvignon blanc grapevines in a Tukulu soil near Stellenbosch (Laker, 2004). Total diurnal leaf water potential during ripening was also higher in these plots compared to the Sauvignon blanc near Stellenbosch. The water stress in the deficit irrigated grapevines in the sandy soils (P1

& P9), showed a cumulative trend (Fig. 3.41). Apparently pre- and post-véraison water deficits are not independent (Ojeda *et al.*, 2002). The occurrence of a pre-véraison water deficit increases the probability of attaining a severe post-véraison deficit and in some cases a cumulative effect of pre- and post-véraison water deficits may occur.

Total diurnal leaf water potential correlated well with Ψ_S (Fig. 3.42). This suggested that Ψ_S could be a reliable indicator of the accumulative amount of water stress that grapevines would experience throughout the day. Although Ψ_{LT} also correlated with Ψ_{PD}, the correlation was not as close as with the Ψ_S (R^2 = 0.5185; se = 3.4; $p \leq 0.001$). The foregoing suggests that low Ψ_{PD} values do not necessarily imply that grapevines will experience more water stress over the warmer part of the day, or visa versa. This is in agreement with earlier findings with Sauvignon blanc grapevines in the Stellenbosch wine region (Laker, 2004). Predawn leaf water potential could also underestimate the water deficits experienced by the grapevines during the day if the soil water content is heterogeneous (Deloire *et al.*, 2005).

3.3.5.2   Leaf and stem water potential during berry ripening

Midday Ψ_L and Ψ_S water potential varied considerably between plots (Table 3.18, Table 3.19, Table 3.20 & Table 3.21). The lowest mean Ψ_L and Ψ_S recorded during berry ripening, i.e. -1.76 MPa and -1.58 MPa, respectively, were lower compared to values measured in Cabernet Sauvignon in the Napa Valley during August when véraison occur (Williams & Araujo, 2002). On other hand, the highest mean Ψ_L and Ψ_S, i.e. -1.13 MPa and -0.58 MPa, respectively, were higher than the values reported by Williams & Araujo (2002).

In the 2006/07 season normal irrigated grapevines experienced more water stress during the day at Kapel compared to closer to the ocean at Koekenaap, irrespective of soil texture (Fig. 3.43). However, this trend did not occur in the deficit irrigated grapevines. This suggested that climate influenced the amount of water stress grapevines would experience when no water stress was induced, but when water deficits were applied, the effect of climate was masked. The same trend occurred during the 2007/08 season, although the effect of climate on grapevine water status appeared to be more pronounced (Fig. 3.44). During this particular season, normal irrigated grapevines at Lutzville and Koekenaap experienced less water stress compared to the ones at Kapel, irrespective of soil texture. Even the deficit irrigated grapevines in the sandy loam soils at Lutzville and Koekenaap as well as those in the sandy soil at Koekenaap experienced less water stress compared to the ones at Kapel. During berry ripening, water stress in normal irrigated grapevines tended to be lower closer to the ocean in both seasons. Over the 22 km decrease in distance to the Atlantic Ocean from Kapel to Koekenaap, Ψ_L and Ψ_S in normal irrigated grapevines decreased approximately 23% and 27%, respectively (Table 3.22 & Table 3.23).

Due to the relatively low mean daily maximum temperature during February in the 2006/07 season, the effect of climate on grapevine water status was probably less

pronounced than in 2007/08 (Fig. 3.9). The higher relative humidity levels during January and February 2007 could also have reduced evapotranspiration rates (Fig. 3.11). These results indicated that differences in grapevine water status between localities also depend on variations in atmospheric conditions between seasons.

Stem water potential has been considered to be less variable than Ψ_L because it is less susceptible to fluctuations in the environmental pressure than Ψ_L (Choné et al., 2000; Bogart, 2006). Hence, Ψ_S is considered to be more representative of the actual level of stress in the entire grapevine. In this regard Ψ_S could give an indication of grapevine water deficit thresholds which should be useful for irrigation management. It was shown that Ψ_S values greater than -1.0 MPa indicate that grapevines are not subjected to water deficits (Ferreyra et al., 2002). According to this threshold, normal irrigated grapevines were not subjected to water deficits during ripening in both seasons, irrespective of soil texture (Fig. 3.45 & Fig. 3.46). The deficit irrigated grapevines in the heavier soils experienced no or little water stress. However, deficit irrigated grapevines in the sandy soils tended to experience more water stress compared to the ones that received normal irrigation, particularly during the warmer 2007/08 season. High levels of water stress, i.e. Ψ_S values equal to or lower than -1.4 MPa (Ferreyra et al., 2002), occurred in grapevines in P1, P7 and P9 during the 2006/07 season and in P1 and P7 during the 2007/08 season (Table 3.19 & Table 3.21). This confirmed that the deficit irrigated grapevines in the sandy soils were subjected to more severe water stress compare to the deficit irrigated ones in the heavy soils.

There was a close correlation between Ψ_L and Ψ_S (Fig. 3.47). Similar results were obtained in studies with Cabernet Sauvignon and other cultivars (Stevens et al., 1995; Williams & Araujo, 2002; Williams & Trout, 2005). According to Williams et al. (1994), the onset of detrimental water stress in grapevines is when Ψ_L reach approximately -1.2 MPa, but this threshold could depend on the soil type. According to this threshold value, grapevines in P14 were not subjected to water stress during ripening in the 2006/07 season (Table 3.18). In the 2007/08 season grapevines in P12 were not subjected to water stress during ripening (Table 3.20). On the other hand, Ψ_L values of ca. -1.7 MPa and lower indicated that grapevines in P3, P5, P7 and P9 were subjected to a high degree of water stress during ripening in the 2006/07 season. During the 2007/08 season only grapevines in P1 and P3 experienced a high level of water stress.

The variation in Ψ_S could be related to soil water status expressed in terms of soil water matric potential (Ψ_M) (Fig. 3.48). The Ψ_S in field grown Thompson Seedless could be related to soil water content by using a quadratic function (Williams & Trout, 2005). Based on the relationship between plant and soil water potential, measurement of Ψ_{PD} and Ψ_S, can be used to determine the effect of soil water content on grapevine water status (Myburgh, 2003b and references therein). The relationship between Ψ_S and Ψ_M was different in the two soil textures in the Lower Olifants River region. In the sandy soils Ψ_S in grapevines decreased substantially more as the Ψ_M decreased than in the

sandy loam soils (Fig. 3.48). The reason for this could be that the unsaturated hydraulic conductivity in sandy soils decreases more rapidly as Ψ_M decreases compared to heavier soils (Fig. 3.49). This could explain why the grapevines in sandy soils experienced more water stress than the ones in the sandy loam soils although Ψ_M values were the same in the two soil types.

Under the conditions of this study, Ψ_L was poorly related to Ψ_M (data not shown). This is in contrast with previous findings that showed there was a relationship between Ψ_L and soil water content (Williams & Trout, 2005). The poor relationship between Ψ_L and Ψ_M was probably caused by different atmospheric conditions prevailing at the various localities which induced different partial stomatal closure responses. It was shown that leaf water potential in grapevines can show some instability or cyclic behaviour during the day if the atmospheric conditions are stable, but the air temperature is high and the RH is low (Myburgh, 2007). Sap flow in grapevines in sandy soil also showed a cyclic behaviour during the day under stable atmospheric conditions (Myburgh & Howell, 2006).

3.4   CONCLUSIONS

In the Lower Olifants River region the proximity of the Atlantic Ocean could play a decisive role in the potential for viticulture cultivation. Three macro climatic regions were identified within the region, i.e. (i) Klawer, (ii) Vredendal and Lutzville and (iii) Ebenhaeser, nearest to the Atlantic Ocean. According to the cool night index, the Lower Olifants River region could be divided into two regions, i.e. (i) Klawer and (ii) Vredendal, Lutzville and Ebenhaeser. This knowledge is important in finding the best terroir for a specific cultivar in the Lower Olifants River region. An in depth study is necessary to describe the effect of the sea breeze mechanism on air temperatures during the berry ripening period.

Klawer is prone to minimum daily temperatures during May of higher than 10ºC which could have an influence on bud break in the following spring. Precaution should be taken at Klawer to prevent delayed budburst, particularly in cultivars susceptible to delayed bud break, e.g. Chardonnay. Using mechanical night harvesting, time must be allowed for grapes to cool down before harvesting commence. In general, minimum daily temperatures during February occurred between 05:00 and 07:00. Lower maximum daily temperatures during February 2007 and November 2007 could be related to high relative humidity and low total daily solar radiation. This caused a lower evaporative demand.

Due to the differences in atmospheric conditions which demarcated the region in distinct macro climatic zones, canopy management practices in vineyards at Ebenhaeser nearest to the ocean, will differ compared to ones at Klawer. The differences in macro climate could also influence long term practices, e.g. deciding on a row direction. It could be considered to plant rows perpendicular to the prevailing wind

direction at Ebenhaeser to obtain "self-sheltered" rows in an attempt to prevent stomatal closure and the reduction of photosynthesis in the grapevine (Greenspan, 2008). This is particularly important for cultivars that struggle to obtain the recommended sugar level in a cool climate. On the other hand, at Kapel grapevines row direction parallel to the prevailing wind direction could be considered to enhance the cooling of grapevines and grapes in the afternoon.

The fine sand content in the soils seemed to be a function of distance from the Atlantic Ocean and altitude. This suggested that the prevailing winds carried the fine sand particles further and higher inland. Root distribution and density varied considerably between plots and did not show any trend that could be related to locality or soil texture. The low organic matter content in the sandy soil could require practices such as winter cover crops, mulching or composting to increase the organic matter content.

Water status in grapevines tended to recover more easily and to higher levels over the course of the day earlier in the season (November) compared to later on (January), irrespective of soil texture. This could have been caused by the change in atmospheric conditions as the season progressed. Grapevines at Lutzville, nearest to the ocean tended to experience less water stress over the course of the day compared to the ones at Kapel. This effect became more pronounced as the season progressed, probably also due to changes in prevailing atmospheric conditions. It seemed that deficit irrigation induced water stress in grapevines in sandy soils to comparable levels, irrespective of proximity to the ocean. Furthermore, diurnal water stress in the sandy soils showed a cumulative trend as the season progressed. These results also suggest that measurement of diurnal leaf water potential cycles at various phenological stages is required to understand the effect of the climate and soil on grapevine water status.

During berry ripening, grapevines at Kapel experienced more water stress compared to the ones at Koekenaap, nearest to the ocean, irrespective of soil texture. However, seasonal variation in atmospheric conditions could influence the effect of the climate. During cool seasons, the effect could be less pronounced compared to warmer ones. In a cool season, deficit irrigated grapevines at Kapel and Koekenaap would experience the same amount of water stress, irrespective of soil texture. However, during a warm season the effect of deficit irrigation would probably be more pronounced.

Deficit irrigation increased water stress in grapevines compared to more frequently irrigated ones. Grapevines in the sandy soils were more easily subjected to water stress compared to the ones in the sandy loam soils. To induce deficit irrigation in grapevines in the sandy loam alluvial soils close to the river, irrigation must be reduced shortly after bud break, which is considerably earlier compared to grapevines in sandy loam soils further away from the river, and particularly in the sandy soils. Root systems in the sandy soils will have a smaller soil volume from which to absorb water and

nutrients compared to the sandy loam soils. Irrigation scheduling and nutrition should be adjusted accordingly.

Stem water potential was a more sensitive indicator of water deficits in grapevines compared to Ψ_L. Stem water potential could be an indicator of accumulative amount of water stress that grapevines would experience throughout the day. The variation in Ψ_S could be related to the variation in Ψ_M. At a given Ψ_M, grapevines in the sandy soils experienced more water stress compared to the ones in sandy loam soils. The reason for this could be that the unsaturated hydraulic conductivity in sandy soils decreases more rapidly as the Ψ_M decreases compared to the heavier sandy loam soils.

3.5   LITERATURE CITED

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Table 3.1 The locality, soil texture and the irrigation strategy of the experiment plots, as well as their co-ordinates, altitude, distance to the Atlantic Ocean, planting date, root stock, plant spacing and trellis system in drip irrigated Cabernet Sauvignon vineyards in the Lower Olifants River region where soil and grapevine water status were monitored during the 2006/07 and 2007/08 seasons.

Plot no.	Locality	Soil texture	Irrigation strategy[1]	Coordinates		Altitude	Distance to Atlantic Ocean	Planting date	Root stock	Plant spacing	Trellis system
				Longitude	Latitude	(m)	(km)			(m x m)	
P1	Kapel	Sand	Deficit irrigation	18.58	-31.76	57.79	33.75	2001	110R	2.74 x 1.50	Perold
P2	Kapel	Sand	Normal	18.58	-31.76	57.79	33.75	2001	110R	2.74 x 1.50	Perold
P3	Kapel	Sandy loam	Deficit irrigation	18.57	-31.76	21.26	33.00	2000	99R	2.70 x 1.50	Lengthened Perold
P4	Kapel	Sandy loam	Normal	18.57	-31.76	21.26	33.00	2000	99R	2.70 x 1.50	Lengthened Perold
P5	Vredendal	Sandy loam	Deficit irrigation	18.50	-31.65	12.51	32.50	2000	99R	2.50 x 1.37	Perold
P6	Vredendal	Sandy loam	Normal	18.50	-31.65	12.51	32.50	2000	99R	2.50 x 1.37	Perold
P7	Vredendal	Sand	Deficit irrigation	18.47	-31.64	64.54	30.00	2002	99R	2.50 x 1.50	Lengthened Perold
P8	Vredendal	Sand	Normal	18.47	-31.64	64.54	30.00	2002	99R	2.50 x 1.50	Lengthened Perold
P9	Lutzville	Sand	Deficit irrigation	18.39	-31.59	21.53	25.50	2002	99R	2.50 x 1.50	Perold
P10	Lutzville	Sand	Normal	18.39	-31.59	21.53	25.50	2002	99R	2.50 x 1.50	Perold
P11	Lutzville	Loamy sand	Deficit irrigation	18.39	-31.59	7.72	25.50	2002	99R	2.50 x 1.50	Perold
P12	Lutzville	Loamy sand	Normal	18.39	-31.59	7.72	25.50	2002	99R	2.50 x 1.50	Perold
P13	Koekenaap	Sand	Deficit irrigation	18.24	-31.56	25.69	13.25	1999	110R	2.75 x 1.50	Lengthened Perold
P14	Koekenaap	Sand	Normal	18.24	-31.56	25.69	13.25	1999	110R	2.75 x 1.50	Lengthened Perold
P15	Koekenaap	Sandy loam	Deficit irrigation	18.22	-31.56	9.56	11.50	1997	110R	2.50 x 1.50	Lengthened Perold
P16	Koekenaap	Sandy loam	Normal	18.22	-31.56	9.56	11.50	1997	110R	2.50 x 1.50	Lengthened Perold

[1] "Deficit irrigation" = vineyards in sandy and loamy soils were irrigated when soil matric potential values reached ca. -0.06 MPa and -0.08 MPa, respectively; "Normal" = vineyards were irrigated according to the growers' schedule.

Table 3.2 Equations developed to convert neutron probe count ratio (CR) to soil water matric potential (Ψ_M) in selected plots representing Cabernet Sauvignon vineyards in the Lower Olifants River region where soil and grapevine water status were monitored during the 2006/07 and 2007/08 seasons.

Plot no.[1]	Locality	Soil texture	Soil depth (mm)	Equation	n	R^2	Standard error	Significance
P1 & P2	Kapel	Sand	0-150	$\Psi_M = EXP(0.6821 + 0.5044/CR)$	57	0.8337	0.313	$p < 0.001$
			150-300	$\Psi_M = EXP(-0.2927 + 1.7455/CR)$	56	0.8718	0.345	$p < 0.001$
			>300	$\Psi_M = EXP(-4.1661 + 5.9645/CR)$	44	0.8937	0.372	$p < 0.001$
P 3 & P4	Kapel	Sandy loam	0-300	$\Psi_M = EXP(13.965 - 12.156*CR^{0.5})$	23	0.9131	0.309	$p < 0.001$
			300-600	$\Psi_M = EXP(21.040 - 18.394*CR^{0.5})$	42	0.9429	0.236	$p < 0.001$
			600-900	$\Psi_M = EXP(22.087 - 18.559*CR^{0.5})$	30	0.9641	0.231	$p < 0.001$
P5 & P6	Vredendal	Sandy loam	0-300	$\Psi_M = EXP(8.0292 - 5.6800*CR^{0.5})$	33	0.9288	0.229	$p < 0.001$
			300-600	$\Psi_M = EXP(8.8378 - 6.1877*CR^{0.5})$	41	0.9500	0.160	$p < 0.001$
			600-900	$\Psi_M = EXP(8.7504 - 5.8634*CR^{0.5})$	42	0.9807	0.096	$p < 0.001$
P7 & P8	Vredendal	Sand	0-150	$\Psi_M = EXP(1.5332 + 0.1264/CR)$	53	0.8220	0.297	$p < 0.001$
			150-300	$\Psi_M = EXP(1.7515 + 0.3689/CR)$	50	0.8580	0.253	$p < 0.001$
			>300	$\Psi_M = EXP(0.1010 + 1.5138/CR)$	43	0.8735	0.346	$p < 0.001$
P9 & P10	Lutzville	Sand	0-150	$\Psi_M = EXP(0.5405 + 0.2989/CR)$	39	0.8505	0.300	$p < 9.001$
			150-300	$\Psi_M = EXP(0.6137 + 0.8792/CR)$	40	0.7985	0.405	$p < 0.001$
			>300	$\Psi_M = EXP(-1.7919 + 2.6302/CR)$	39	0.9485	0.258	$p < 0.001$
P11 & P12	Lutzville	Loamy sand	0-300	$\Psi_M = EXP(9.9400 - 8.5160*CR^{0.5})$	22	0.9261	0.265	$p < 0.001$
			300-600	$\Psi_M = EXP(13.317 - 11.462*CR^{0.5})$	29	0.9291	0.300	$p < 0.001$
			600-900	$\Psi_M = EXP(11.195 - 9.6060*CR^{0.5})$	32	0.9392	0.231	$p < 0.001$
P13 & P14	Koekenaap	Sand	0-300	$\Psi_M = EXP(0.8252 + 0.4713/CR)$	56	0.8955	0.239	$p < 0.001$
			300-600	$\Psi_M = EXP(-1.1179 + 1.8065/CR)$	48	0.9579	0.256	$p < 0.001$
P15 & P16	Koekenaap	Sandy loam	0-300	$\Psi_M = EXP(11.367 - 9.5317*CR^{0.5})$	33	0.9140	0.336	$p < 0.001$
			300-600	$\Psi_M = EXP(14.328 - 12.506*CR^{0.5})$	45	0.9257	0.254	$p < 0.001$
			600-900	$\Psi_M = EXP(15.283 - 13.604*CR^{0.5})$	42	0.9546	0.185	$p < 0.001$

Table 3.3 The Winkler index, heliotermal index and cool night index for plots where soil and grapevine water status were monitored in Cabernet Sauvignon vineyards in the Lower Olifants River region during the 2006/07 and 2007/08 seasons.

Plot no.[1]	Locality	Soil texture	Irrigation	Winkler index				Huglin heliotermal index				Cool night index[2]			
				2006/07		2007/08		2006/07		2007/08		2006/07		2006/07	
P1	Kapel	Sand	Deficit irrigation	2 755	V	2 979	V	3 090	HI_{+3}	3 499	HI_{+3}	17.7	CI_{-1}	17.4	CI_{-1}
P2	Kapel	Sand	Normal	2 755	V	2 979	V	3 090	HI_{+3}	3 499	HI_{+3}	17.7	CI_{-1}	17.4	CI_{-1}
P3	Kapel	Sandy loam	Deficit irrigation	2 755	V	2 979	V	3 090	HI_{+3}	3 499	HI_{+3}	17.7	CI_{-1}	17.4	CI_{-1}
P4	Kapel	Sandy loam	Normal	2 755	V	2 979	V	3 090	HI_{+3}	3 499	HI_{+3}	17.7	CI_{-1}	17.4	CI_{-1}
P5	Vredendal	Sandy loam	Deficit irrigation	2 252	V	2 281	V	2790	HI_{+2}	2878	HI_{+2}	14.1	CI_{-1}	14.8	CI_{-1}
P6	Vredendal	Sandy loam	Normal	2 252	V	2 281	V	2790	HI_{+2}	2878	HI_{+2}	14.1	CI_{-1}	14.8	CI_{-1}
P7	Vredendal	Sand	Deficit irrigation	2 252	V	2 281	V	2790	HI_{+2}	2878	HI_{+2}	14.1	CI_{-1}	14.8	CI_{-1}
P8	Vredendal	Sand	Normal	2 252	V	2 281	V	2790	HI_{+2}	2878	HI_{+2}	14.1	CI_{-1}	14.8	CI_{-1}
P9	Lutzville	Sand	Deficit irrigation	2 164	IV	2 228	V	2663	HI_{+2}	2783	HI_{+2}	14.3	CI_{-1}	14.9	CI_{-1}
P10	Lutzville	Sand	Normal	2 164	IV	2 228	V	2663	HI_{+2}	2783	HI_{+2}	14.3	CI_{-1}	14.9	CI_{-1}
P11	Lutzville	Loamy sand	Deficit irrigation	2 164	IV	2 228	V	2663	HI_{+2}	2783	HI_{+2}	12.6	CI_{+1}	12.9	CI_{+1}
P12	Lutzville	Loamy sand	Normal	2 164	IV	2 228	V	2663	HI_{+2}	2783	HI_{+2}	12.6	CI_{+1}	12.9	CI_{+1}
P13	Koekenaap	Sand	Deficit irrigation	1 891	III	1 900	III	2 270	HI_{+1}	2 358	HI_{+1}	14.3	CI_{-1}	14.6	CI_{-1}
P14	Koekenaap	Sand	Normal	1 891	III	1 900	III	2 270	HI_{+1}	2 358	HI_{+1}	14.3	CI_{-1}	14.6	CI_{-1}
P15	Koekenaap	Sandy loam	Deficit irrigation	1 891	III	1 900	III	2 270	HI_{+1}	2 358	HI_{+1}	13.0	CI_{+1}	12.9	CI_{+1}
P16	Koekenaap	Sandy loam	Normal	1 891	III	1 900	III	2 270	HI_{+1}	2 358	HI_{+1}	13.0	CI_{+1}	12.9	CI_{+1}

[1] Refer to Table 3.1 for description of the plots.

[2] The month before harvest was used to determine the CI.

Table 3.4 Long term mean daily maximum temperature and mean daily minimum temperature measured at weather stations near Klawer, Vredendal, Lutzville and Ebenhaeser in the Lower Olifants River region.

Month	Daily maximum temperature (ºC)				Daily minimum temperature (ºC)			
	Klawer	Vredendal	Lutzville	Ebenhaeser	Klawer	Vredendal	Lutzville	Ebenhaeser
September	25.49	24.59	23.88	22.61	11.82	7.83	8.97	8.79
October	28.90	26.75	26.39	23.55	13.69	10.24	10.08	10.41
November	30.84	28.32	27.47	24.72	14.99	12.13	11.97	11.89
December	31.77	28.62	27.85	25.64	16.23	13.07	13.15	13.45
January	33.23	31.58	29.88	26.53	17.19	15.10	14.62	14.64
February	33.44	30.96	30.50	27.21	17.48	14.51	14.79	14.67
March	32.11	30.65	30.12	27.17	16.63	13.12	13.23	13.04
April	28.51	28.01	28.51	25.73	14.79	10.63	11.07	11.43
May	25.25	24.22	24.67	23.26	12.50	8.88	9.76	9.80
June	21.61	21.94	22.06	21.20	10.02	7.18	7.34	7.34
July	21.97	21.61	22.39	20.87	9.75	5.98	7.11	6.84
August	22.20	20.77	20.92	19.88	9.41	6.25	7.22	7.41

Table 3.5 Long term mean relative humidity and total monthly rainfall measured at weather stations near Klawer, Vredendal, Lutzville and Ebenhaeser in the Lower Olifants River region.

Month	Mean relative humidity (%)				Total monthly rainfall (mm)			
	Klawer	Vredendal	Lutzville	Ebenhaeser	Klawer	Vredendal	Lutzville	Ebenhaeser
September	52.21	63.08	65.34	69.58	14.54	5.25	6.81	8.49
October	49.32	59.16	64.05	68.56	17.68	6.18	8.47	10.47
November	49.48	58.57	62.41	68.92	8.67	12.96	3.16	6.92
December	51.53	58.13	63.23	68.90	7.39	17.66	3.97	5.76
January	52.32	58.28	63.87	69.62	5.10	8.66	2.16	7.57
February	52.37	60.74	65.54	71.36	4.87	6.43	3.49	2.29
March	48.96	56.38	61.88	66.97	5.79	3.95	2.20	3.10
April	52.96	60.87	65.21	68.46	18.57	15.92	7.73	11.61
May	56.91	66.35	66.61	70.68	36.11	24.84	25.27	20.82
June	55.29	68.18	64.36	68.54	43.51	36.18	19.14	20.12
July	51.47	67.82	66.98	67.78	37.51	32.46	22.30	25.19
August	57.37	71.89	71.49	71.79	33.79	22.96	21.43	34.88

Table 3.6 Long term mean daily wind speed, total daily solar radiation and total daily reference evapotranspiration measured at weather stations near Klawer, Vredendal, Lutzville and Ebenhaeser in the Lower Olifants River region.

Month	Mean daily wind speed (m/s)				Total daily radiation (MJ/m^2)				Reference evapotranspiration (mm/day)			
	Klawer	Vredendal	Lutzville	Ebenhaeser	Klawer[1]	Vredendal	Lutzville	Ebenhaeser	Klawer[2]	Vredendal	Lutzville	Ebenhaeser
September	1.45	2.64	1.75	3.55	21.18	16.95	18.25	19.07	5.29	4.49	4.10	5.14
October	1.70	3.30	2.02	4.14	25.04	21.84	24.28	23.82	6.45	5.95	5.47	6.33
November	1.79	3.72	2.00	4.58	28.5	25.96	27.56	28.40	7.22	7.14	6.12	6.86
December	1.82	3.81	2.31	4.62	30.37	27.36	29.65	30.59	8.07	7.36	6.80	6.31
January	1.67	3.71	2.35	4.47	31.76	26.55	29.05	29.69	8.90	7.66	6.94	6.93
February	1.58	3.38	2.21	4.07	26.31	23.48	25.88	26.06	7.38	7.05	6.42	6.37
March	1.70	2.96	2.05	3.61	22.8	20.28	22.17	22.18	6.56	6.31	5.79	5.92
April	1.39	2.38	1.59	2.84	17.5	15.12	16.18	16.82	4.71	4.57	4.08	4.80
May	1.28	2.15	1.58	2.98	10.32	10.78	12.06	12.37	2.77	3.14	2.79	3.85
June	1.77	2.03	1.71	2.96	9.6	9.20	10.39	11.27	2.53	2.63	2.35	3.35
July	1.38	1.95	1.72	2.98	9.88	10.20	11.34	11.87	2.30	2.67	2.55	3.63
August	1.31	2.26	1.83	3.25	14.37	11.74	14.27	14.00	3.36	2.91	2.90	3.88

[1] Just 2007/08 season's data - This station was converted to an automatic weather station in September 2007. Before then a mechanical weather station was used.

[2] Just 2007/08 season's data - This station was converted to an automatic weather station in September 2007. Before then a mechanical weather station was used, that use the A-pan to calculate the total evapotranspiration per day (mm) which gave a bigger value in the summer months, because it does not bring into calculation the climatic factors, like the Penman-Monthieth (FAO-56) does for the automatic weather station.

Table 3.7 Chemical analyses of soils in the Cabernet Sauvignon vineyards in the Lower Olifants River region where soil and grapevine water status were monitored during the 2006/07 and 2007/08 seasons.

Plot no.[1]	Locality	Soil depth (mm)	pH (KCl)	Ec (dS/m)	Stone (Vol %)	P (mg/kg)	K (mg/kg)	Exchangeable cations (cmol(+)/kg)				Micro nutrients (mg/kg)				C (%)
								Na	K	Ca	Mg	Cu	Zn	Mn	B	
P1 & P2	Kapel	0-300	6.9	0.19	7	145	209	0.34	0.53	3.21	2.45	3.08	3.9	16.0	0.22	0.20
		300-600	6.2	0.17	20	29	341	0.50	0.87	2.66	3.71	0.85	0.7	23.9	0.23	0.08
P3 & P4	Kapel	0-300	5.7	0.13	1	139	230	0.29	0.59	4.48	2.11	1.39	2.6	18.1	0.41	0.43
		300-600	7.1	0.17	2	6	232	0.33	0.59	6.27	2.92	0.51	0.7	10.6	0.43	0.18
		600-900	6.7	0.18	1	126	175	0.28	0.45	4.18	2.68	0.66	0.7	9.0	0.44	0.18
P5 & P6	Vredendal	0-300	7.2	0.21	1	19	180	0.14	0.46	5.74	2.20	0.79	1.9	23.3	0.14	0.28
		300-600	7.0	0.14	1	12	120	0.13	0.31	3.58	1.29	0.67	1.0	11.3	0.06	0.19
		600-900	6.3	0.12	1	100	113	0.52	0.29	3.35	1.37	0.76	0.8	9.1	0.12	0.08
P7 & P8	Vredendal	0-300	5.5	0.08	1	118	88	0.08	0.23	1.81	0.47	0.84	4.7	8.4	0.09	0.17
		300-600	5.7	0.08	1	16	73	0.08	0.19	0.96	0.64	0.20	0.5	5.8	0.03	0.06
P9 & P10	Lutzville	0-300	8.0	0.11	2	4	127	0.09	0.33	8.40	0.91	0.13	0.6	5.4	0.07	0.18
		300-600	8.0	0.11	3	4	83	0.08	0.21	8.45	0.89	0.30	0.8	10.7	0.04	0.20
		600-900	8.1	0.17	7	2	132	0.15	0.34	17.55	2.26	0.03	0.0	**0.0**	0.03	0.18
P11 & P12	Lutzville	0-300	7.7	0.15	1	25	273	0.12	0.70	9.92	1.27	0.75	2.1	14.1	0.05	0.21
		300-600	7.7	0.13	1	23	210	0.09	0.54	11.66	1.22	0.67	2.0	13.5	0.16	0.27
		600-900	7.7	0.16	1	20	184	0.08	0.47	9.47	1.13	0.74	1.4	22.0	0.08	0.28
P13 & P14	Koekenaap	0-300	6.9	0.09	1	12	116	0.08	0.30	1.85	0.93	0.57	1.0	9.9	0.07	0.19
		300-600	6.0	0.08	1	13	180	0.16	0.46	1.88	1.63	0.24	0.2	3.7	0.04	0.06
P15 & P16	Koekenaap	0-300	6.4	0.15	1	45	224	0.53	0.57	1.75	1.93	0.85	0.8	15.1	0.75	0.18
		300-600	7.6	0.88	1	8	363	1.49	0.93	9.75	2.88	0.42	0.5	14.5	0.79	0.18
		600-900	7.6	0.86	1	8	354	1.56	0.90	13.96	3.09	0.23	0.3	8.2	0.72	0.22

[1] Refer to Table 3.1 for description of the plots.

Table 3.8 Estimated stone fraction, particle size analyses, textural class and bulk density of the soils Cabernet Sauvignon vineyards in the Lower Olifants River region where soil and grapevine water status were monitored during the 2006/07 and 2007/08 seasons.

Plot no.[1]	Locality	Soil depth (mm)	Stone (Vol%)	Clay (%)	Silt (%)	Fine Sand (%)	Medium Sand (%)	Coarse Sand (%)	Soil textural class	Bulk density (Mg/m³)
P1 & P2	Kapel	0-300	7	2.8	5.6	71.4	11.7	8.5	Sand	1.53
		300-600	20	3.0	6.0	64.6	12.9	13.5	Sand	-[2]
		> 600	-	-	-	-	-	-	Dorbank	-[2]
P3 & P4	Kapel	0-300	1	15.6	12.6	54.1	11.5	6.2	Sandy loam	1.58
		300-600	2	21.8	13.6	51.7	9.0	3.9	Sandy clay loam	1.57
		600-900	1	17.8	13.4	46.5	16.2	6.1	Sandy loam	1.60
P5 & P6	Vredendal	0-300	1	10.2	19.2	62.3	7.8	0.5	Sandy loam	1.68
		300-600	1	7.6	15.0	70.6	6.6	0.2	Sandy loam	1.41
		600-900	1	7.4	14.2	59.1	17.2	2.1	Loamy sand	1.58
P7 & P8	Vredendal	0-300	1	1.4	0.4	79.6	15.6	3.0	Sand	1.61
		300-600	1	0.8	1.4	78.4	15.4	4.0	Sand	1.66
		> 600	-	-	-	-	-	-	Dorbank	-[2]
P9 & P10	Lutzville	0-300	2	0.4	2.4	48.3	45.3	3.6	Sand	1.64
		300-600	3	1.6	2.0	45.9	46.8	3.7	Sand	1.66
		600-900	7	2.6	4.4	38.4	34.5	20.1	Sand	1.65
P11 & P12	Lutzville	0-300	1	7.0	5.2	50.0	34.8	2.8	Loamy sand	1.46
		300-600	1	5.2	6.6	49.2	36.3	2.7	Loamy sand	1.56
		600-900	1	3.6	9.6	59.5	25.9	1.4	Loamy sand	1.69
P13 & P14	Koekenaap	0-300	1	0.8	3.8	46.9	44.1	4.4	Sand	1.53
		300-600	1	3.0	2.8	44.0	44.6	5.6	Sand	1.75
		> 600	-	-	-	-	-	-	Dorbank	-[2]
P15 & P16	Koekenaap	0-300	1	11.2	9.2	29.5	43.3	6.8	Sandy loam	1.63
		300-600	1	19.4	9.0	32.1	34.0	5.5	Sandy loam	1.67
		600-900	1	18.4	10.6	34.6	31.0	5.4	Sandy loam	1.45

[1] Refer to Table 3.1 for description of the plots.

[2] To stony for soil core sampling.

Table 3.9 Phenological dates of Cabernet Sauvignon vineyards in the Lower Olifants River region where soil and grapevine water status were monitored during the 2006/07 and 2007/08 seasons.

Plot no.[1]	Locality	Soil texture	Irrigation	Bud break		Flowering		Véraison		Harvest	
				2006/07	2007/08	2006/07	2007/08	2006/07	2007/08	2006/07	2007/08
P1	Kapel	Sand	Deficit irrigation	20 September	29 September	23 October	29 October	5 January	3 January	30 January	5 February
P2	Kapel	Sand	Normal	20 September	29 September	23 October	29 October	5 January	7 January	30 January	5 February
P3	Kapel	Sandy loam	Deficit irrigation	15 September	19 September	20 October	26 October	9 January	9 January	30 January	1 February
P4	Kapel	Sandy loam	Normal	15 September	19 September	20 October	26 October	9 January	9 January	7 February	13 February
P5	Vredendal	Sandy loam	Deficit irrigation	25 September	26 September	26 October	7 November	16 January	15 January	7 March	7 March
P6	Vredendal	Sandy loam	Normal	25 September	26 September	26 October	7 November	16 January	15 January	14 March	14 March
P7	Vredendal	Sand	Deficit irrigation	25 September	2 October	29 October	3 November	10 January	14 January	7 March	11 March
P8	Vredendal	Sand	Normal	25 September	20 September	29 October	28 October	10 January	12 January	14 March	7 March
P9	Lutzville	Sand	Deficit irrigation	8 September	15 September	24 October	3 November	4 January	9 January	1 March	7 March
P10	Lutzville	Sand	Normal	8 September	13 September	24 October	22 October	4 January	13 January	7 March	7 March
P11	Lutzville	Loamy sand	Deficit irrigation	16 September	17 September	27 October	26 October	10 January	18 January	21 March	19 March
P12	Lutzville	Loamy sand	Normal	16 September	17 September	27 October	26 October	10 January	20 January	5 April	27 March
P13	Koekenaap	Sand	Deficit irrigation	26 September	24 September	6 November	7 November	18 January	13 January	14 March	11 March
P14	Koekenaap	Sand	Normal	26 September	27 September	6 November	7 November	18 January	17 January	28 March	19 March
P15	Koekenaap	Sandy loam	Deficit irrigation	27 September	28 September	10 November	9 November	24 January	28 January	21 March	19 March
P16	Koekenaap	Sandy loam	Normal	27 September	28 September	10 November	9 November	24 January	28 January	21 March	27 March

[1] Refer to Table 3.1 for description of the plots.

Table 3.10 Irrigation amounts applied during phenological stages according to the normal irrigation strategies in eight Cabernet Sauvignon vineyards representing different localities, soil and texture where soil and grapevine water status were monitored during the 2006/07 and 2007/08 seasons in the Lower Olifants River region.

Plot no[1]	Locality	Soil texture	Irrigation strategy	Bud break to flowering (mm)		Flowering to véraison (mm)		Véraison to harvest (mm)		Total from bud break to harvest (mm)	
				2006/07	2007/08	2006/07	2007/08	2006/07	2007/08	2006/07	2007/08
P2	Kapel	Sand	Normal	107	106	223	140	126	103	456	349
P4		Sandy loam	Normal	42	97	213	175	67	75	323	347
P6	Vredendal	Sandy loam	Normal	55	39	172	210	319	94	547	344
P8		Sand	Normal	95	42	247	47	195	184	536	272
P10	Lutzville	Sand	Normal	34	52	93	142	73	98	200	292
P12		Loamy sand	Normal	119	0	150	51	164	114	433	165
P14	Koekenaap	Sand	Normal	160	113	242	178	279	162	682	454
P16		Sandy loam	Normal	35	29	30	90	82	84	148	203

[1] Refer to Table 3.1 for description of the plots.

Table 3.11 Percentage of normal irrigation applied during different phenological stages to deficit irrigated Cabernet Sauvignon in eight plots representing different localities and soil texture where soil and grapevine water status were monitored during the 2006/07 and 2007/08 seasons in the Lower Olifants River region.

Plot no[1]	Locality	Soil texture	Irrigation strategy	Bud break to flowering (%)		Flowering to véraison (%)		Véraison to harvest (%)	
				2006/07	2007/08	2006/07	2007/08	2006/07	2007/08
P1	Kapel	Sand	Deficit	92	100	52	70	31	37
P3		Sandy loam	Deficit	67	100	35	5	0	28
P5	Vredendal	Sandy loam	Deficit	100	0	0	14	0	0
P7		Sand	Deficit	100	100	44	[2]	45	26
P9	Lutzville	Sand	Deficit	100	100	91	72	51	[2]
P11		Loamy sand	Deficit	29	0	31	0	0	0
P13	Koekenaap	Sand	Deficit	100	100	12	36	9	22
P15		Sandy loam	Deficit	100	100	0	48	15	18

[1] Refer to Table 3.1 for description of the plots. [2] Faulty water meter

Table 3.12 Mean soil water matric potential during different phenological stages in 16 plots in Cabernet Sauvignon vineyards representing different localities, soil texture and irrigation strategies as determined during the 2006/07 and 2007/08 seasons in the Lower Olifants River region.

Plot no[1]	Locality	Soil texture	Irrigation strategy	Bud break to flowering (MPa)		Flowering to véraison (MPa)		Véraison to harvest (MPa)	
				2006/07	2007/08	2006/07	2007/08	2006/07	2007/08
P1	Kapel	Sand	Deficit irrigation	-0.006	-0.005	-0.030	-0.034	-0.031	-0.053
P2			Normal	-0.004	-0.005	-0.010	-0.010	-0.016	-0.020
P3		Sandy loam	Deficit irrigation	-0.009	-0.007	-0.046	-0.059	-0.084	-0.075
P4			Normal	-0.008	-0.008	-0.021	-0.026	-0.040	-0.056
P5	Vredendal	Sandy loam	Deficit irrigation	-0.013	-0.028	-0.049	-0.062	-0.078	-0.086
P6			Normal	-0.012	-0.021	-0.023	-0.023	-0.019	-0.042
P7		Sand	Deficit irrigation	-0.012	-0.011	-0.025	-0.034	-0.037	-0.054
P8			Normal	-0.012	-0.011	-0.012	-0.010	-0.012	-0.012
P9	Lutzville	Sand	Deficit irrigation	-0.013	-0.007	-0.041	-0.036	-0.060	-0.039
P10			Normal	-0.014	-0.012	-0.036	-0.019	-0.066	-0.018
P11		Loamy sand	Deficit irrigation	-0.009	-0.018	-0.034	-0.050	-0.070	-0.073
P12			Normal	-0.004	-0.018	-0.009	-0.026	-0.019	-0.016
P13	Koekenaap	Sand	Deficit irrigation	-0.004	-0.003	-0.032	-0.016	-0.033	-0.022
P14			Normal	-0.005	-0.005	-0.005	-0.005	-0.005	-0.005
P15		Sandy loam	Deficit irrigation	-0.008	-0.014	-0.054	-0.038	-0.077	-0.066
P16			Normal	-0.005	-0.007	-0.033	-0.017	-0.023	-0.023

[1] Refer to Table 3.1 for description of the plots.

Table 3.13 Root number, distribution and density of Cabernet Sauvignon grapevines in 16 plots in vineyards where soil and grapevine water status were monitored in the Lower Olifants River region during the 2006/07 and 2007/08 seasons.

Plot no.[1]	Locality	Soil texture	Root numbers			Distribution (%)			Density (roots/m^2)
			0-300 mm	300-600 mm	600-900 mm	0-300 mm	300-600 mm	600-900 mm	
P1 & P2	Kapel	Sand	181	219	275	26.8	32.4	40.7	253
P3 & P4	Kapel	Sandy loam	136	117	224	28.5	24.5	47.0	179
P5 & P6	Vredendal	Sandy loam	202	178	182	35.9	31.7	32.4	211
P7 & P8	Vredendal	Sand	260	227	240	35.8	31.2	33.0	273
P9 & P10	Lutzville	Sand	97	148	129	25.9	39.6	34.5	140
P11 & P12	Lutzville	Loamy sand	56	119	58	24.0	51.1	24.9	87
P13 & P14	Koekenaap	Sand	151	61	19	65.4	26.4	8.2	87
P15 & P16	Koekenaap	Sandy loam	133	249	237	21.5	40.2	38.3	232

[1] Refer to Table 3.1 for description of the plots.

Table 3.14 Effect of locality, soil type and irrigation strategy on diurnal leaf water potential (Ψ_L) changes in Cabernet Sauvignon measured in the Lower Olifants River region on 6 November 2006 (pea size).

Plot no.[1]	Locality	Soil texture	Irrigation strategy	Ψ_L (MPa) 04:00	08:00	12:00	16:00	20:00	24:00
P1	Kapel	Sand	Deficit	-0.48 bc[2]	-0.92 cd	-1.15 b	-1.43 ab	-0.58 b	-0.54 a
P2			Normal	-0.39 bcd	-0.93 bcd	-1.35 a	-1.48 a	-0.66 a	-0.42 b
P3		Sandy loam	Deficit	-0.58 b	-1.08 a	-1.30 ab	-1.45 a	-0.67 a	-0.55 a
P4			Normal	-0.42 bcd	-1.07 ab	-1.13 b	-1.51 a	-0.66 a	-0.52 a
P9	Lutzville	Sand	Deficit	-0.72 a	-1.03 abc	-1.23 ab	-1.28 c	-0.50 c	-0.48 ab
P10			Normal	-0.37 cd	-0.83 d	-1.13 b	-1.31 bc	-0.34 d	-0.28 c
P11		Loamy sand	Deficit	-0.52 b	-0.89 cd	-1.11 b	-1.41 d	-0.33 d	-0.19 c
P12			Normal	-0.32 d	-0.90 cd	-1.15 b	-1.07 d	-0.29 d	-0.23 c

[1] Refer to Table 3.1 for description of the plots. [2] Values designated by the same letter within a column do not differ significantly ($p \leq 0.05$).

Table 3.15 Effect of locality, soil type and irrigation strategy on diurnal leaf water potential (Ψ_L) changes in Cabernet Sauvignon measured in the Lower Olifants River region on 19 December 2006 (pre-véraison).

Plot no.[1]	Locality	Soil texture	Irrigation strategy	Ψ_L (MPa) 04:00	08:00	12:00	16:00	20:00	24:00
P1	Kapel	Sand	Deficit	-0.78 a[2]	-1.12 c	-1.62 a	-1.39 b	-1.16 a	-0.92 a
P2			Normal	-0.42 c	-0.94 de	-1.48 ab	-1.23 cd	-0.77 c	-0.51 c
P3		Sandy loam	Deficit	-0.58 b	-1.25 b	-1.45 bc	-1.33 bc	-0.86 bc	-0.70 b
P4			Normal	-0.45 c	-1.07 cd	-1.30 cd	-1.22 d	-0.63 d	-0.55 c
P9	Lutzville	Sand	Deficit	-0.24 d	-1.39 a	-1.53 ab	-1.54 a	-0.97 b	-0.68 b
P10			Normal	-0.18 d	-0.86 ef	-1.50 ab	-1.30 bcd	-0.54 d	-0.28 d
P11		Loamy sand	Deficit	-0.22 d	-0.77 fg	-1.28 d	-1.06 e	-0.38 e	-0.34 d
P12			Normal	-0.17 d	-0.69 g	-1.01 e	-0.98 e	-0.33 e	-0.29 d

[1] Refer to Table 3.1 for description of the plots. [2] Values designated by the same letter within a column do not differ significantly ($p \leq 0.05$).

Table 3.16 Effect of locality, soil type and irrigation strategy on diurnal leaf water potential (Ψ_L) changes in Cabernet Sauvignon measured in the Lower Olifants River region on 29 January 2007 (ripening).

Plot no.[1]	Locality	Soil texture	Irrigation strategy	Ψ_L (MPa)					
				04:00	08:00	12:00	16:00	20:00	24:00
P1	Kapel	Sand	Deficit	-0.74 a[2]	-0.72 bc	-1.93 a	-1.76 a	-1.39 a	-1.06 a
P2			Normal	-0.40 b	-0.61 c	-1.67 b	-1.27 c	-0.64 c	-0.51 d
P3		Sandy loam	Deficit	-0.40 b	-0.73 b	-1.88 a	-1.62 b	-0.83 b	-0.63 c
P4			Normal	-0.33 bc	-0.43 d	-1.65 b	-1.33 c	-0.67 c	-0.46 d
P9	Lutzville	Sand	Deficit	-0.72 a	-0.87 a	-1.83 a	-1.67 ab	-1.41 a	-0.90 b
P10			Normal	-0.22 cd	-0.27 e	-0.90 d	-0.92 e	-0.37 d	-0.23 e
P11		Loamy sand	Deficit	-0.30 bcd	-0.63 bc	-1.28 c	-1.00 d	-0.42 d	-0.52 d
P12			Normal	-0.18 d	-0.48 d	-0.91 d	-0.88 e	-0.34 d	-0.24 e

[1] Refer to Table 3.1 for description of the plots.

[2] Values designated by the same letter within a column do not differ significantly ($p \leq 0.05$).

Table 3.17 Total diurnal leaf water potential (Ψ_{LT}) measured in eight selected Cabernet Sauvignon plots in the Lower Olifants River region during the 2006/07 season.

Plot no.[1]	Locality	Soil texture	Irrigation strategy	Ψ_{LT} (MPa^2) November 2006	December 2006	January 2007
P1	Kapel	Sand	Deficit irrigation	21.4 e[2]	27.3 g	28.2 f
P2			Normal	20.1 c	20.8 d	18.8 d
P3		Sandy loam	Deficit irrigation	22.3 f	23.3 e	22.7 e
P4			Normal	21.1 de	21.1 d	18.0 c
P9	Lutzville	Sand	Deficit irrigation	20.6 cd	25.9 f	29.8 g
P10			Normal	16.6 b	18.0 c	12.4 a
P11		Loamy sand	Deficit irrigation	16.3 b	15.6 b	15.9 b
P12			Normal	15.7 a	13.4a	12.1 a

[1] Refer to Table 3.1 for description of the plots.

[2] Values designated by the same letter within a column do not differ significantly ($p \leq 0.05$).

Table 3.18 Leaf water potential (Ψ_L) measured during ripening in Cabernet Sauvignon in 16 plots representing different localities, soil texture and irrigation strategies in the Lower Olifants River region during the 2006/07 season.

Plot no.[1]	Locality	Soil texture	Irrigation strategy	Ψ_L (MPa) 9 January	Ψ_L (MPa) 30 January	Ψ_L (MPa) 22 February
P1	Kapel	Sand	Deficit irrigation	-1.52 cde[2]	-1.74 ab	-1.57 fg
P2			Normal	-1.57 abcd	-1.60 c	-1.63 ef
P3		Sandy loam	Deficit irrigation	-1.64 a	-1.85 a	-1.79 bc
P4			Normal	-1.53 bcde	-1.74 ab	-1.84 ab
P5	Vredendal	Sandy loam	Deficit irrigation	-1.60 ab	-1.83 a	-1.68 de
P6			Normal	-1.53 bcde	-1.73 ab	-1.61 ef
P 7		Sand	Deficit irrigation	-1.58 abc	-1.79 a	-1.93 a
P8			Normal	-1.46 ef	-1.74 ab	-1.69 de
P9	Lutzville	Sand	Deficit irrigation	-1.63 a	-1.82 a	-1.73 cd
P10			Normal	-1.53 bcde	-1.22 f	-1.60 ef
P11		Loamy sand	Deficit irrigation	-1.49 def	-1.40 de	-1.43 hi
P12			Normal	-1.26 h	-1.28 ef	-1.21 j
P13	Koekenaap	Sand	Deficit irrigation	-1.43 fg	-1.43 d	-1.49 gh
P14			Normal	-0.99 i	-1.23 f	-1.17 j
P15		Sandy loam	Deficit irrigation	-1.53 bcde	-1.67 bc	-1.49 gh
P16			Normal	-1.35 g	-1.43 d	-1.38 i

[1] Refer to Table 3.1 for description of the plots.

[2] Values designated by the same letter within a column do not differ significantly ($p \leq 0.05$).

Table 3.19 Stem water potential (Ψ_s) measured during ripening in Cabernet Sauvignon in 16 plots representing different localities, soil texture and irrigation strategies in the Lower Olifants River region during the 2006/07 season.

Plot no.[1]	Locality	Soil form	Irrigation strategy	(Ψ_s) (MPa) 9 January	30 January	22 February
P 1	Kapel	Sand	Deficit irrigation	-1.30 a[2]	-1.63 ab	-0.99 f
P2			Normal	-1.03 bc	-0.90 g	-1.38 a
P3		Sandy loam	Deficit irrigation	-1.03 bc	-1.23 cd	-1.13 de
P4			Normal	-0.85 fgh	-0.98 fg	-1.30 b
P5	Vredendal	Sandy loam	Deficit irrigation	-0.88 efgh	-1.28 c	-1.10 e
P6			Normal	-0.93 def	-1.05 ef	-0.77 h
P7		Sand	Deficit irrigation	-1.26 a	-1.55 b	-1.28 b
P8			Normal	-1.00 cd	-1.17 d	-0.97 f
P9	Lutzville	Sand	Deficit irrigation	-0.95 cde	-1.70 a	-1.45 a
P10			Normal	-0.83 gh	-0.54 i	-1.19 cd
P11		Loamy sand	Deficit irrigation	-0.91 defg	-0.93 g	-0.86 g
P12			Normal	-0.79 h	-0.71 h	-0.65 i
P13	Koekenaap	Sand	Deficit irrigation	-1.12 b	-1.23 cd	-1.26 bc
P14			Normal	-0.57 i	-0.59 i	-0.58 i
P15		Sandy loam	Deficit irrigation	-1.04 bc	-1.15 de	-1.08 e
P16			Normal	-0.95 cde	-0.92 g	-0.88 g

[1] Refer to Table 3.1 for description of the plots.

[2] Values designated by the same letter within a column do not differ significantly ($p \leq 0.05$).

Table 3.20 Leaf water potential (Ψ_L) measured during ripening in Cabernet Sauvignon in 16 plots representing different localities, soil types and irrigation strategies in the Lower Olifants River region during the 2007/08 season.

Plot no.[1]	Locality	Soil texture	Irrigation strategy	Ψ_L (MPa)		
				9 January	31 January	18 February
P1	Kapel	Sand	Deficit irrigation	-1.88 ab[2]	-1.51 cdef	[3]
P2			Normal	-1.74 cd	-1.64 ab	[3]
P3		Sandy loam	Deficit irrigation	-1.97 a	-1.56 bcd	[3]
P4			Normal	-1.78 bc	-1.57 bc	[3]
P5	Vredendal	Sandy loam	Deficit irrigation	-1.78 bc	-1.41 fg	-1.58 b
P6			Normal	-1.73 cd	-1.41 fg	-1.43 c
P7		Sand	Deficit irrigation	-1.73 cd	-1.64 ab	-1.69 ab
P8			Normal	-1.64 d	-1.44 efg	-1.64 ab
P9	Lutzville	Sand	Deficit irrigation	-1.70 cd	-1.71 a	-1.22 de
P10			Normal	-1.37 fg	-1.52 cde	-1.08 f
P11		Loamy sand	Deficit irrigation	-1.50 e	-1.18 h	-1.17 ef
P12			Normal	-1.30 gh	-1.14 h	-0.95 g
P13	Koekenaap	Sand	Deficit irrigation	-1.46 ef	-1.53 cde	-1.59 b
P14			Normal	-1.23 h	-1.46 defg	-1.28 d
P15		Sandy loam	Deficit irrigation	-1.36 fg	-1.37 g	-1.71 a
P16			Normal	-1.23 h	-1.20 h	-1.43 c

[1] Refer to Table 3.1 for description of the plots.

[2] Values designated by the same letter within a column do not differ significantly ($p \leq 0.05$).

[3] Plots were already harvested when (Ψ_L) readings were carried out.

Table 3.21 Stem water potential (Ψ_s) measured during ripening in Cabernet Sauvignon on 16 plots representing different localities, soil texture and irrigation strategies in the Lower Olifants River region during the 2007/08 season.

Plot no[1]	Locality	Soil texture	Irrigation strategy	(Ψ_s) (MPa) 9 January	31 January	18 February
P1	Kapel	Sand	Deficit irrigation	-1.78 a[2]	-1.38 bc	[3]
P2			Normal	-1.28 c	-1.02 f	[3]
P3		Sandy loam	Deficit irrigation	-1.44 b	-1.21 d	[3]
P4			Normal	-1.13 d	-1.17 de	[3]
P5	Vredendal	Sandy loam	Deficit irrigation	-1.00 ef	-0.98 fg	-0.73 e
P6			Normal	-0.94 f	-0.86 g	-0.76 e
P7		Sand	Deficit irrigation	-1.50 b	-1.51 ab	-1.41 a
P8			Normal	-0.98 ef	-1.20 d	-1.15 c
P9	Lutzville	Sand	Deficit irrigation	-1.50 f	-1.55 a	-0.71 e
P10			Normal	-1.08 b	-1.27 cd	-0.62 f
P11		Loamy sand	Deficit irrigation	-0.73 g	-0.60 h	-0.61 f
P12			Normal	-0.63 h	-0.67 h	-0.51 g
P13	Koekenaap	Sand	Deficit irrigation	-1.08 de	-1.04 ef	-1.31 b
P14			Normal	-0.78 g	-0.86 g	-0.73 e
P15		Sandy loam	Deficit irrigation	-1.18 cd	-1.03 ef	-1.24 b
P16			Normal	-0.96 f	-0.93 fg	-0.93 d

[1] Refer to Table 3.1 for description of the plots.

[2] Values designated by the same letter within a column do not differ significantly ($p \leq 0.05$).

[3] Plots were already harvested when (Ψ_s) readings were carried out.

Table 3.22 The effect of distance from the Atlantic Ocean and irrigation strategy on mean leaf water potential (Ψ_L) and mean stem water potential (Ψ_s) during ripening in Cabernet Sauvignon grapevines determined at four localities in the Lower Olifants River region during the 2006/07 season.

Locality	Distance from Atlantic Ocean (km)	Mean (Ψ_L) (MPa)		Mean (Ψ_s) (MPa)	
		Normal irrigation	Deficit irrigation	Normal irrigation	Deficit irrigation
Kapel	33.4	-1.66	-1.69	-1.07	-1.22
Vredendal	31.3	-1.63	-1.73	-0.98	-1.23
Lutzville	25.5	-1.35	-1.58	-0.77	-1.14
Koekenaap	12.4	-1.26	-1.51	-0.75	-1.15

Table 3.23 The effect of distance from the Atlantic Ocean and irrigation strategy on mean leaf water potential (Ψ_L) and mean stem water potential (Ψ_S) during ripening in Cabernet Sauvignon grapevines determined at four localities in the Lower Olifants River region during the 2007/08 season.

Locality	Distance from Atlantic Ocean (km)	Mean (Ψ_L) (MPa)		Mean (Ψ_S) (MPa)	
		Normal irrigation	Deficit irrigation	Normal irrigation	Deficit irrigation
Kapel	33.4	-1.68	-1.73	-1.15	-1.45
Vredendal	31.3	-1.55	-1.64	-0.98	-1.19
Lutzville	25.5	-1.23	-1.41	-0.80	-0.95
Koekenaap	12.4	-1.3	-1.5	-0.88	-1.15
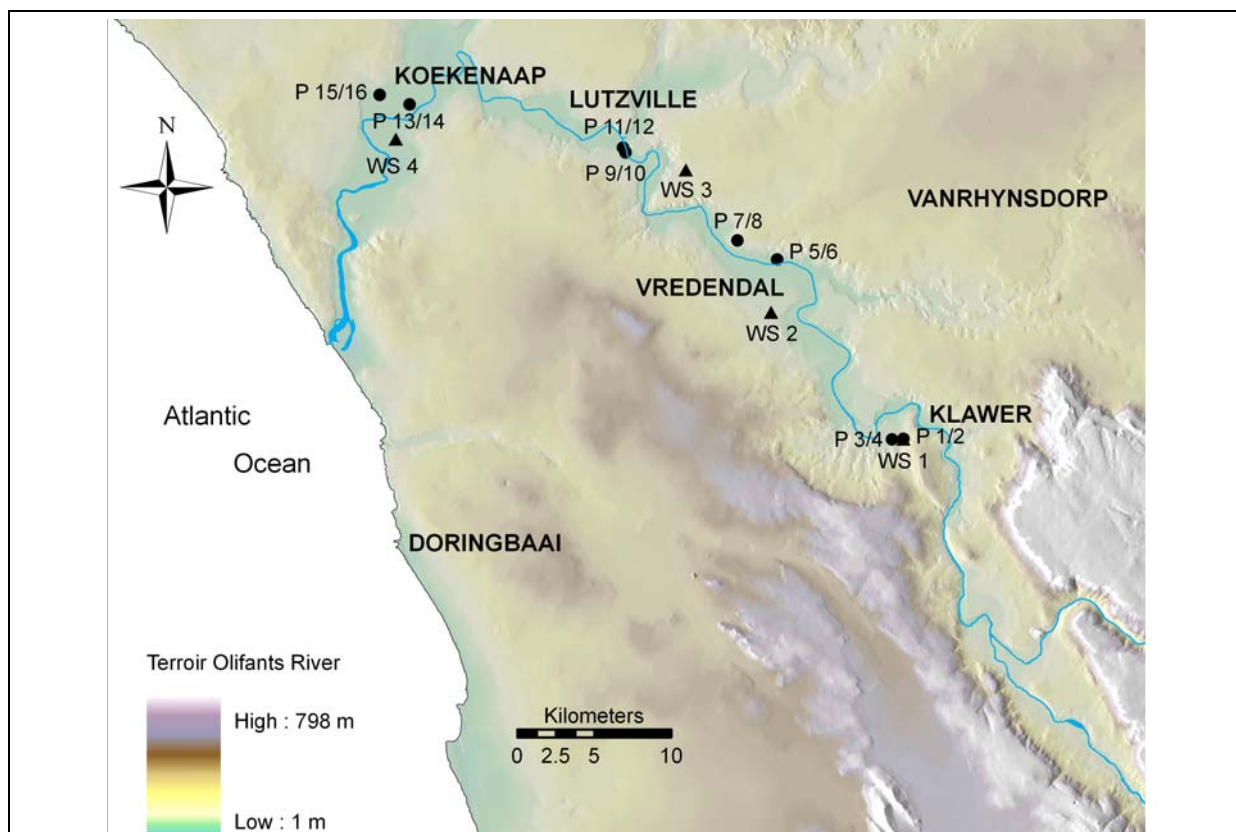
Figure 3.1 The localities of the 16 experiment plots (P1 to P16) and weather stations (WS1 to WS4) at different distances from the Atlantic Ocean in the study area.
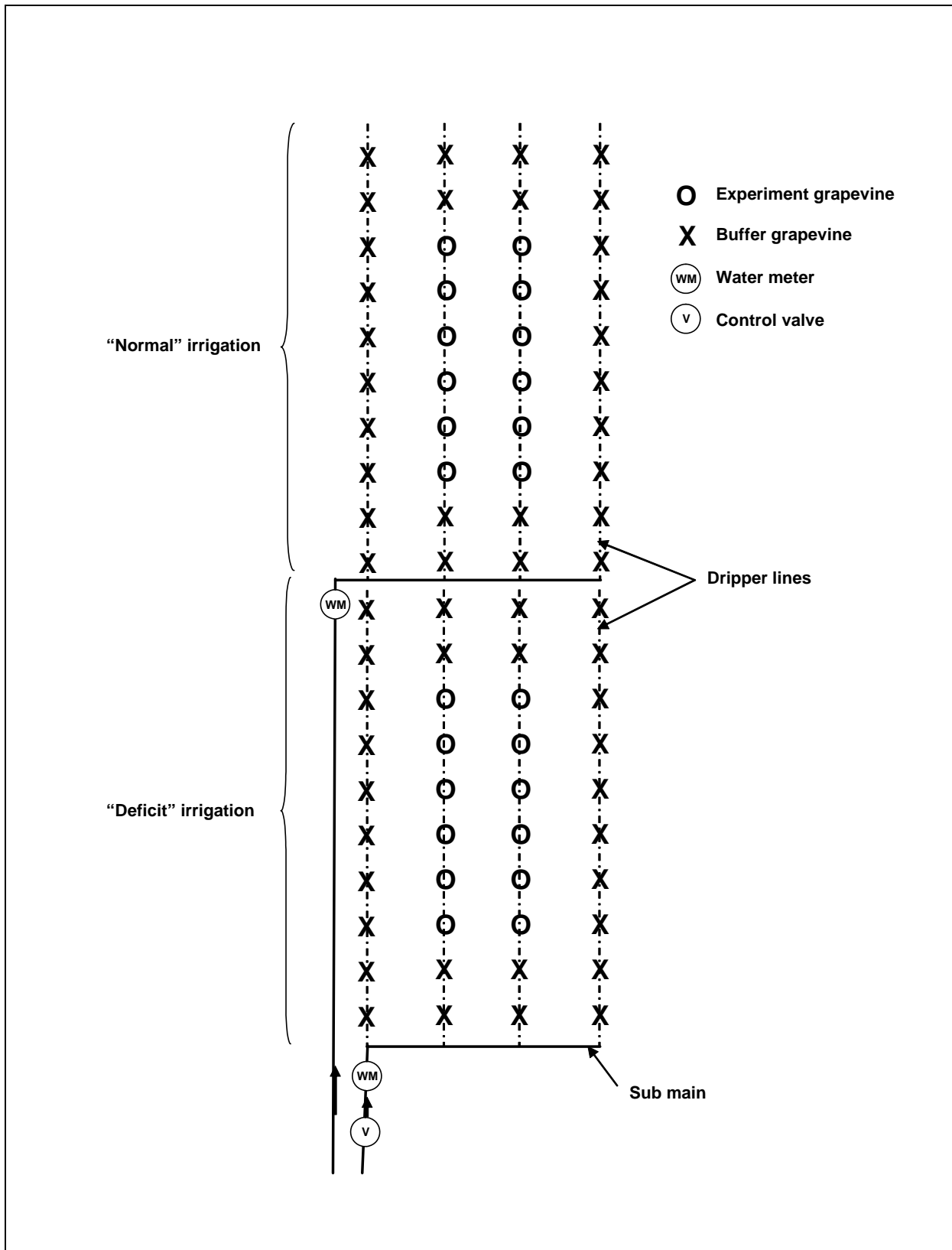
Figure 3.2 Schematic diagram of the experiment plot layout in Cabernet Sauvignon vineyards in the Lower Olifants River region where soil and grapevine water status were monitored during the 2006/07 and 2007/08 seasons.
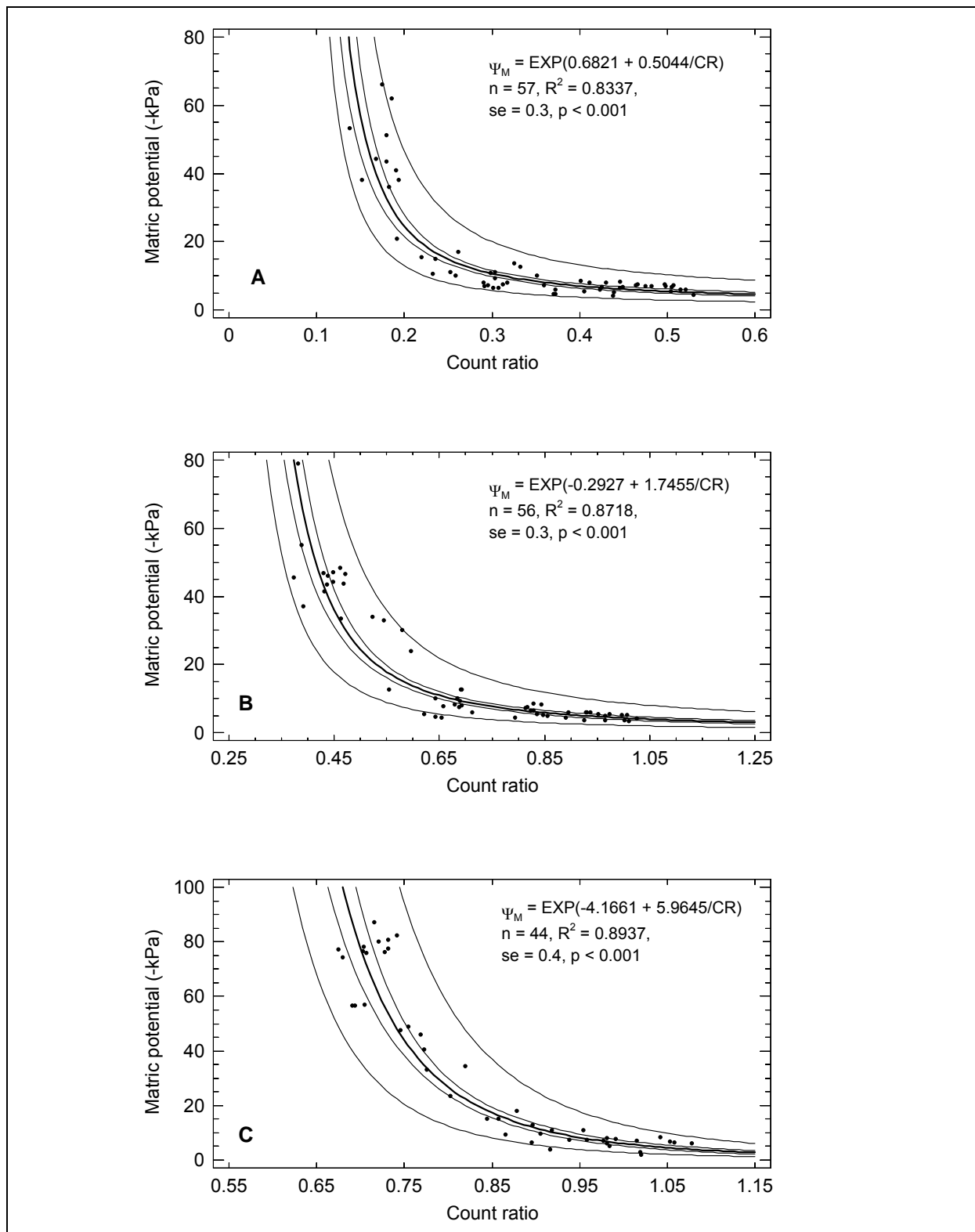
Figure 3.3 Relationship between the soil water matric potential and neutron probe count ratio at (A) 150 mm, (B) 300 mm and (C) 600 mm depth in a sandy soil at Kapel (P1 & P2) in the Lower Olifants River region.

$\Psi_M = EXP(13.965 - 12.156*CR^{0.5})$
n = 23, R^2 = 0.9131,
se = 0.3, p < 0.001

$\Psi_M = EXP(21.040 - 18.394*CR^{0.5})$
n = 42, R^2 = 0.9429,
se = 0.2, p < 0.001

$\Psi_M = EXP(22.087 - 18.559*CR^{0.5})$
n = 30, R^2 = 0.9641,
se = 0.2, p < 0.001
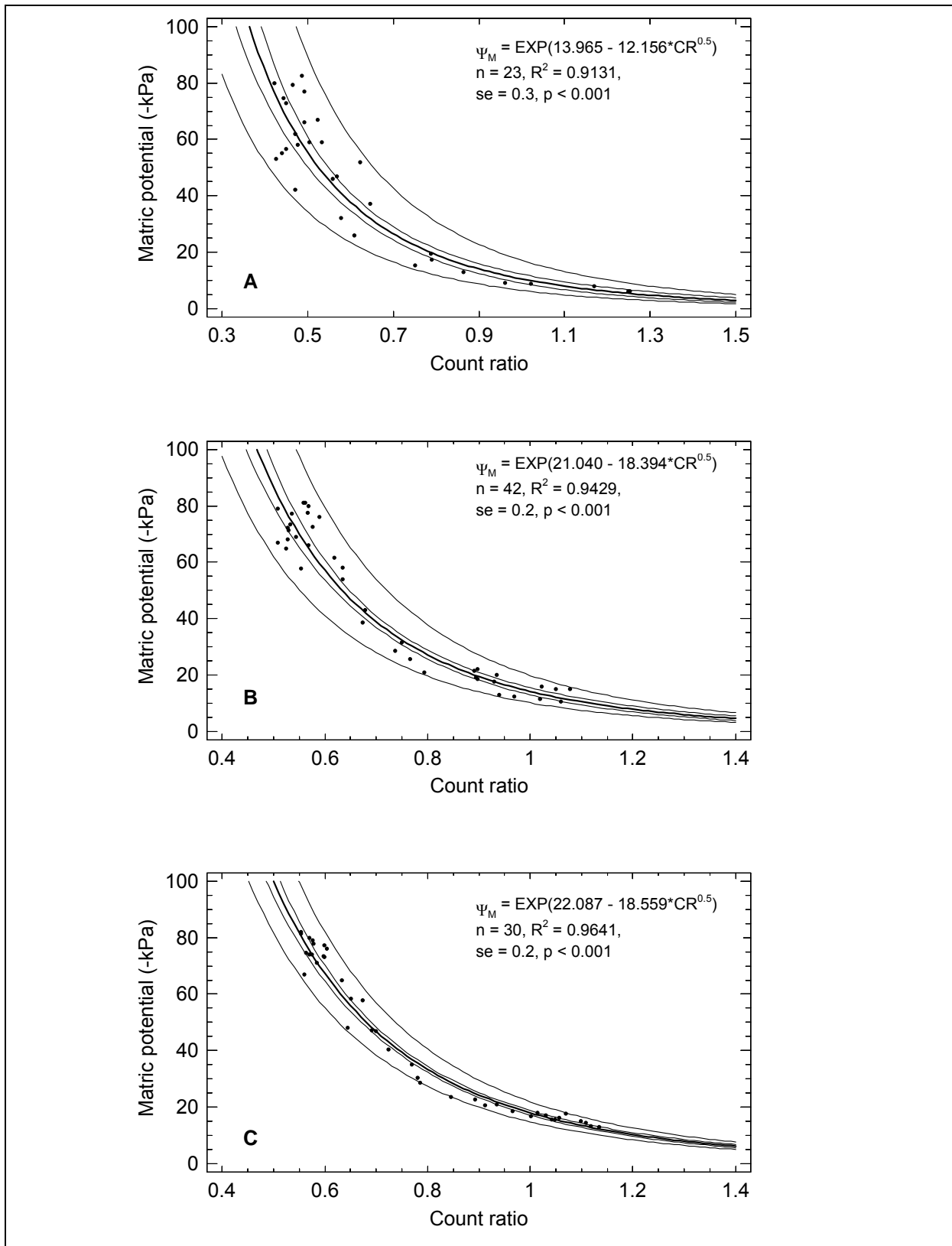
Figure 3.4 Relationship between the soil water matric potential and neutron probe count ratio at (A) 300 mm, (B) 600 mm and (C) 900 mm depth in a sandy loam soil at Kapel (P3 & P4) in the Lower Olifants River region.
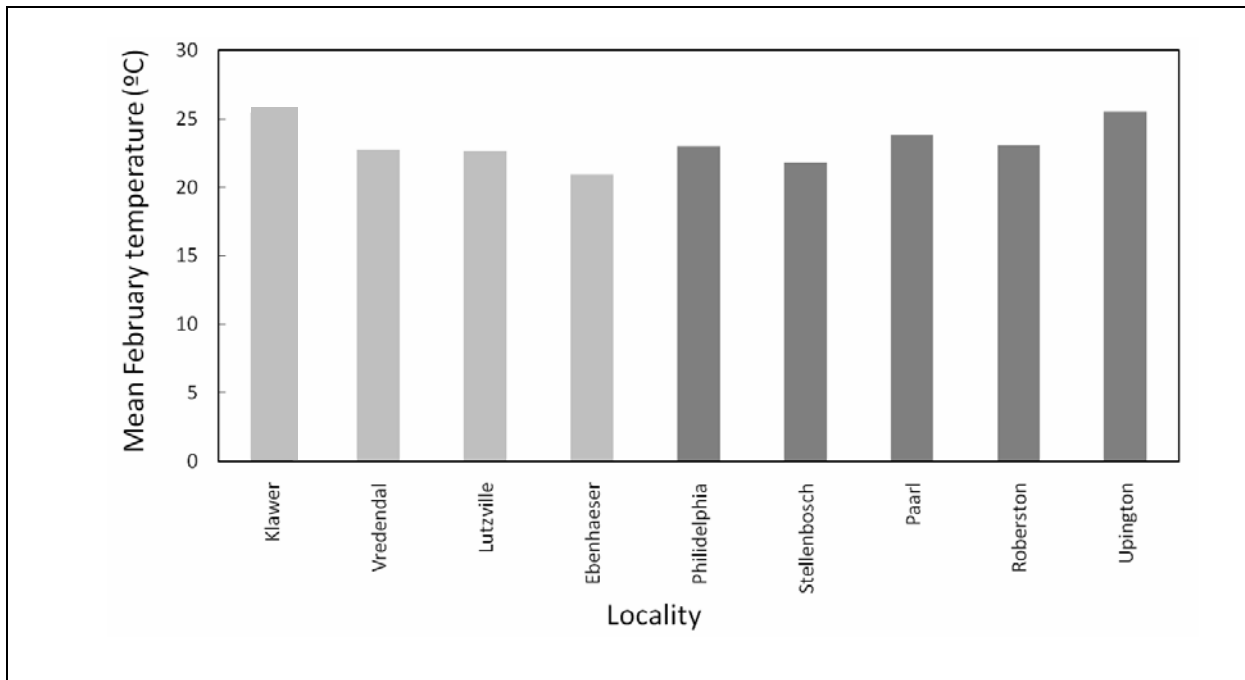
Figure 3.5   Mean February temperature (MFT) at different localities in the wine producing regions of the Western Cape.
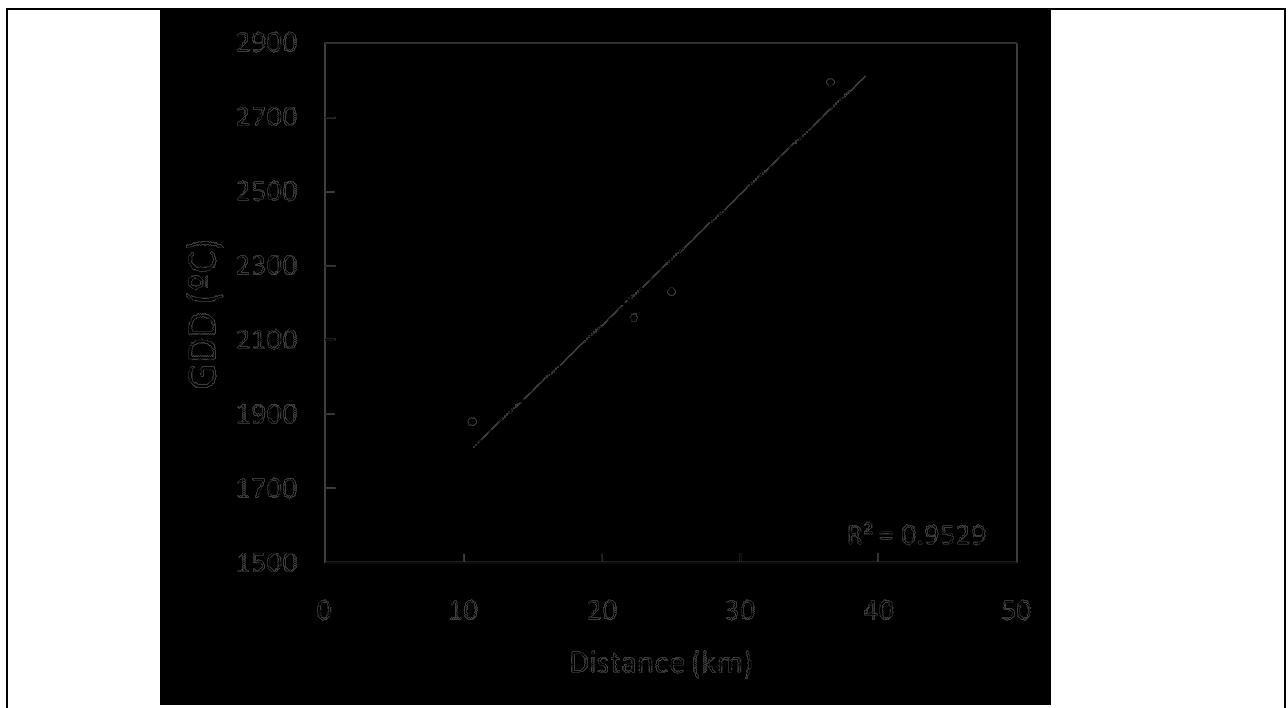
Figure 3.6   Effect of distance to the Atlantic Ocean on viticultural potential in the Lower Olifants River region according to the Winkler index (GDD).
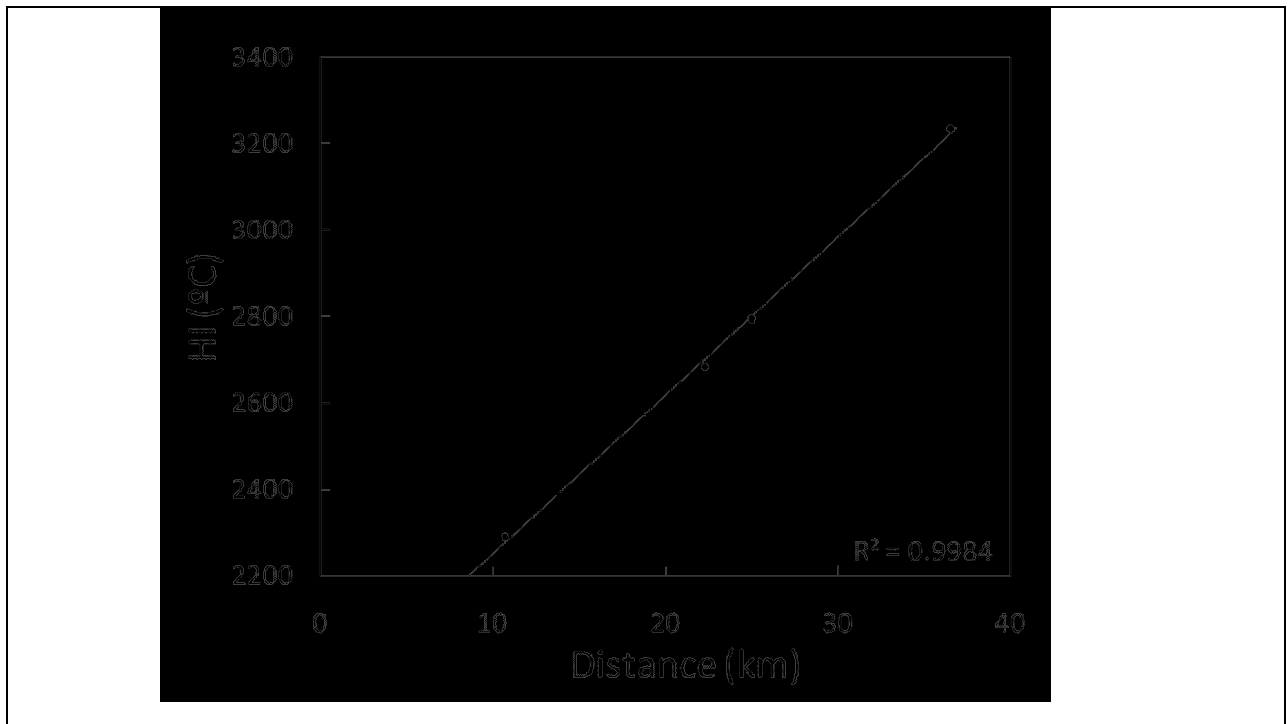
Figure 3.7 Effect of distance to the Atlantic Ocean on viticultural potential in the Lower Olifants River region according to the Heliothermal Index (HI).
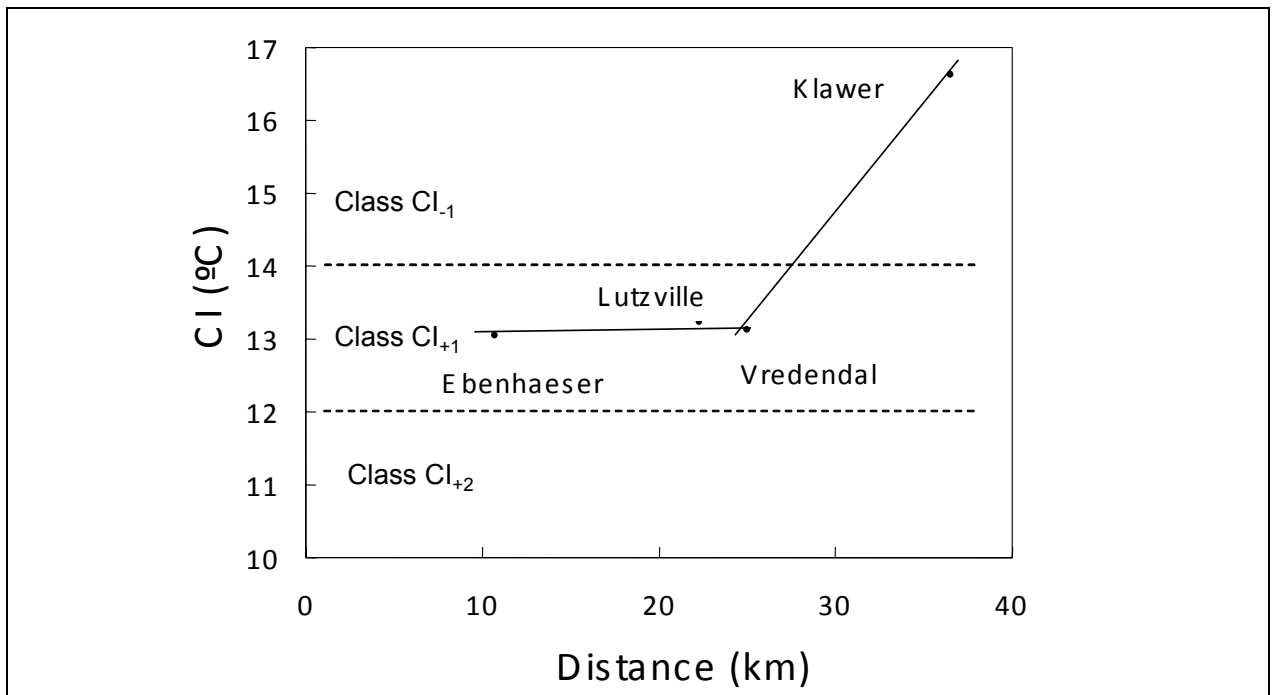
Figure 3.8 Effect of distance to the Atlantic Ocean on viticultural potential in the Lower Olifants River region according to the Cool Night Index (CI).
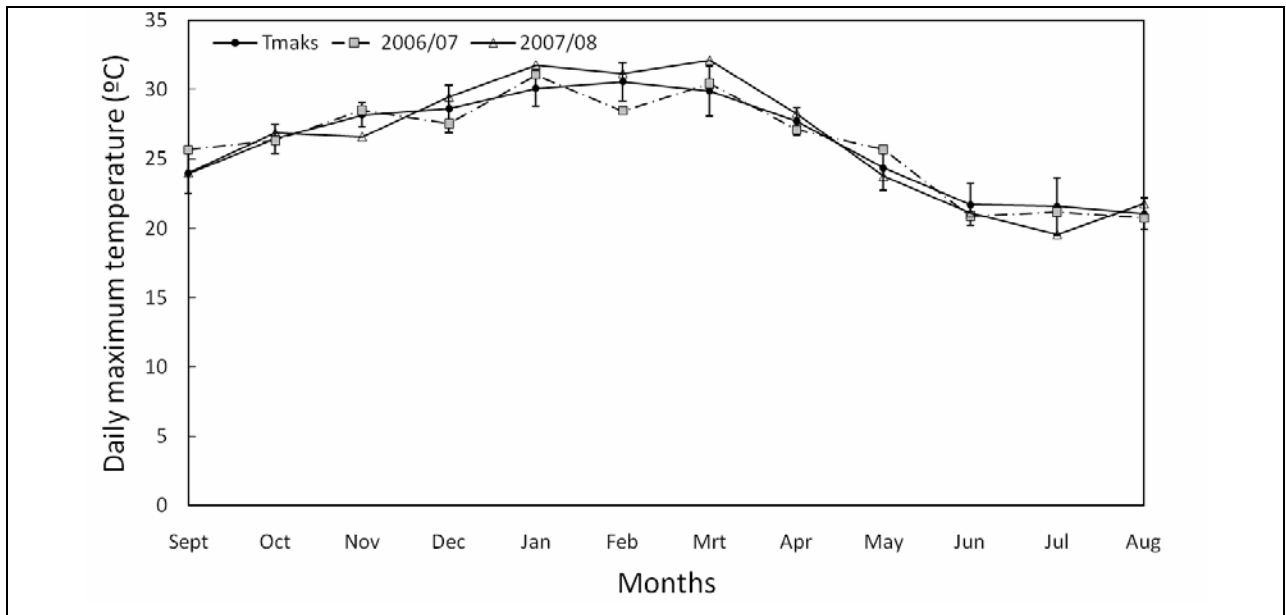
Figure 3.9 **Mean daily maximum temperature during the 2006/07 and 2007/08 seasons compared to the long term mean (Tmaks) measured at four weather stations in the Lower Olifants River region.**
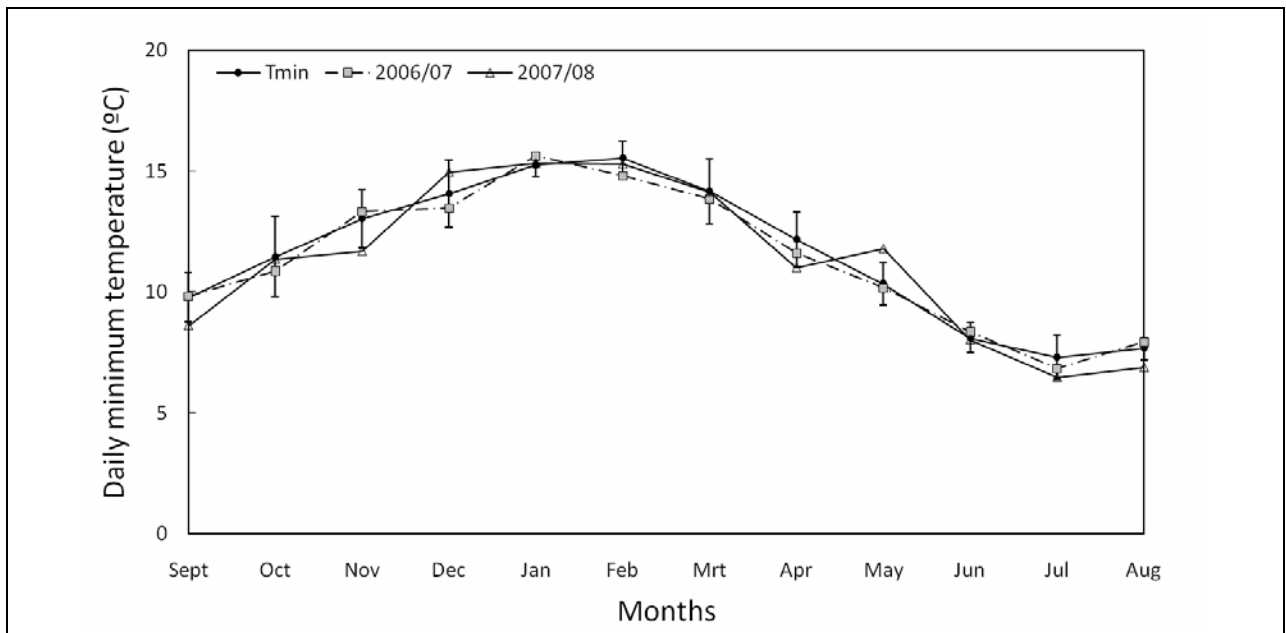
Figure 3.10 **Mean daily minimum temperature during the 2006/07 and 2007/08 seasons compared to the long term mean (Tmin) measured at four weather stations in the Lower Olifants River region.**
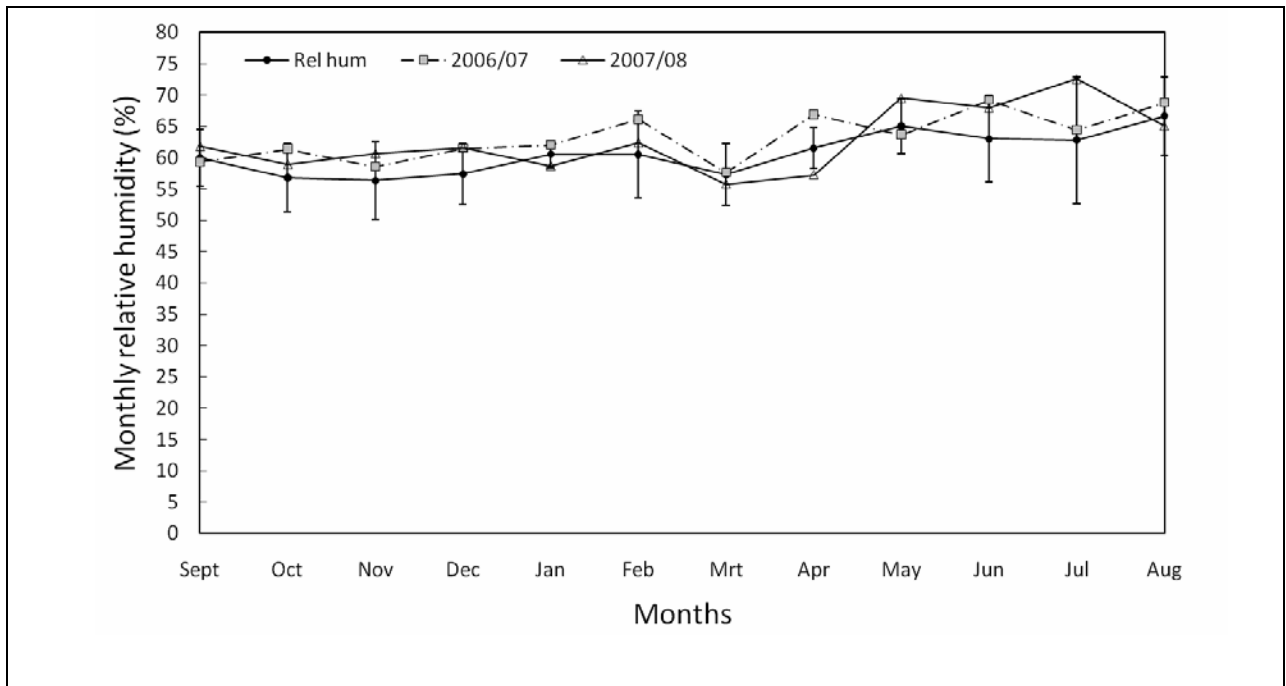
Figure 3.11 Mean monthly relative humidity during the 2006/07 and 2007/08 seasons compared to the long term mean (Rel hum) measured at four weather stations in the Lower Olifants River region.
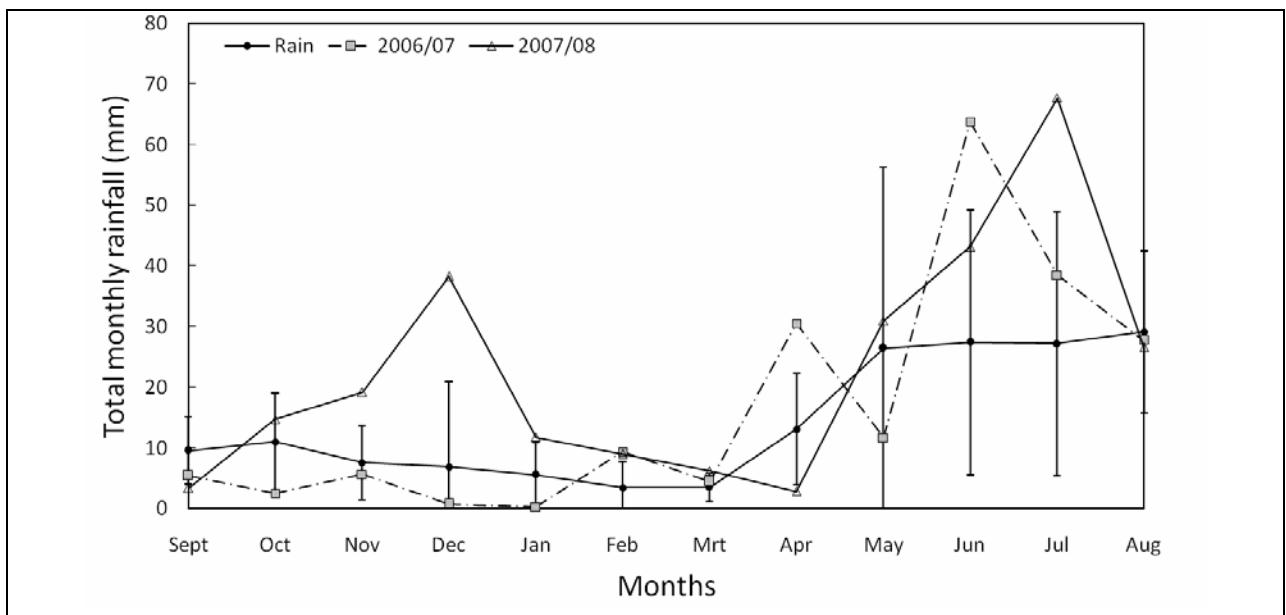
Figure 3.12 Total monthly rainfall during the 2006/07 and 2007/08 seasons compared to the long term mean (Rain) measured at four weather stations in the Lower Olifants River region.
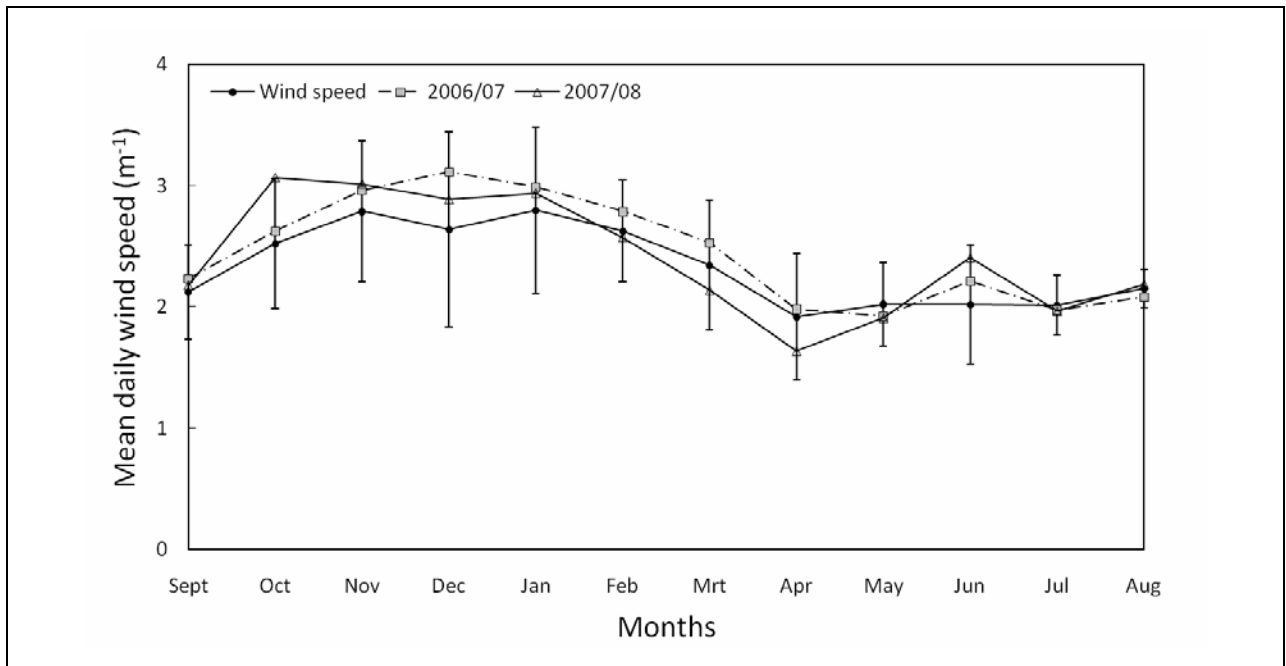
Figure 3.13 Mean daily wind speed during the 2006/07 and 2007/08 seasons compared to the long term mean (Wind speed) measured at four weather stations in the Lower Olifants River region.
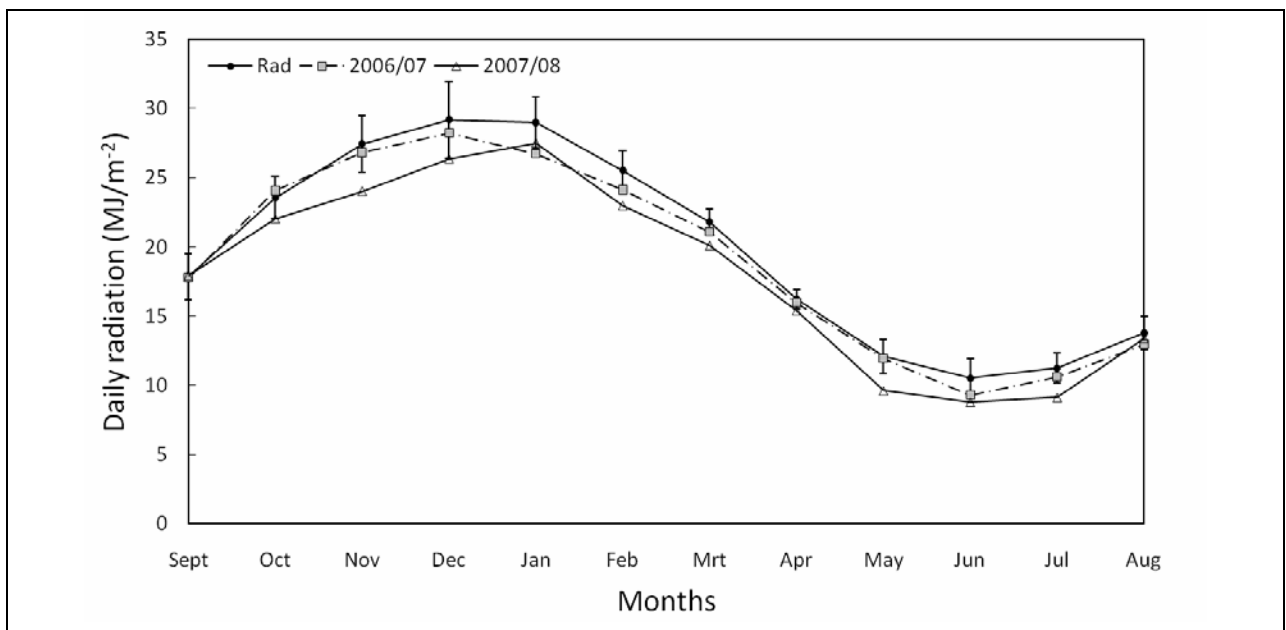
Figure 3.14 Mean daily radiation during the 2006/07 and 2007/08 seasons compared to the long term mean (Rad) measured at four weather stations in the Lower Olifants River region.
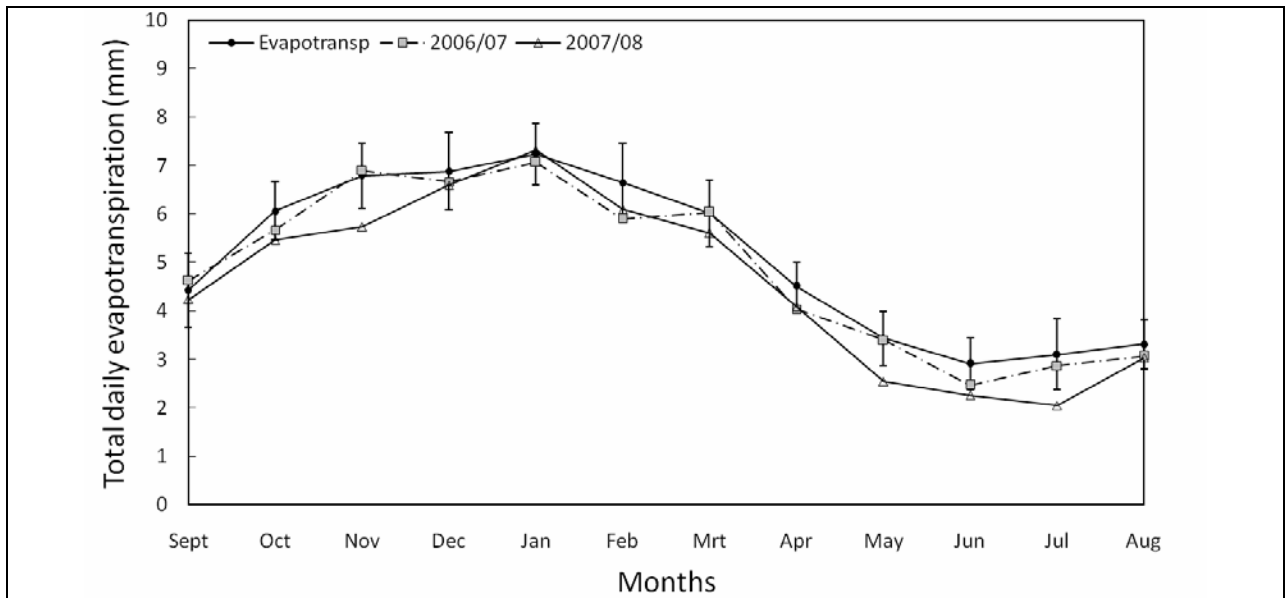
Figure 3.15 Mean daily reference evapotranspiration during the 2006/07 and 2007/08 seasons compared to the long term mean (Evapotransp) measured at four weather stations in the Lower Olifants River region.
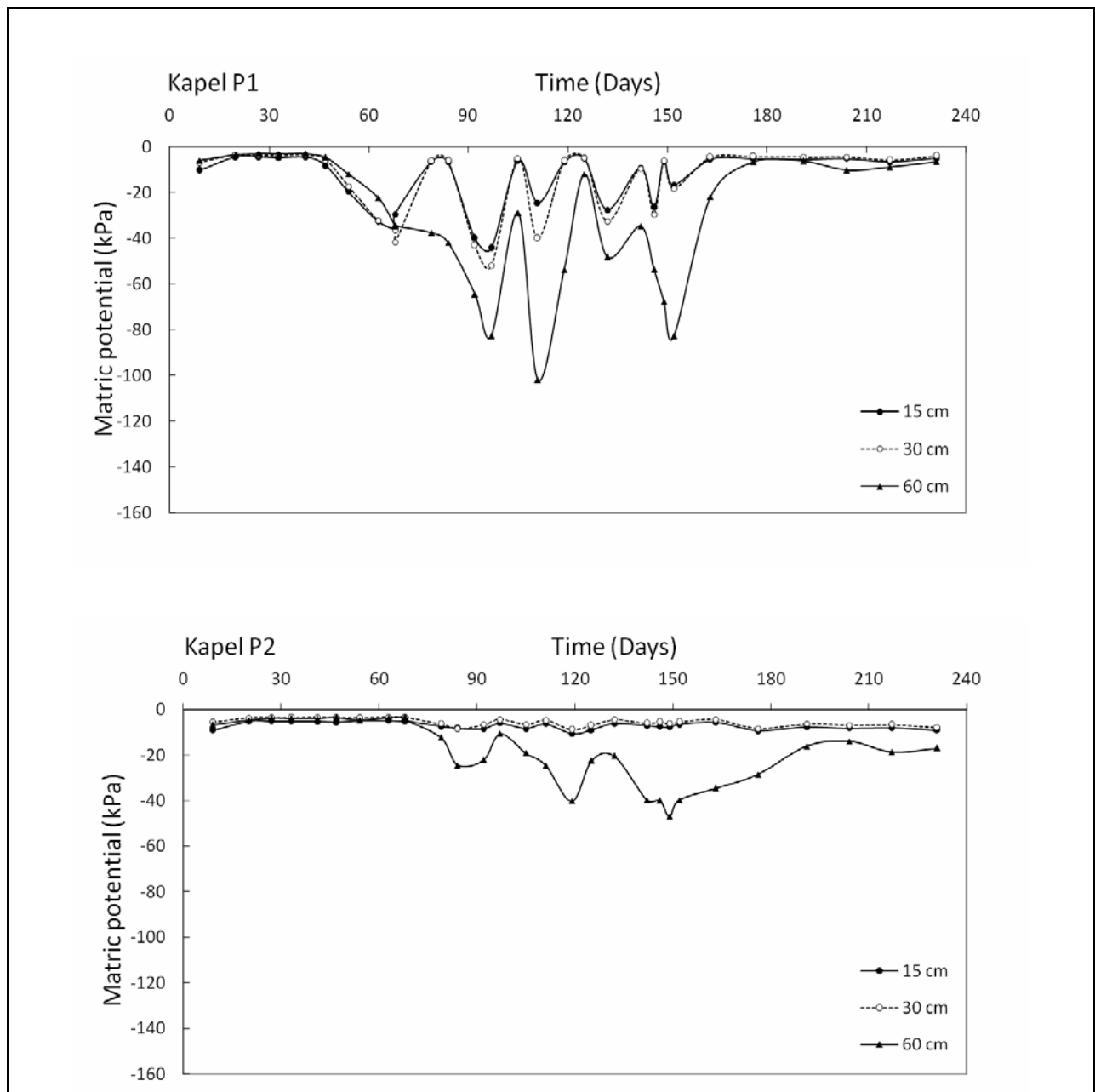
Figure 3.16 Variation in soil water matric potential in a sandy soil where deficit irrigation (Kapel P1) and normal irrigation (Kapel P2) strategies were applied during the 2006/07 season in the Lower Olifants River region.
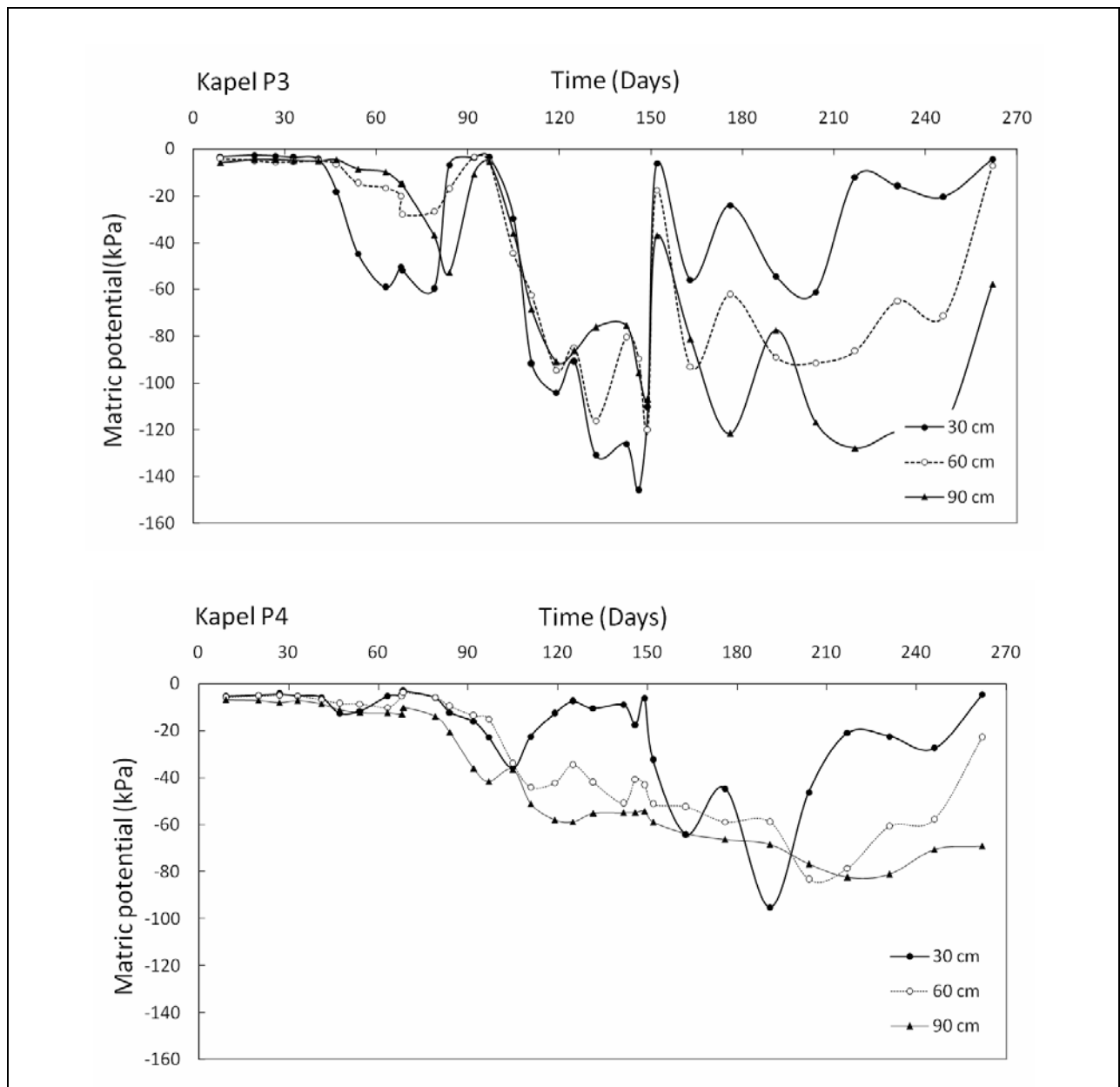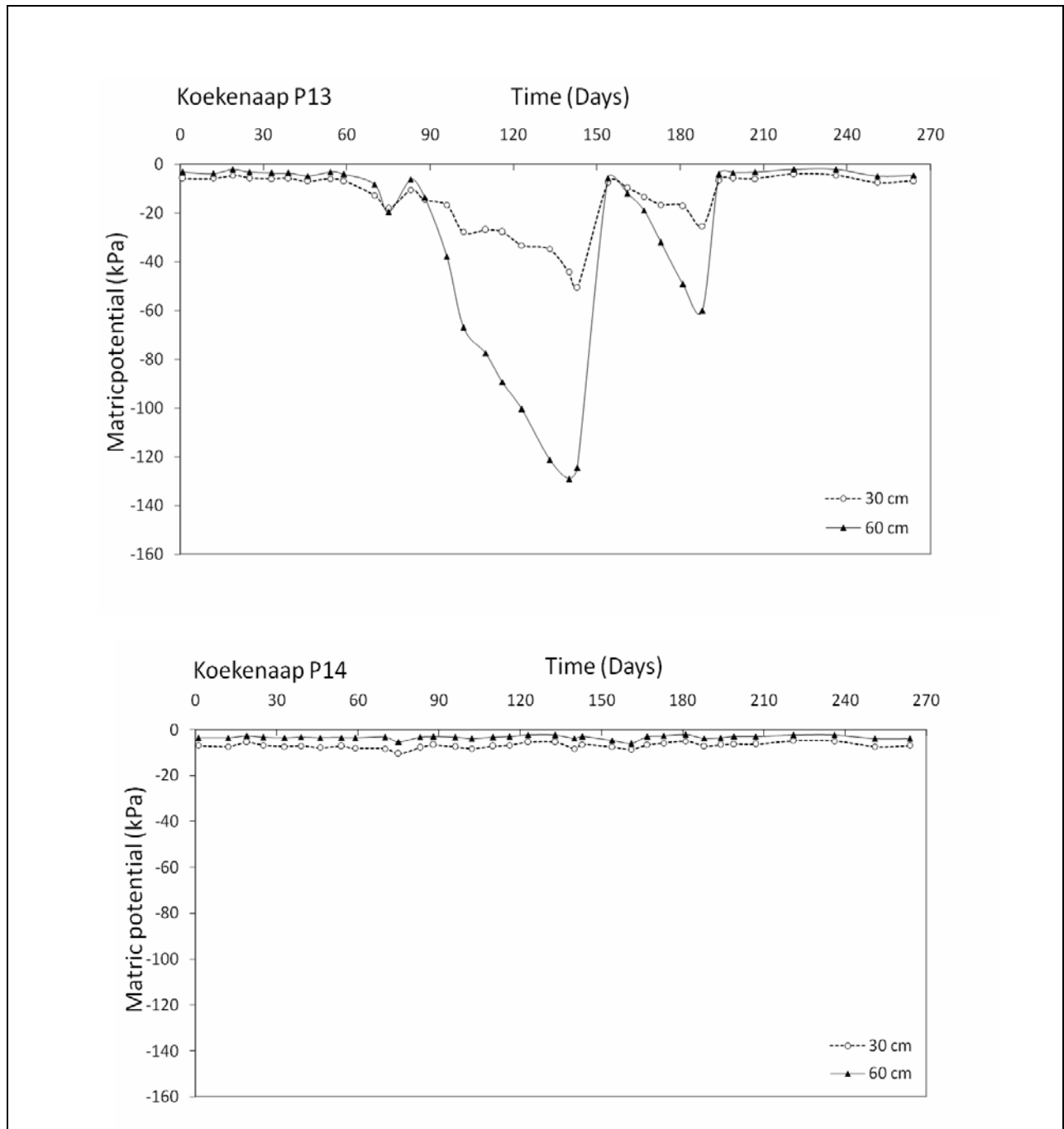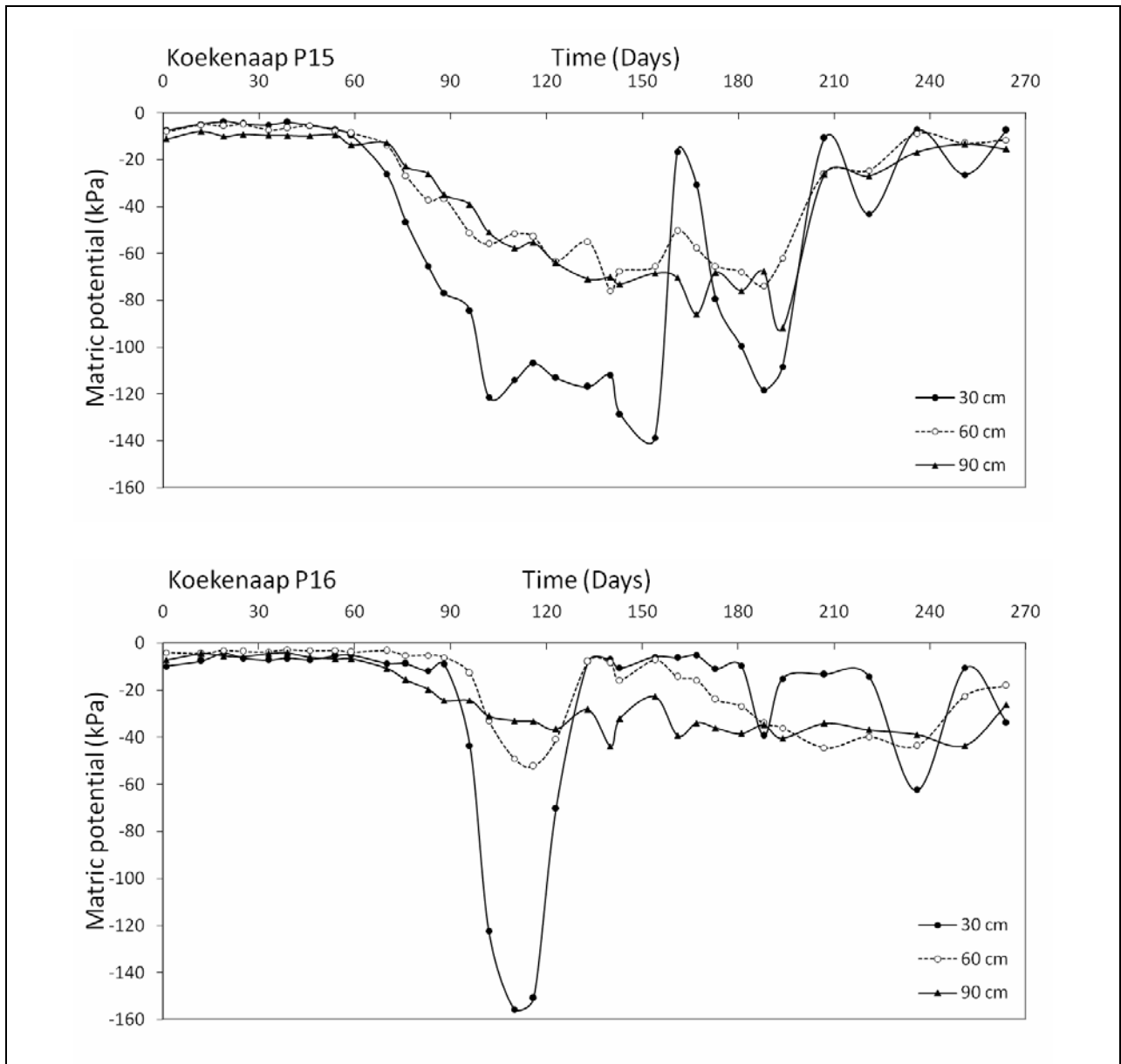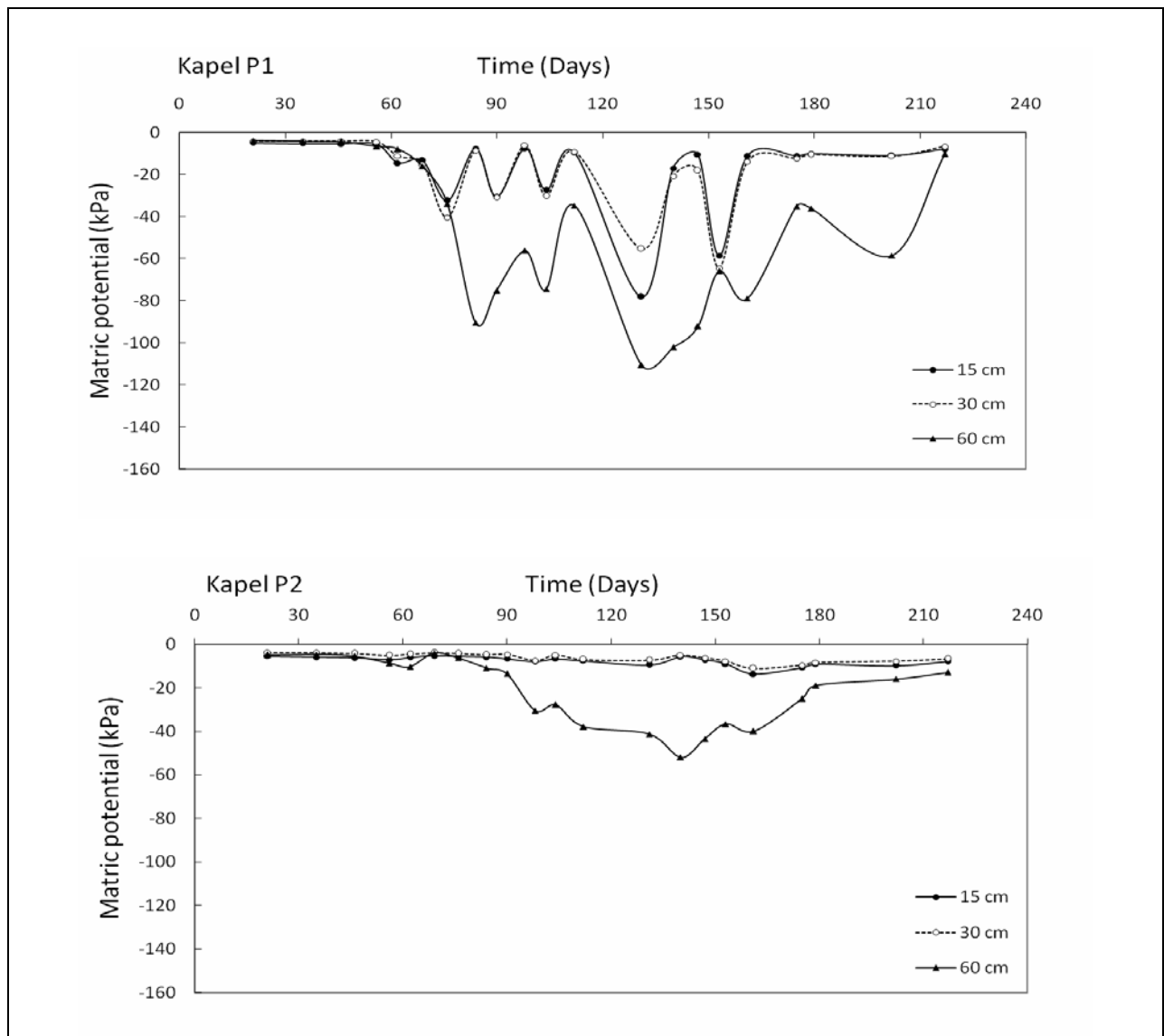
Figure 3.17 Variation in soil water matric potential in a sandy loam soil where deficit irrigation (Kapel P3) and normal irrigation (Kapel P4) strategies were applied during the 2006/07 season in the Lower Olifants River region.
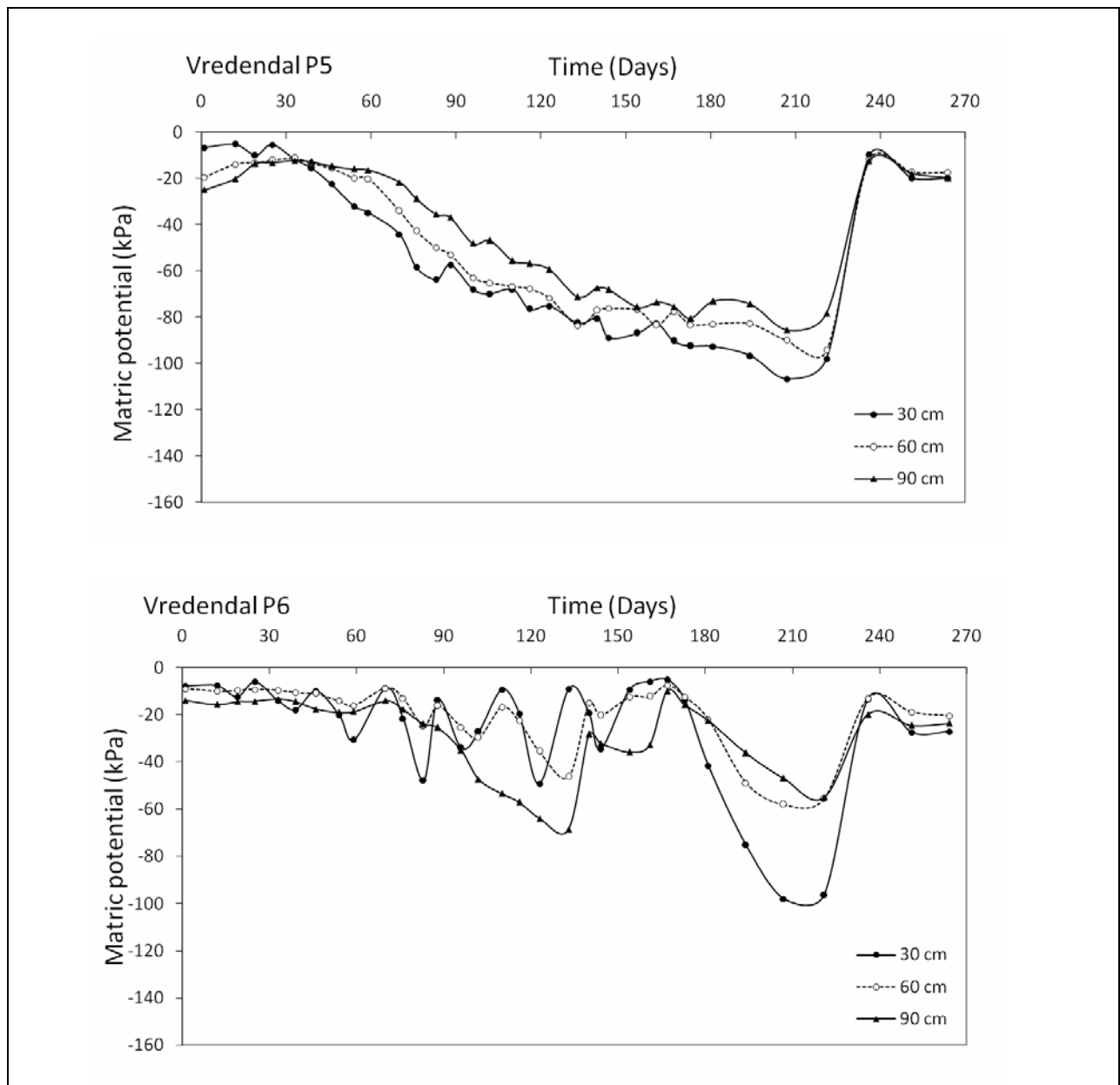
Figure 3.18 Variation in soil water matric potential in a sandy loam soil where deficit irrigation (Vredendal P5) and normal irrigation (Vredendal P5)strategies were applied during the 2006/07 season in the Lower Olifants River region.
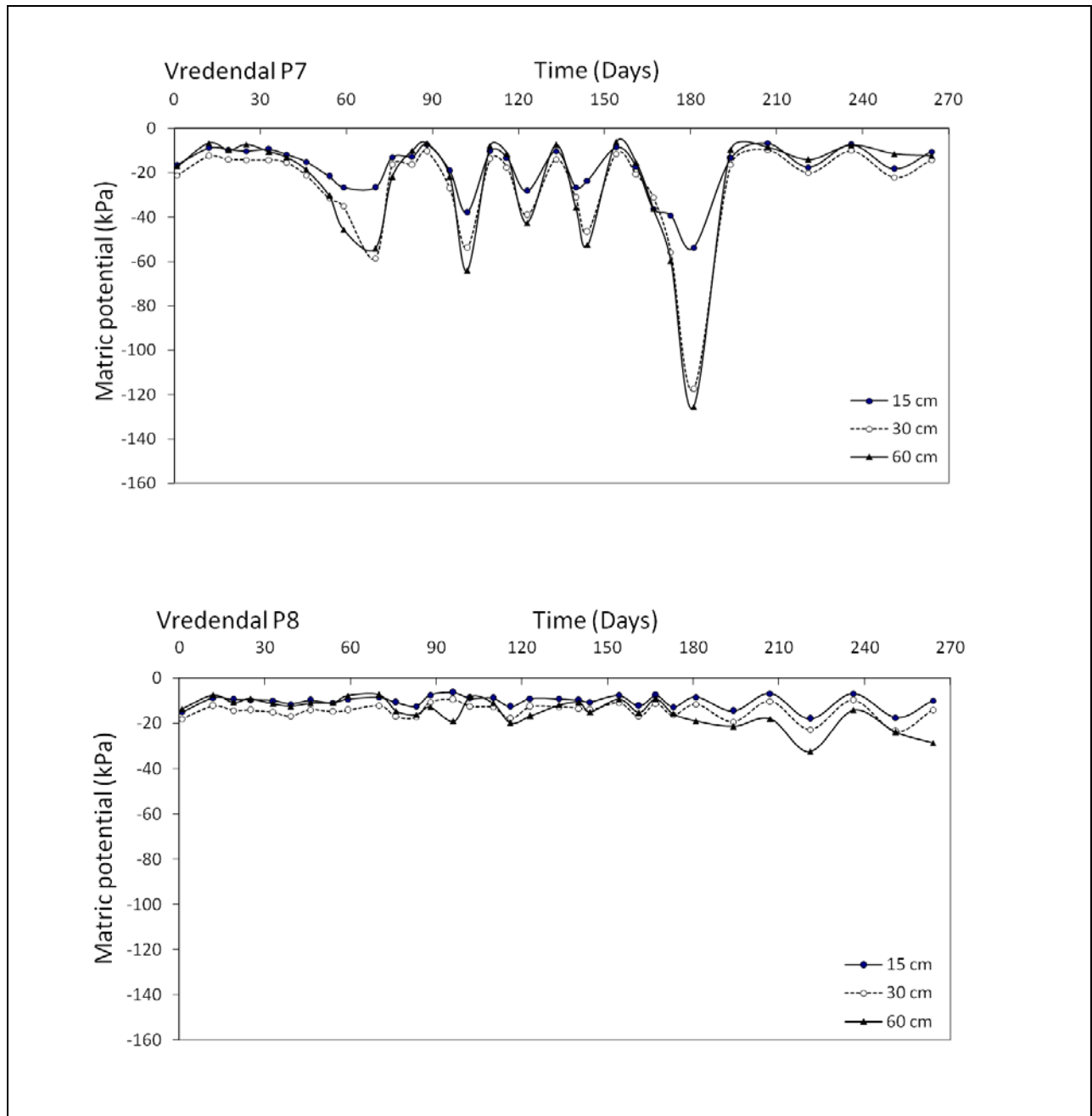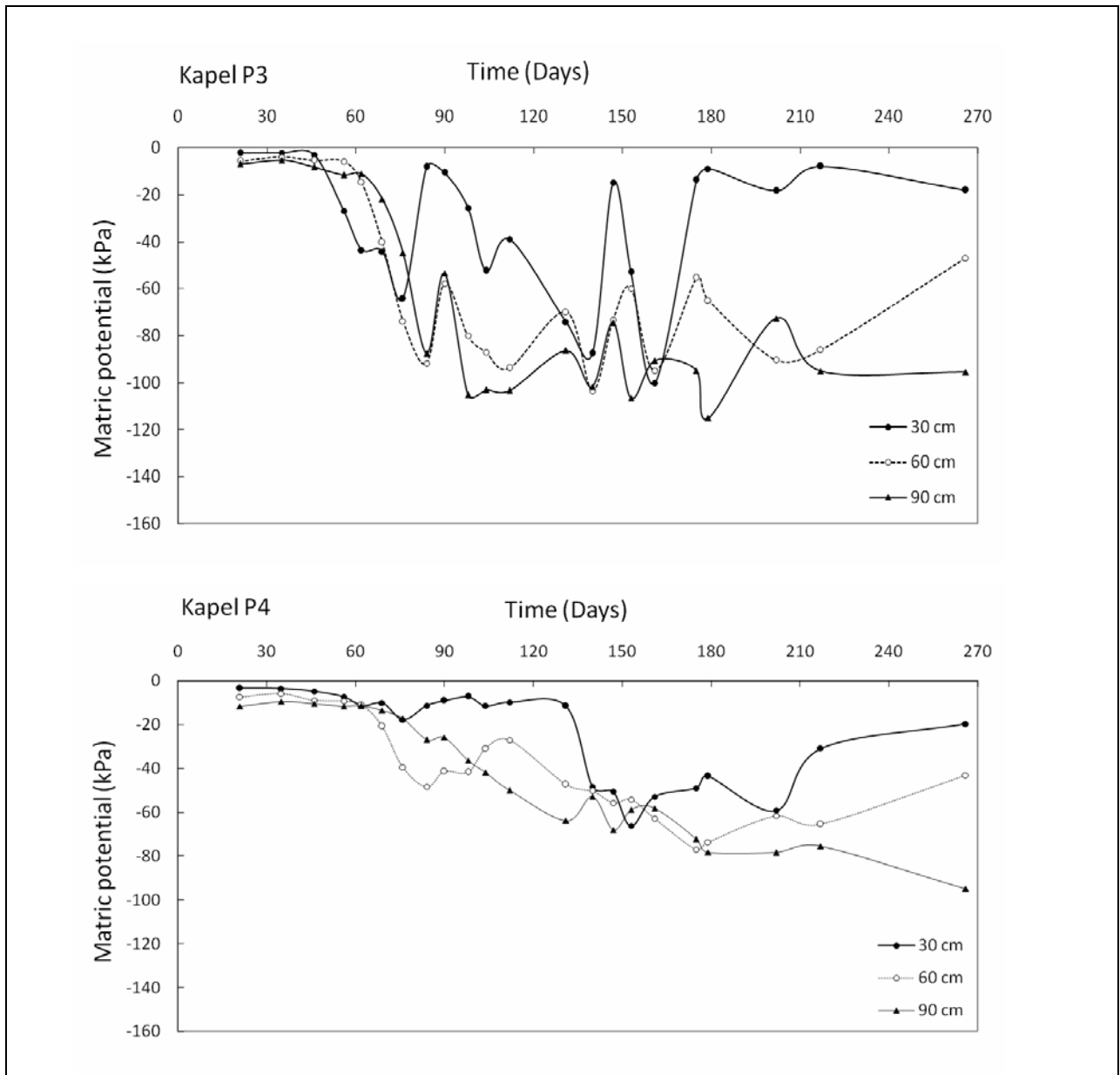
Figure 3.19   Variation in soil water matric potential in a sandy soil where deficit irrigation (Vredendal P7) and normal irrigation (Vredendal P8) strategies were applied during the 2006/07 season in the Lower Olifants River region.
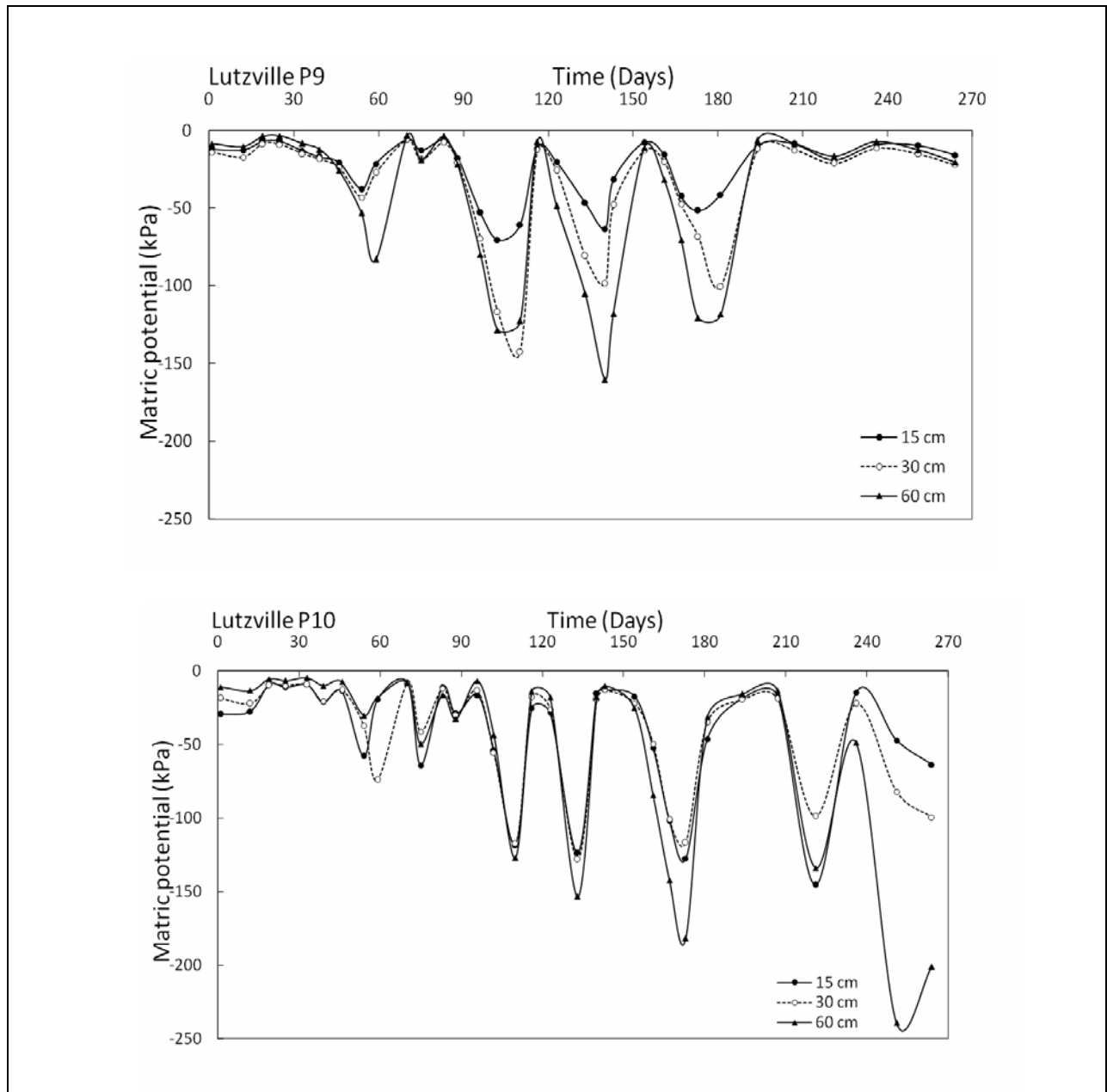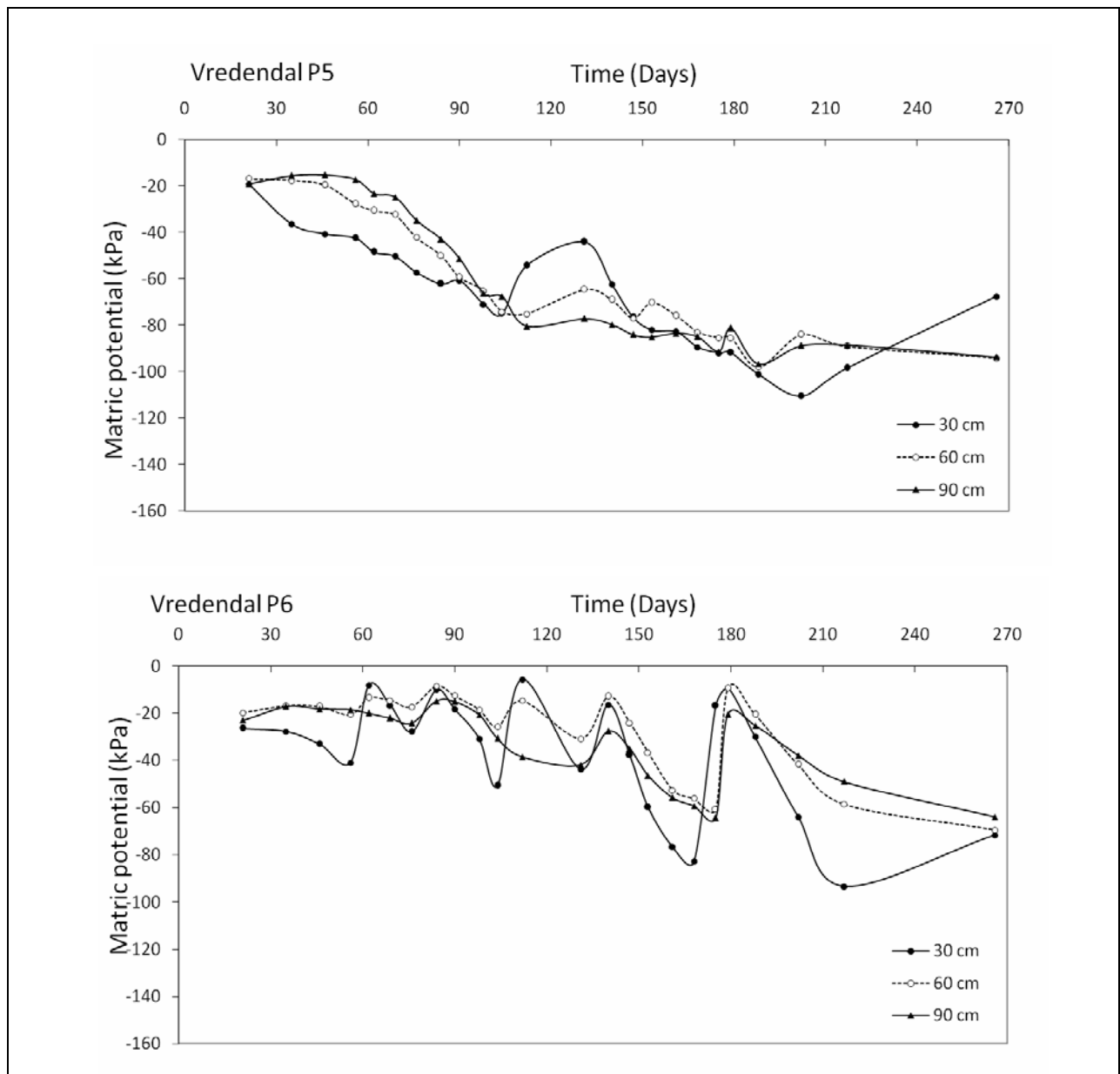
Figure 3.20   Variation in soil water matric potential in a sandy soil where deficit irrigation (Lutzville P9) and normal irrigation (Lutzville P10) strategies were applied during the 2006/07 season in the Lower Olifants River region.
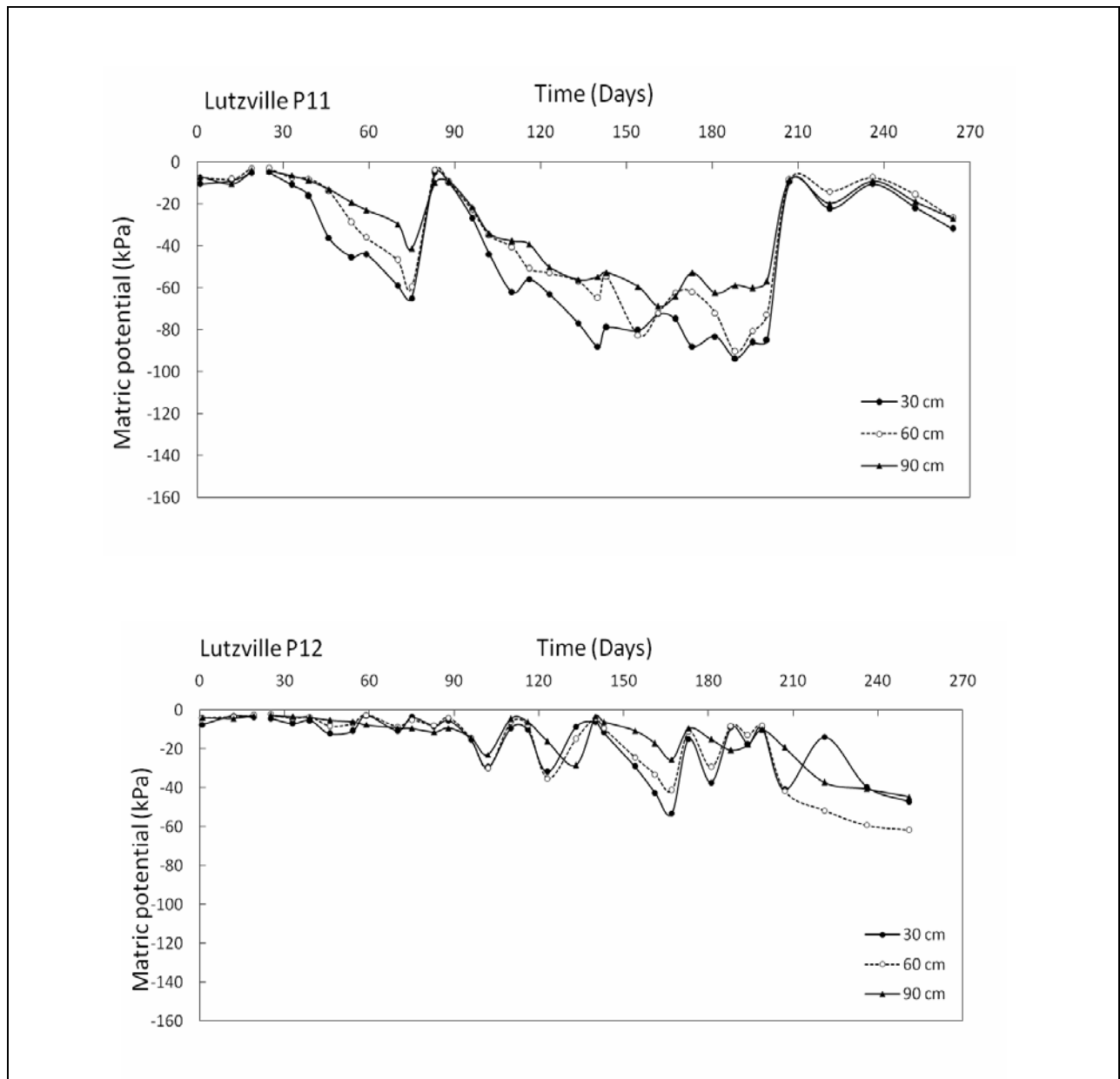
Figure 3.21 Variation in soil water matric potential in a loamy sand soil where deficit irrigation (Lutzville P11) and normal irrigation (Lutzville P12) strategies were applied during the 2006/07 season in the Lower Olifants River region.
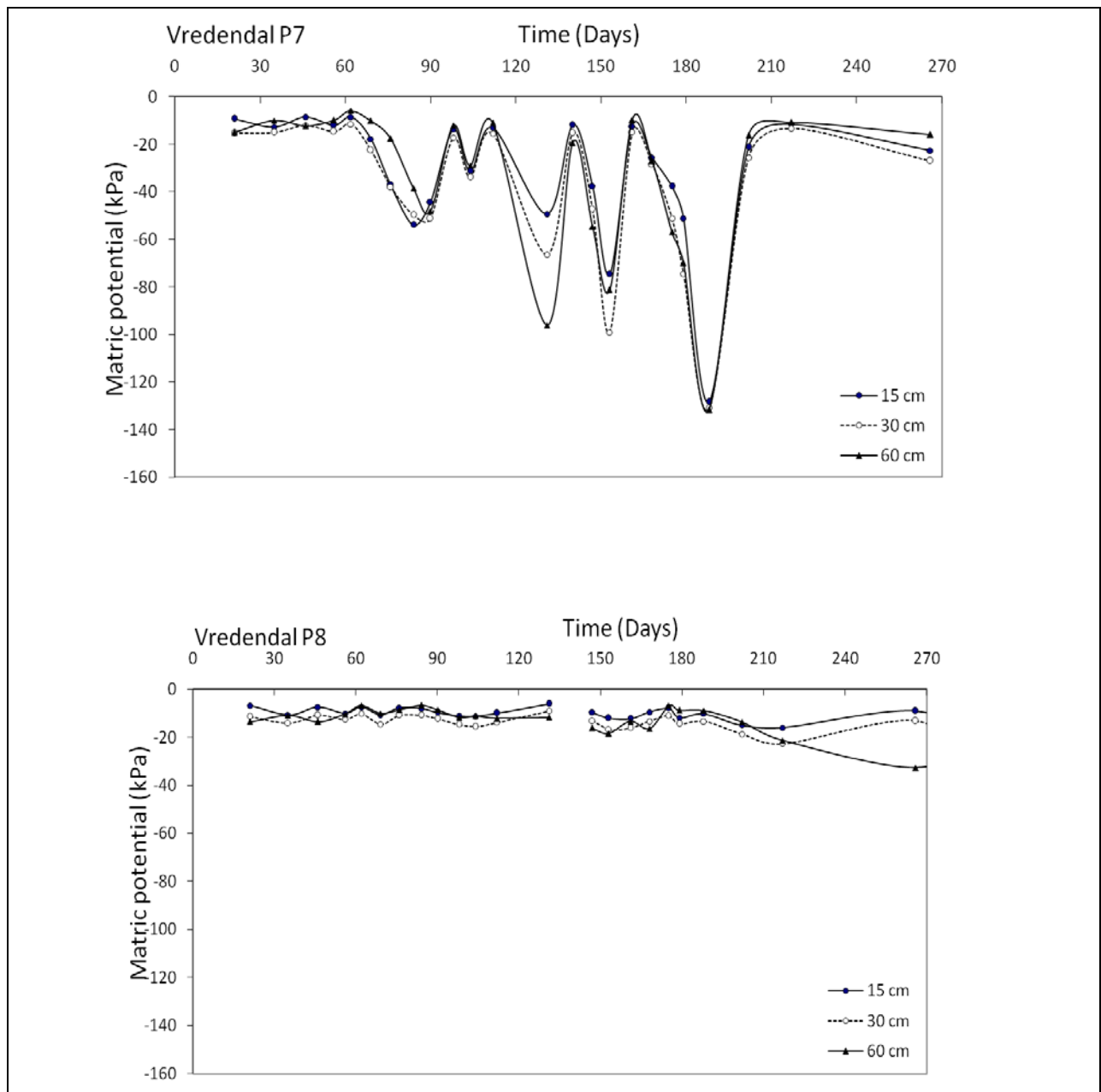
Figure 3.22   Variation in soil water matric potential in a sandy soil where deficit irrigation (Koekenaap P13) and normal irrigation (Koekenaap P14) strategies were applied during the 2006/07 season in the Lower Olifants River region.

Figure 3.23 Variation in soil water matric potential in a sandy loam soil where deficit irrigation (Koekenaap P15) and normal irrigation (Koekenaap P16) strategies were applied during the 2006/07 season in the Lower Olifants River region.

Figure 3.24   Variation in soil water matric potential in a sandy soil where deficit irrigation (Kapel P1) and normal irrigation (Kapel P2) strategies were applied during the 2007/08 season in the Lower Olifants River region.
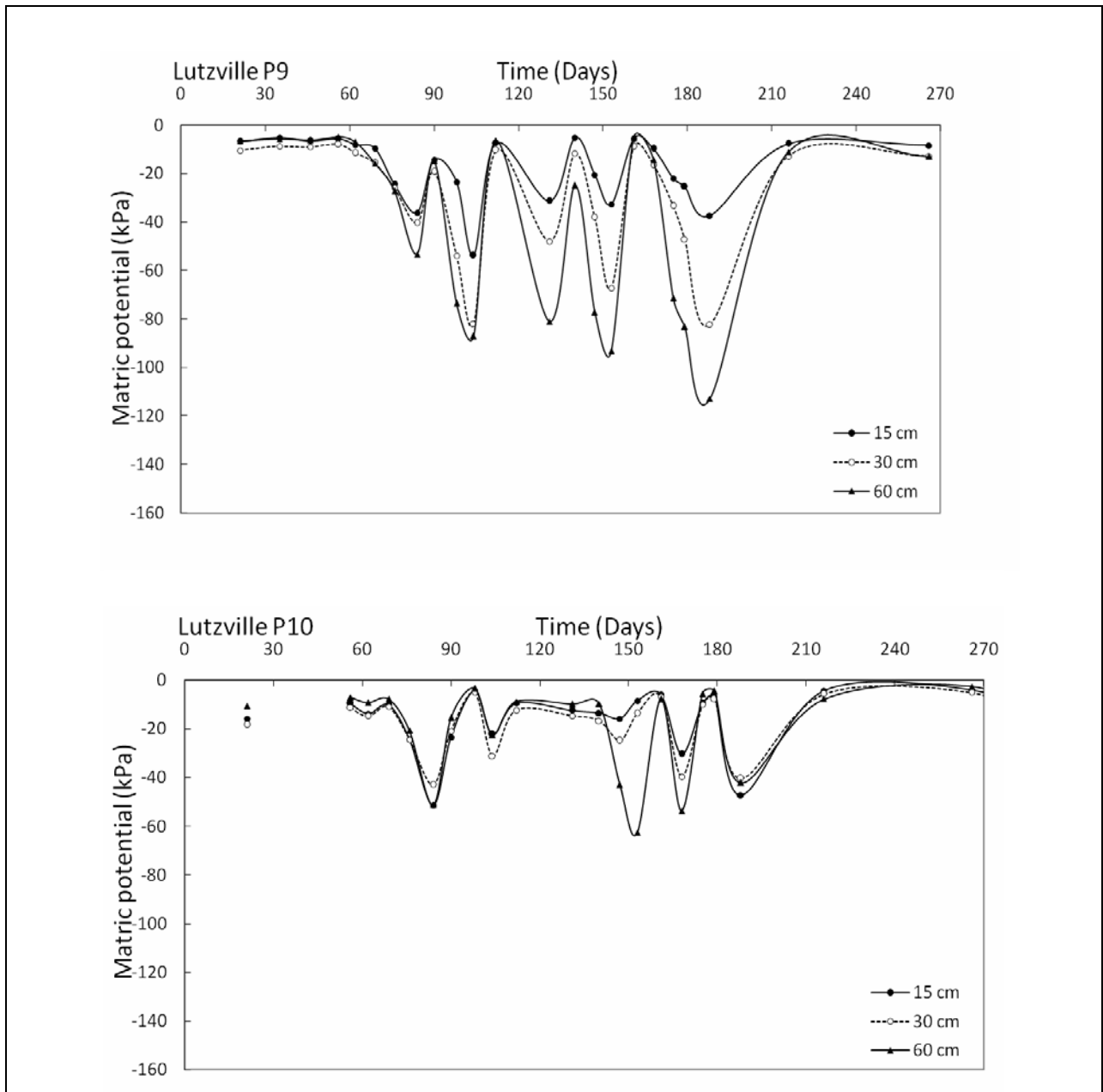
Figure 3.25 Variation in soil water matric potential in a sandy loam soil where deficit irrigation (Kapel P3) and normal irrigation (Kapel P4) strategies were applied during the 2007/08 season in the Lower Olifants River region.
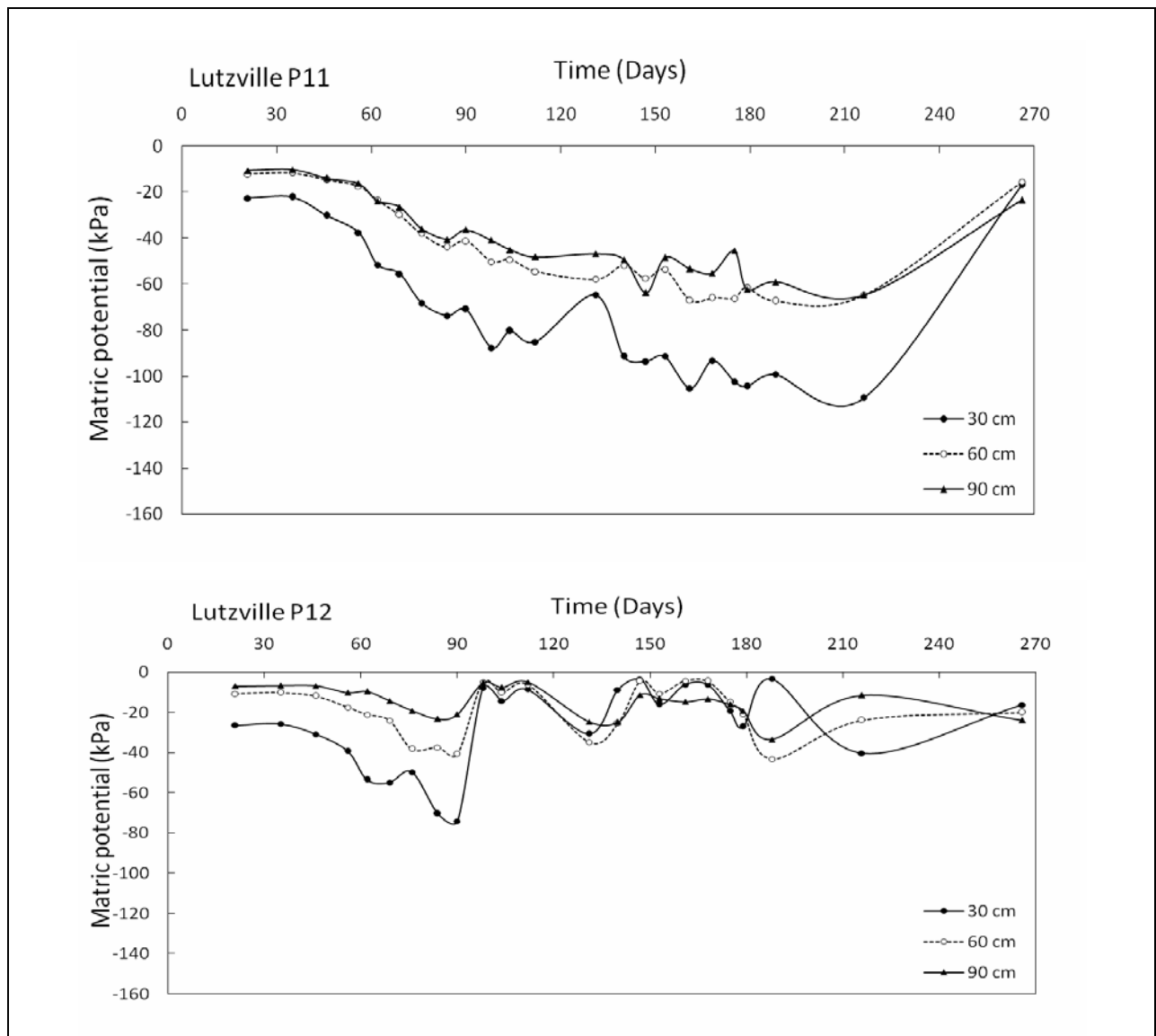
Figure 3. Variation in soil water matric potential in a sandy loam soil where deficit irrigation (Vredendal P5) and normal irrigation (Vredendal P6) strategies were applied during the 2007/08 season in the Lower Olifants River region.
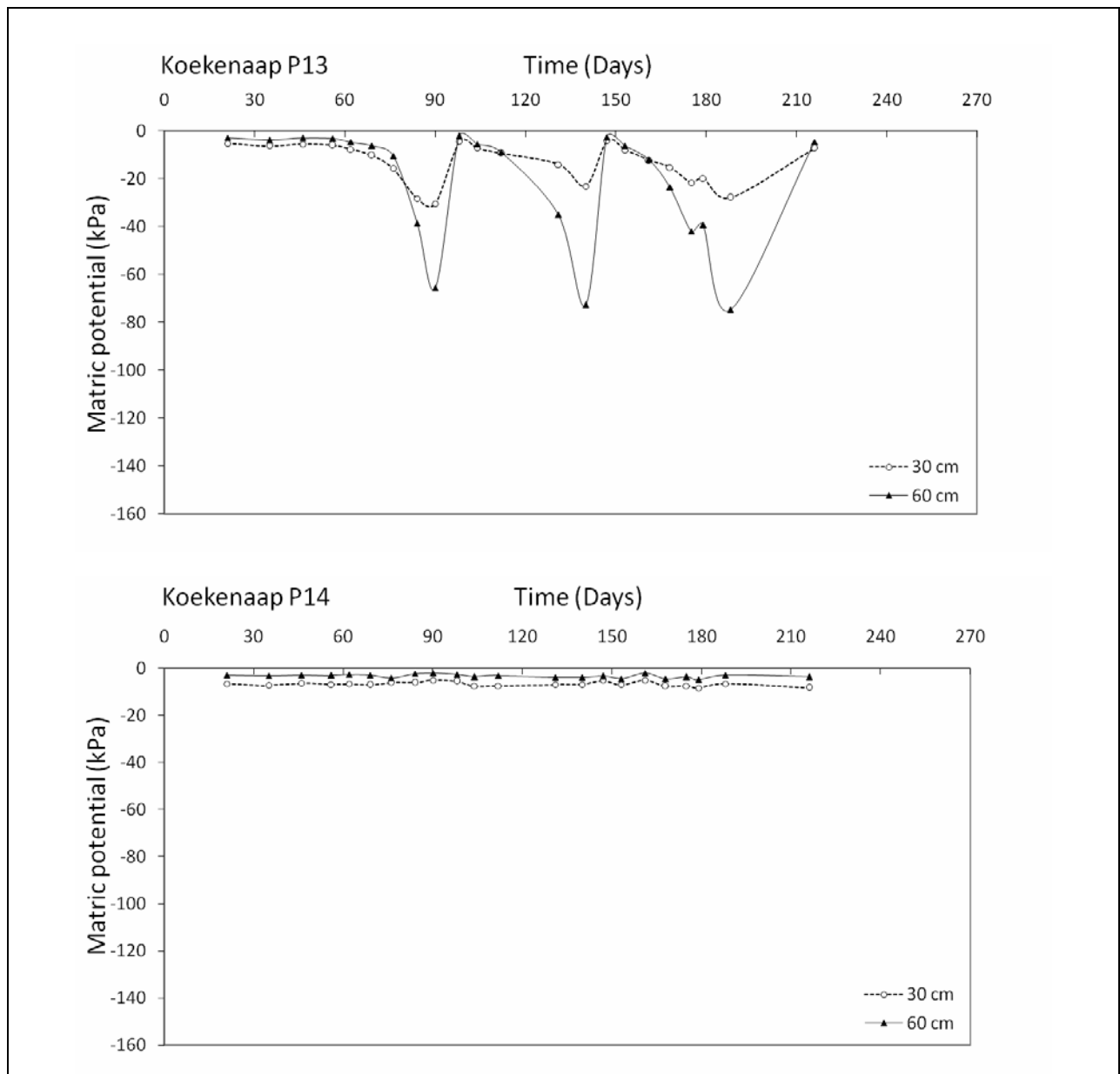
Figure 3.27   Variation in soil water matric potential in a sandy soil where deficit irrigation (Vredendal P7) and normal irrigation (Vredendal P8) strategies were applied during the 2007/08 season in the Lower Olifants River region.
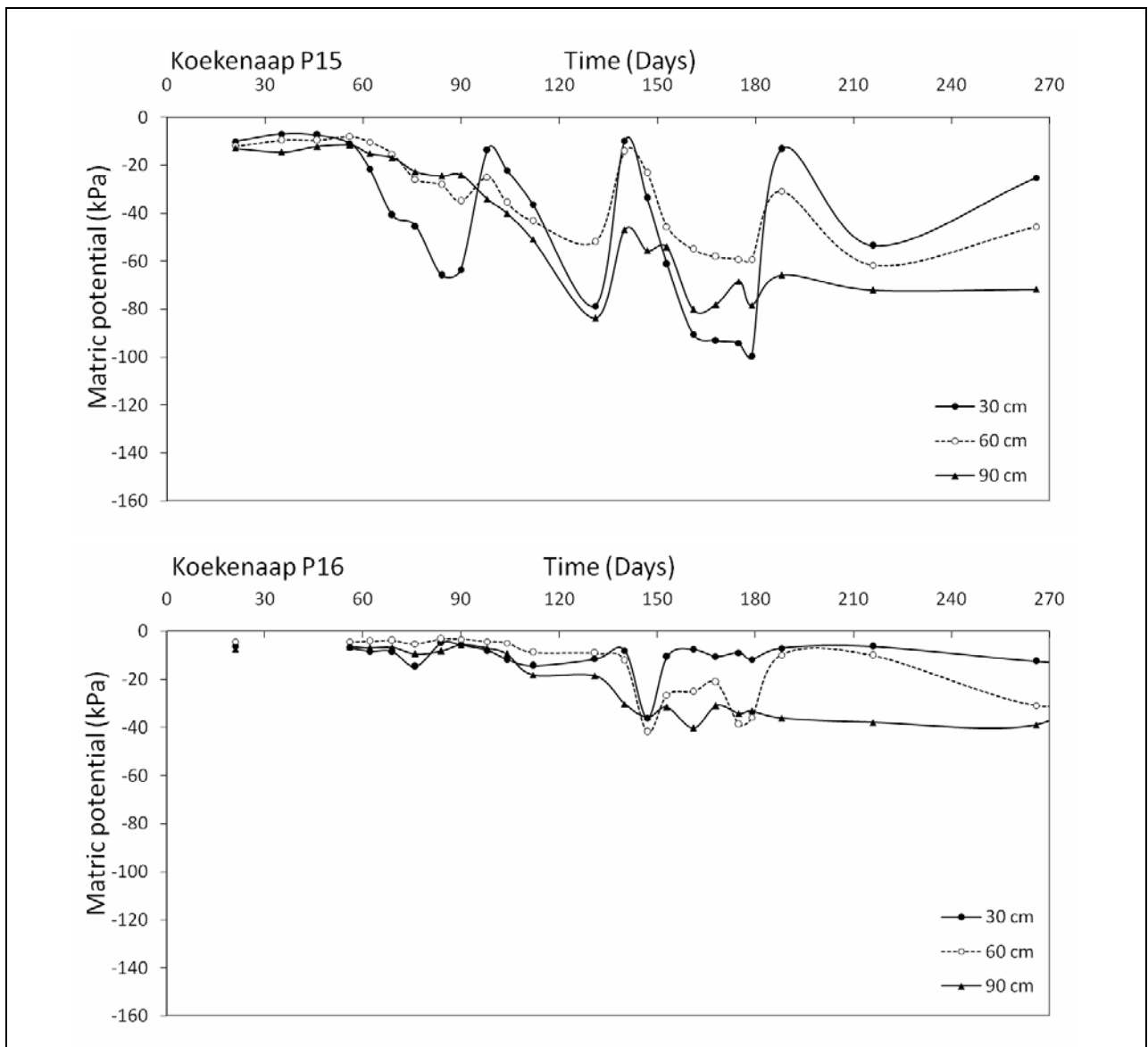
Figure 3.28   Variation in soil water matric potential in a sandy soil where deficit irrigation (Lutzville P9) and normal irrigation (Lutzville P10) strategies were applied during the 2007/08 season in the Lower Olifants River region.

Figure 3.29 Variation in soil water matric potential in a loamy sand soil where deficit irrigation (Lutzville P11) and normal irrigation (Lutzville P12) strategies were applied during the 2007/08 season in the Lower Olifants River region.

Figure 3.30   Variation in soil water matric potential in a sandy soil where deficit irrigation (Koekenaap P13) and normal irrigation (Koekenaap P14) strategies were applied during the 2007/08 season in the Lower Olifants River region.

Figure 3.31 Variation in soil water matric potential in a sandy loam soil where deficit irrigation (Koekenaap P15) and normal irrigation (Koekenaap P16) strategies were applied during the 2007/08 season in the Lower Olifants River region.
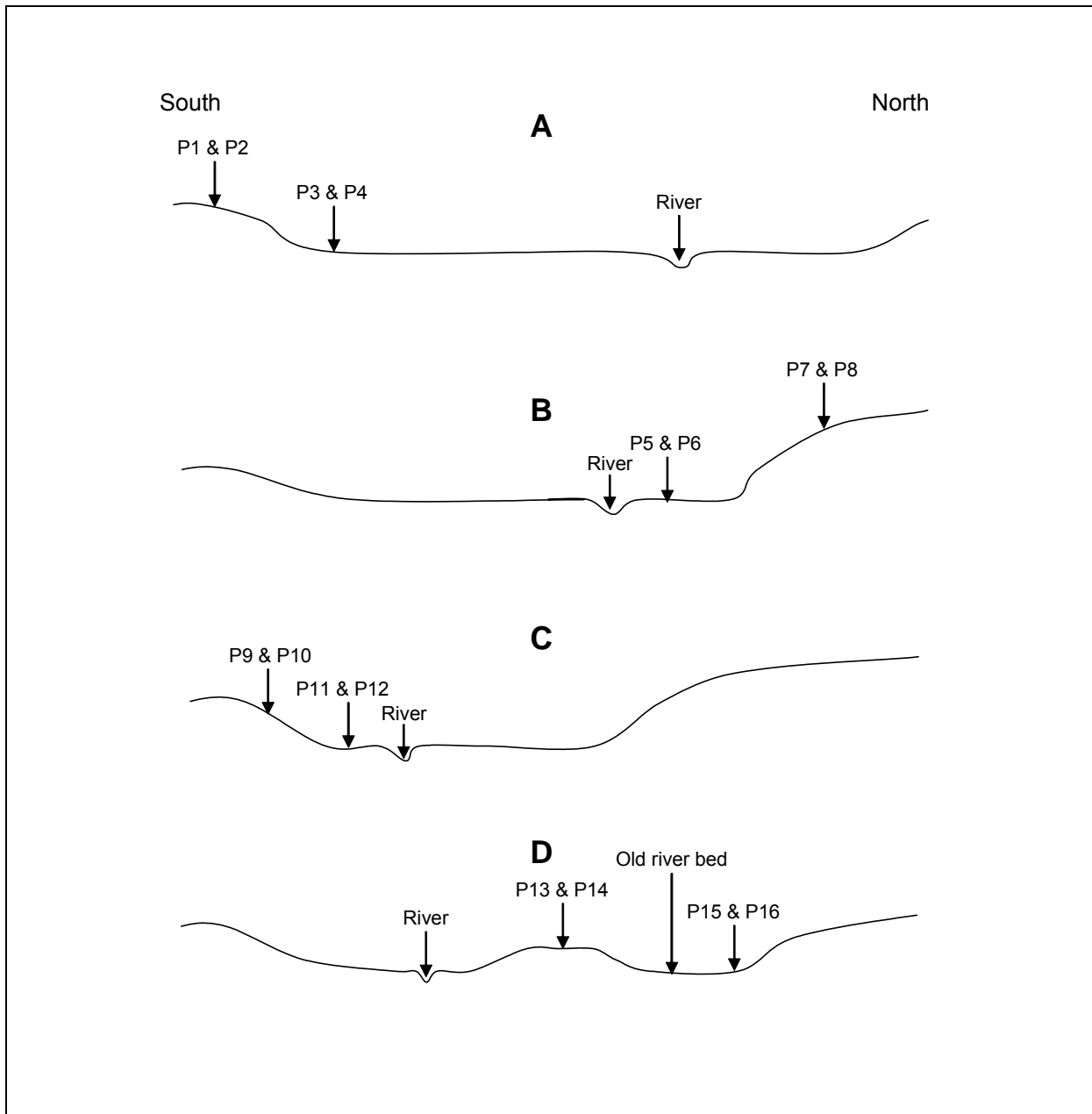
Figure 3.32 Schematic cross sections of the Lower Olifants river region to indicate where the different experiment plots were located with respect to the main flow of the river at (A) Kapel, (B) Vredendal, (C) Lutzville and (D) Koekenaap, respectively. P5 and P6 as well as P11 and P12 were submerged when the Olifants River flooded it banks during the winter months.

Figure 3.33 Grapevine root distribution at Kapel (P1 & P2) in a sandy soil representative of the Garies soil form (Soil Classification Work Group, 1991). The soil profile consists of an orthic A horizon over a red apedal B horizon. The underlying material is dorbank.

Figure 3.34 Grapevine root distribution at Kapel (P3 & P4) in a sandy loam soil representative of the Valsrivier soil form (Soil Classification Work Group, 1991). The soil profile consists of an orthic A horizon over a pedocutanic B horizon. The underlying material is unconsolidated.

Figure 3.35 **Grapevine root distribution at Vredendal (P5 & P6) in a sandy loam soil representative of the Dundee soil form (Soil Classification Work Group, 1991). The soil profile consists of stratified alluvium.**

Figure 3.36 Grapevine root distribution at Vredendal (P7 & P8) in a sandy soil representative of the Plooysburg soil form (Soil Classification Work Group, 1991). The soil profile consists of an orthic A horizon over a red apedal B horizon. The underlying material is a hard carbonate horizon.

Figure 3.37 Grapevine root distribution at Lutzville (P9 & P10) in a sandy soil representative of the Augrabies soil form (Soil Classification Work Group, 1991). The soil profile consists of an orthic A horizon over a neocarbonate B horizon.


Figure 3.38   Grapevine root distribution at Lutzville (P11 & P12) in a loamy sand soil representative of the Dundee soil form (Soil Classification Work Group, 1991). The soil profile consists of stratified alluvium.

Figure 3.39   Grapevine root distribution at Koekenaap (P13 & P14) in a sandy soil representative of the Garies soil form (Soil Classification Work Group, 1991). The soil profile consists of an orthic A horizon over a red apedal B horizon. The underlying material is dorbank.


Figure 3.40   Grapevine root distribution at Koekenaap (P15 & P16) in a sandy loam soil representative of the Avalon soil form (Soil Classification Work Group, 1991). The soil profile consists of an orthic A horizon over a yellow brown apedal B horizon on a soft plinthic B horizon.
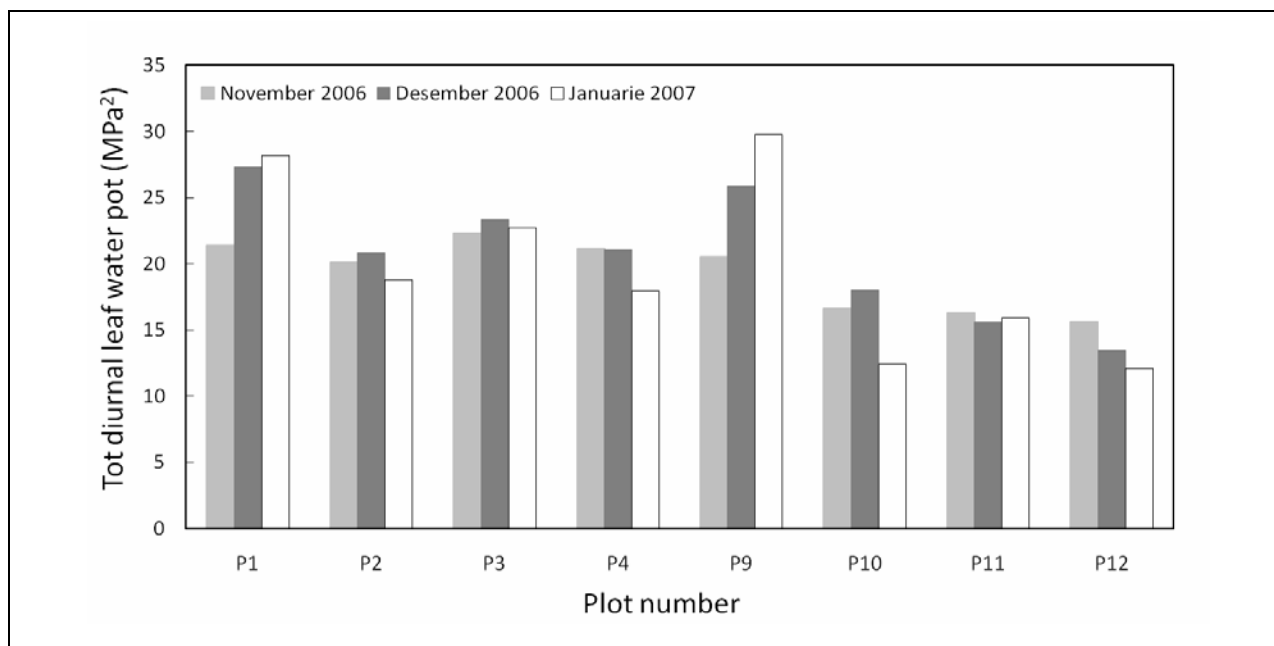
Figure 3.41 Total diurnal grapevine leaf water potential measured in November, December and January during the 2006/07 season at Kapel (P1 to P4) and Lutzville (P9 to P12) in the Lower Olifants River region. Refer to Table 3.1 for a description of the plots.
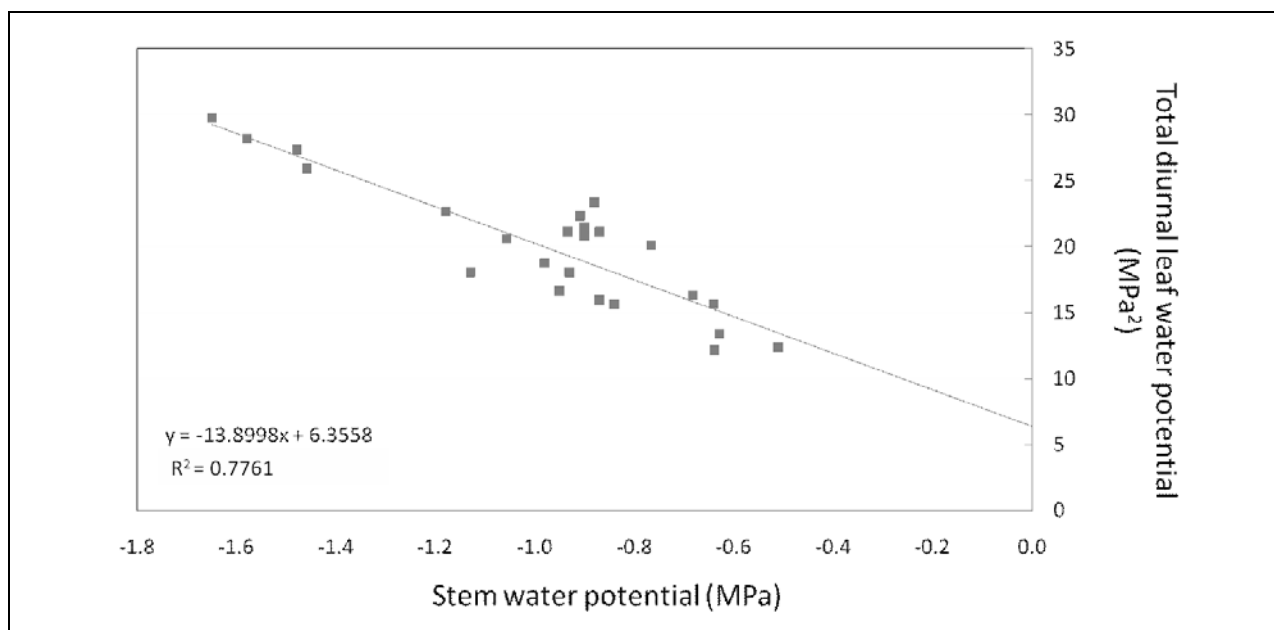
Figure 3.42 Relationship between total diurnal leaf water potential and midday stem water potential in Cabernet Sauvignon grapevines as measured during the 2006/07 season in the Lower Olifants River region.
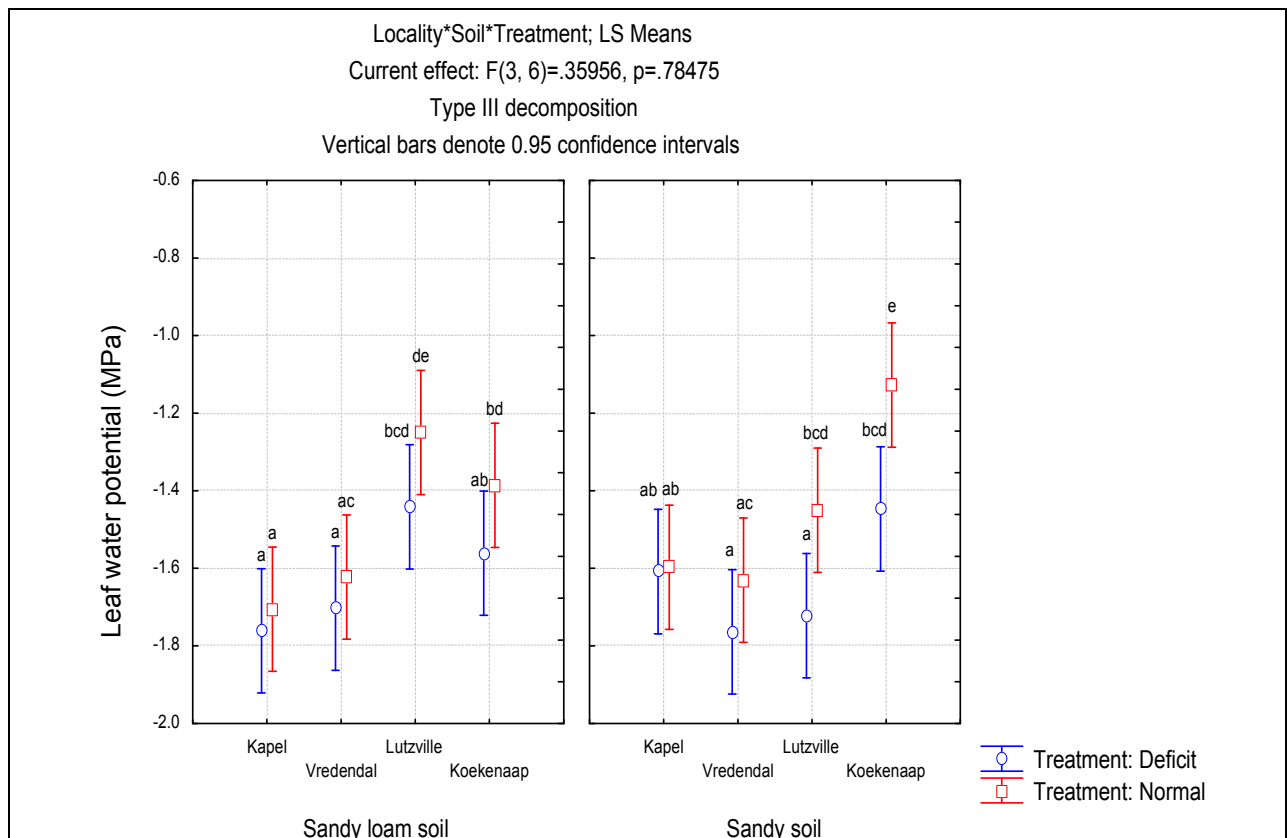
Figure 3.43 The effects of soil texture, locality and deficit irrigation vs normal irrigation on the midday leaf water potential in Cabernet Sauvignon during berry ripening in the 2006/07 season in the Lower Olifants River region.
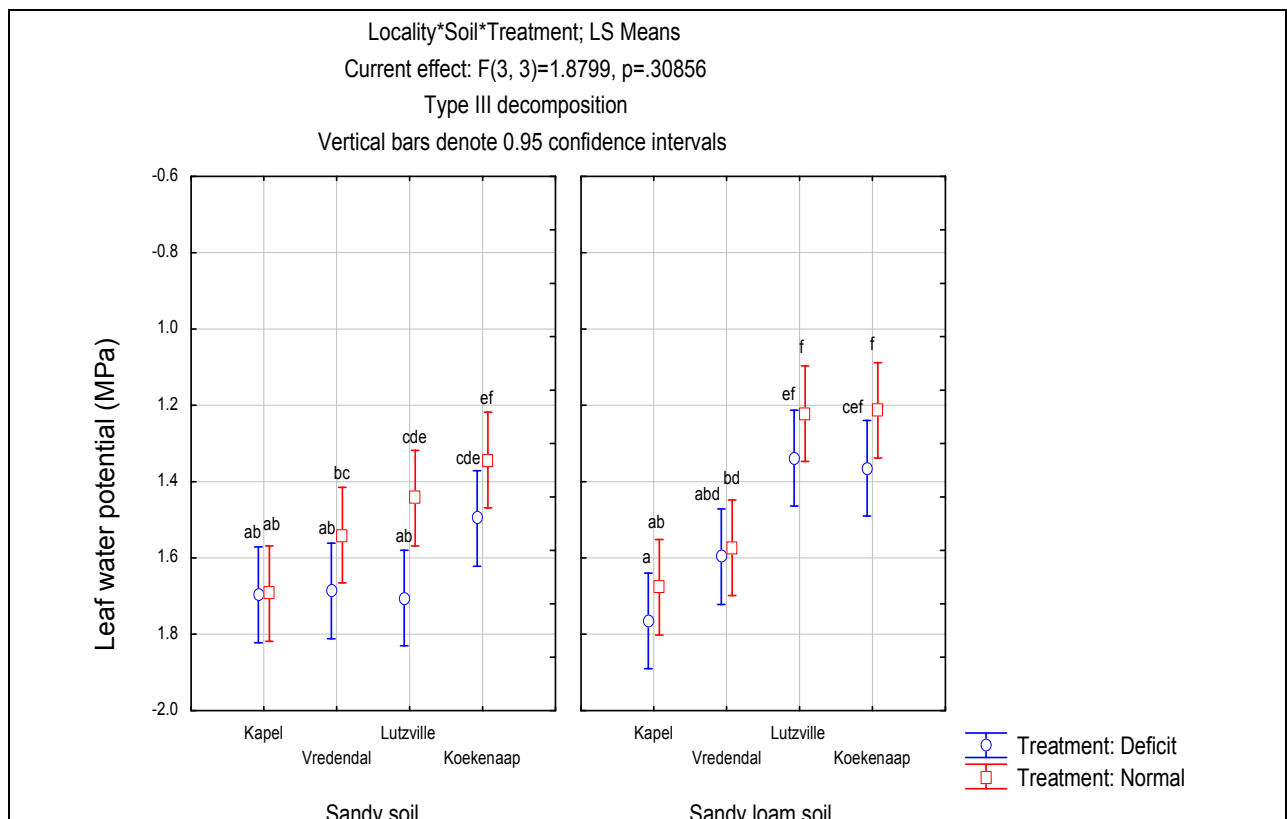
Figure 3.44 The effects of soil texture, locality and deficit irrigation vs normal irrigation on the midday leaf water potential in Cabernet Sauvignon grapevines during berry ripening in the 2007/08 season in the Lower Olifants River region.

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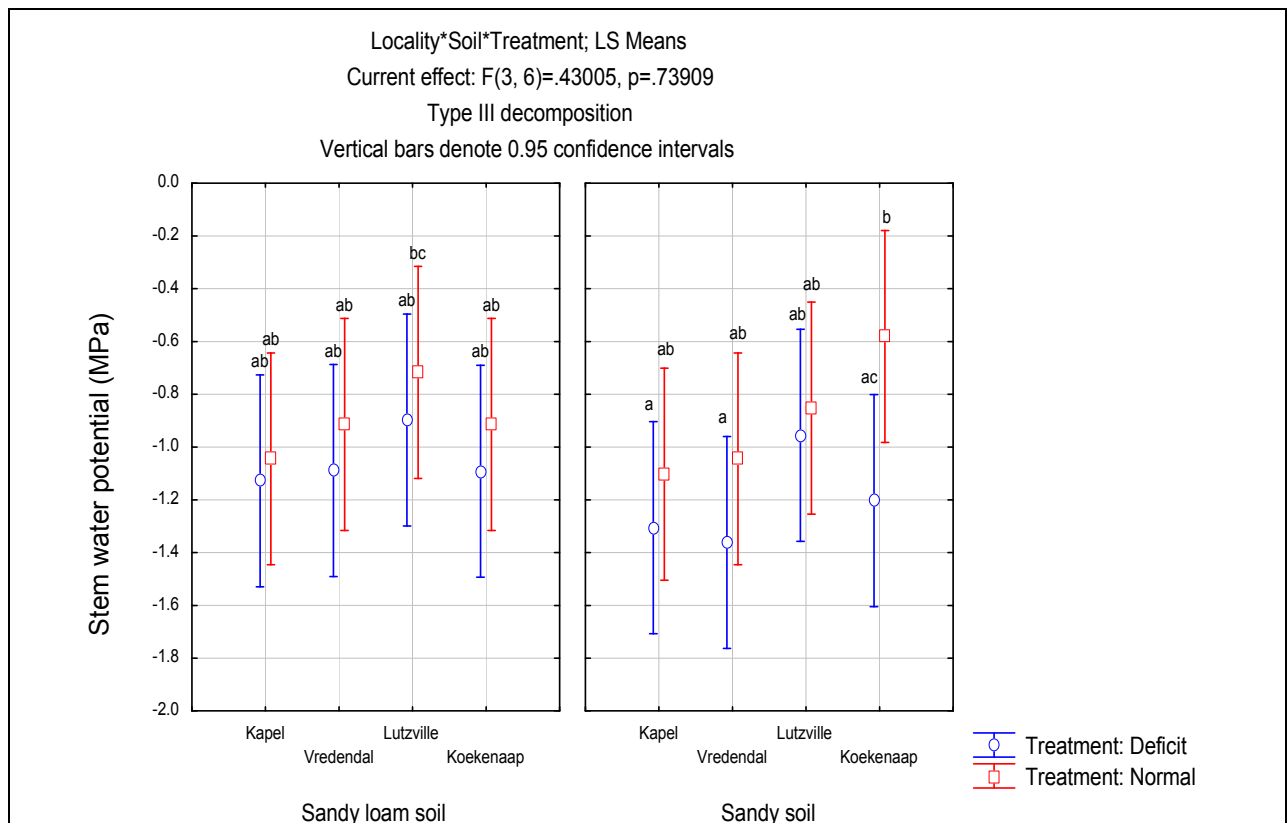
Figure 3.45 The effects of soil texture, locality and deficit irrigation vs normal irrigation on the midday stem water potential in Cabernet Sauvignon grapevines during berry ripening in the 2006/07 season in the Lower Olifants River region.

Figure 3.46 The effects of soil texture, locality and deficit irrigation vs normal irrigation on the midday stem water potential in Cabernet Sauvignon grapevines during berry ripening in the 2007/08 season in the Lower Olifants River region.

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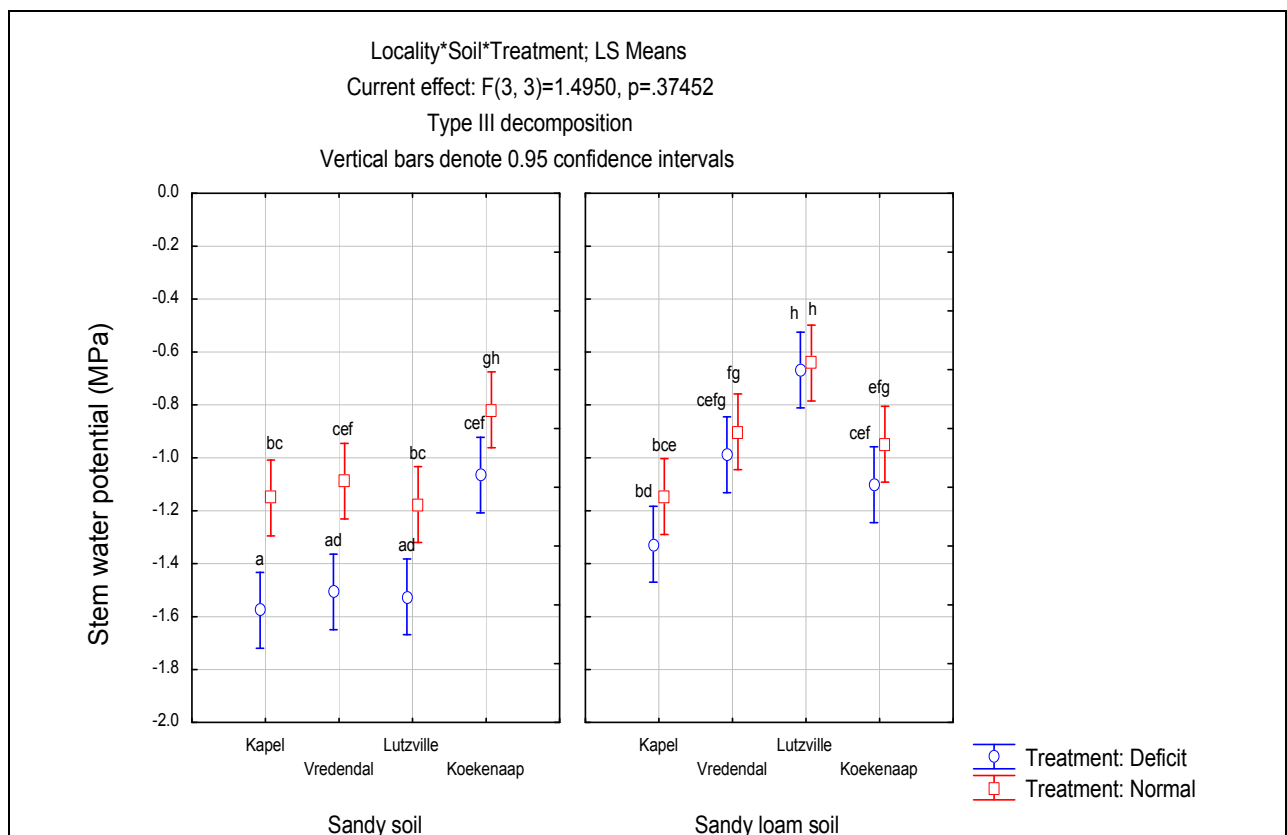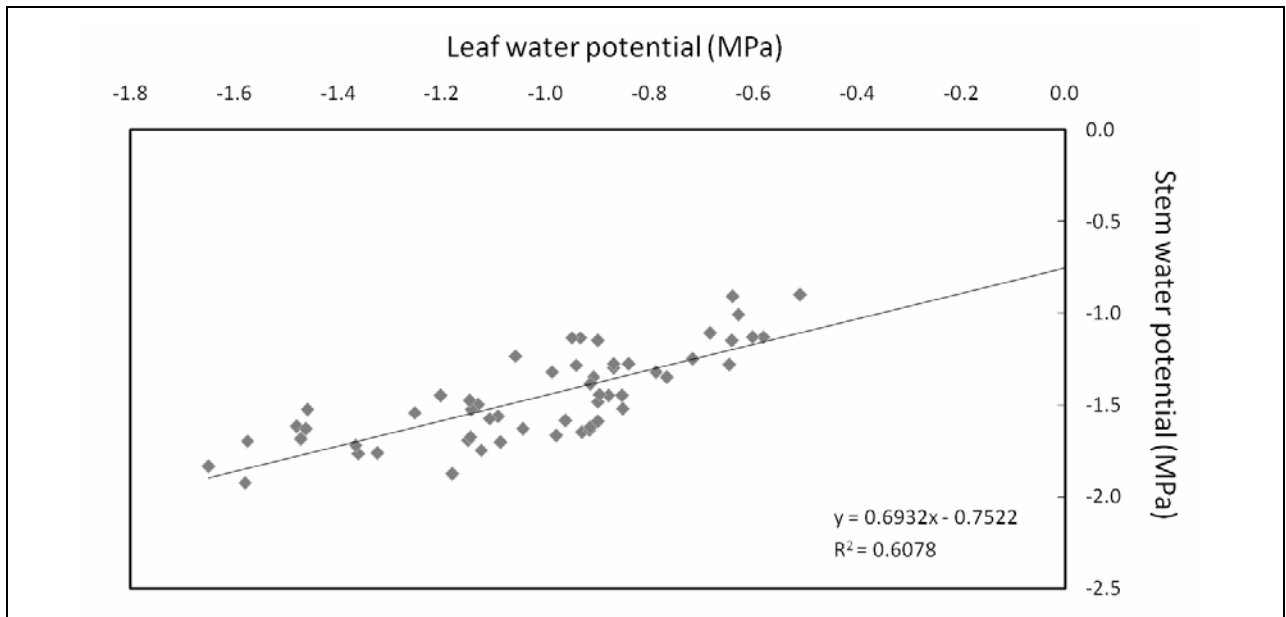
Figure 3.47   Relationship between midday stem water potential and leaf water potential in Cabernet Sauvignon as measured during the 2006/07 and 2007/08 seasons in the Lower Olifants River region.
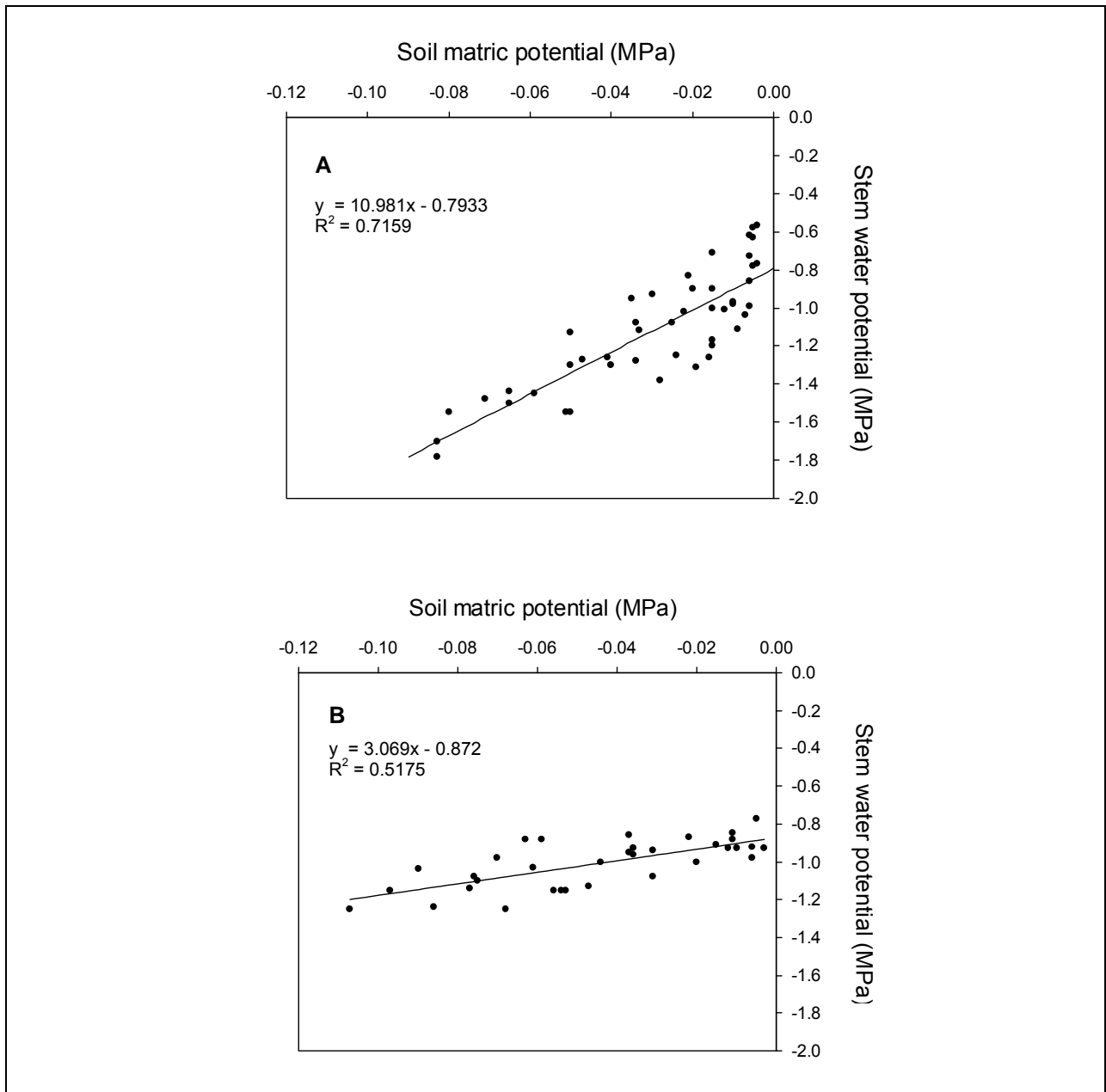
Figure 3.48 The relationship between midday stem water potential in Cabernet Sauvignon grapevines and soil water matric potential in (A) sandy soil and (B) sandy loam soil as determined during the 2006/07 and 2007/08 seasons in the Lower Olifants River region.

Figure 3.49   The influence of soil texture on the relationship between soil unsaturated hydraulic conductivity and soil water matric potential (Ψ_M) (adapted from Hillel, 1998).

Chapter 4

RESEARCH RESULTS

The effect of climate, soil and irrigation on vegetative growth and yield

THE EFFECT OF CLIMATE, SOIL AND IRRIGATION ON VEGETATIVE GROWTH AND YIELD

4.1 INTRODUCTION

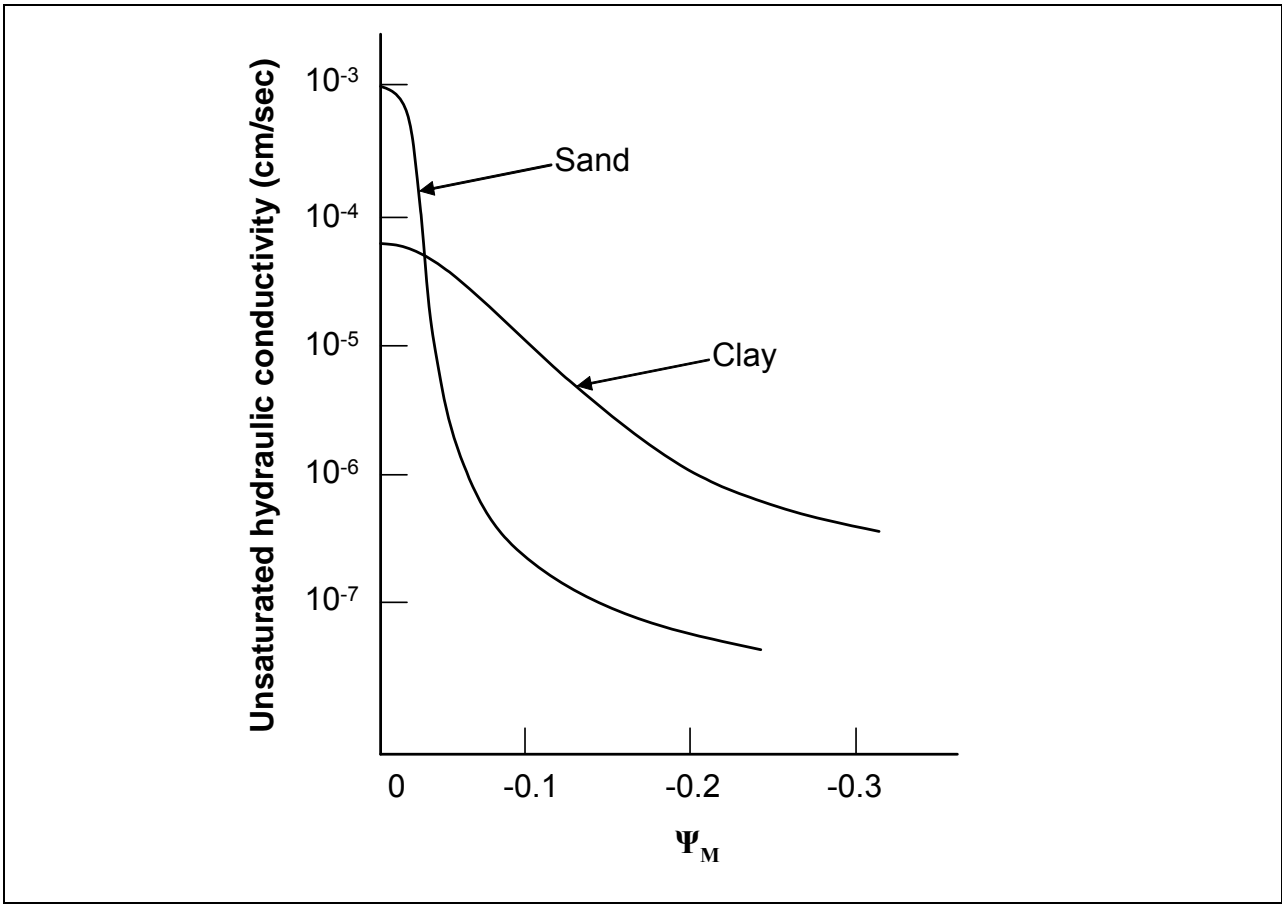Cabernet Sauvignon is regarded as a vigorous, low yielding grapevine cultivar (De Villiers, 1986). In the future, such low yielding, and in most cases non-profitable cultivars, will have to make way for higher yielding, more profitable cultivars. Since Cabernet Sauvignon is extensively planted in South Africa, another option would be to adapt management in such a way that input costs are reduced and/or the income is increased through improved wine quality. Water resources are limited in many of the grape growing regions in South Africa. In addition to restricted availability, the reality of increased water tariffs can increase production costs substantially. Consequently, one of the objectives of winegrowers should be to limit the use of irrigation water in such a way that vineyards will still produce acceptable yields and wine quality. Winegrowers have found that by imposing a pre-determined, measurable level of water stress at a particular stage of grapevine growth, they can enhance the value of grapes, while they save money on labour and energy bills (Bogart, 2006).

Soil water content has a significant positive impact on the vegetative growth of grapevines (Tesic *et al.*, 2001). However, as readily available soil water is depleted the grapevine adjusts to the drier soil conditions by reducing shoot growth (Kasimatis, 1967 and references therein). Most studies concerning grapevine response to irrigation have demonstrated that water deficits affect vegetative growth to a greater extent compared to reproductive growth. Studies with potted grapevines indicated that root growth is less sensitive to water deficits than shoot growth (Williams, 2000).

Excessive irrigation, high shoot vigour, shade, high gibberellin (GA) levels and a reduction in bud carbohydrates have all been associated with primary bud necrosis (PBN) in Shiraz (Collins & Rawnsley, 2008 and references therein). Previous research showed a strong positive relationship between vigour and bunch stem necrosis in Cabernet Sauvignon grapevines during the first season of applying management practices to manipulate vigour and the source to sink relationship (Pickering *et al.*, 2007). In the second season the relationship was not as strong, but still positive. The success of management practices will be influenced by the environmental conditions, particularly near flowering. A study carried out in the Stellenbosch region in South Africa showed that shading decreased bunch mass, berry mass and yield of Cabernet Sauvignon (Archer & Strauss, 1989). In addition to shading, vigorous growth could also reduce the temperature of the differentiating buds (Gladstones, 1992 and references therein). The differentiation of fruitful as opposed to purely vegetative buds, as well as the number of bunches per bud and shoot, were favoured by high temperatures during early bud development in late spring. Adequate heat and sunshine are essential in the following spring and summer (Archer & Strauss, 1989).

The distribution of photosynthetic products within grapevines is regulated by the source to sink relationship (Johnson *et al.*, 1982). Under mild water deficits vegetative growth is not in competition with reproductive development as a sink of photosynthetic products and the fruits are the primary sinks (Choné *et al.*, 2001). Partitioning of assimilates between sites of production and sites of accumulation or utilisation ultimately determines yield and grape composition (Hunter & Myburgh, 2001).

Exposure of shoots to light had a significant effect on potential bud fruitfulness in Cabernet Sauvignon in the central San Joaquin Valley, California (Sánchez & Dokoozlian, 2005). Maximum potential fruitfulness occurred at ca. one-third of full sunlight where above-canopy quantum solar irradiance was ca. 2 000 µmol.m^{-2}.s^{-1}. However, this response could not be traced to localize light interception by individual buds, but rather to the light microclimate surrounding shoots. Fruitfulness could be more easily optimized in canopy systems which encourage uniform shoot development and light exposure. The contribution of secondary buds to increased fruitfulness during higher light regimes was due to an increase in the number of primordial (Sánchez & Dokoozlian, 2005). In contrast, both number of primordial and diameter of primordial in primary buds, tended to increase with light exposure.

Soil type could have an indirect effect on vegetative growth through regulation of the water supply to the grapevine as well as through the composition or mineral content of the soil (Fregoni, 1977; Seguin, 1986). The invigorating effect of fertile soil was recorded some 2 000 years ago: "the fattest and most fertile soil suffers from rankness of growth" (Due, 1988 and references therein). The best wine was produced by grapevines which were rather low in vigour. The association of low vigour and high quality is not peculiar to the grapevine, but can also be seen in fruit production (Due, 1988 and references therein).

Berry growth depends principally on water supply. The growth rate of grape berries from véraison to maturity may be divided into three phases, during which growth rate clearly correlated with the water status of the plant (Deloire *et al.*, 2005 and references therein). Alexander (1965) suggested that grape berries are extremely sensitive to water stress for approximately four weeks after flowering, followed by a more resistant period. Insufficient water during the early period of rapid berry enlargement prevents the attainment of normal berry size, applying water after this period, will not enable undersized berries to become normal (Kasimatis, 1967 and references therein). Berry size is further decreased when severe water deficits occur in grapevines over several years in succession (Vaadia & Kasimatis, 1961).

Water stress significantly reduced berry weight and berry size of Cabernet Sauvignon grapevines in Chile (Ferreyra *et al.*, 2004). The yield was primarily reduced when no water was applied between budburst and véraison. Water stress also reduced berry size and yield of seven year old Cabernet Sauvignon grapevines in Chile, particularly if water deficit was applied during the pre-véraison period (Acevedo *et al.*, 2004). On the other hand, in dry land vineyards in the Coastal Region of South Africa limited irrigation could increase berry size and yield without any negative effects on wine

quality (Myburgh, 2006). Hence, low frequency irrigation in vineyards in the Coastal Region could increase the profitability of vineyards.

The control effect of temperature on grapevine growth is difficult to define. Regardless of the uncertainties, it was found that the optimal mean temperature for grapevine fastest growth is from 23ºC to 25ºC. However, growth rate quantified in terms main stem elongation behaved differently. Both stem thickness and internode length declined progressively above 20ºC day/15ºC night temperature. This resulted in vigorous growth, but poor fruitfulness in grapevines growing under consistent cool conditions. At temperatures which are moderately below the optimum for growth rate, any surplus sugar available in the plant is preferably directed to stem growth, i.e. at least during the vegetative growth period. This strategy has evolved for plants in temperate climates where early growth is normally at sub-optimal temperatures. It is not in a species' survival interest to switch its main efforts to reproduction until the plants are large enough and until temperatures and day length are approaching or passing an optimum later in the season (Gladstones, 1992 and references therein). A fairly wide range of sunshine hours related positively to yield and quality, but only if temperature and relative humidity remained favourable (Gladstones, 1992 and references therein). Grapevine size decreased as the cool limit of its cultivation was approached (Due, 1988 and references therein). Furthermore, excessive vigour is not expected in hot inland climates, but should be fully expected in mild, humid, maritime climates.

The aim of this study was to determine the effect of climate, soil and irrigation on vegetative growth and yield in drip irrigated Cabernet Sauvignon in the Lower Olifants River region.

4.2   MATERIALS AND METHODS

4.2.1 EXPERIMENT LAYOUT

Measurements were carried out in eight commercial drip irrigated Cabernet Sauvignon vineyards in the Lower Olifants River region. Refer to Chapter 3 for the details of the vineyards and the experiment layout.

4.2.2 VEGETATIVE MEASUREMENTS

4.2.2.1 Canopy characteristics in the season

Canopy characteristics were determined in all 16 plots just before harvest. The canopy score sheet (Smart & Robinson, 1991), with adapted criteria for South African conditions (Archer, 2002), was used to estimate potential wine grape quality before harvest. The leaf layer number (LLN), percentage interior leaves and interior clusters as well as gaps in the canopy were determined using the point quadrat analysis method (Smart & Robinson, 1991). Fifty measurements were carried out per plot. The canopy external leaf area perimeter (CELAP) was estimated in all plots according to the

procedure described by Murisier (1996) and Zufferey (2000). The estimated total leaf area per grapevine was calculated according to the procedure described by Myburgh (1998). The CELAP and total leaf area were used to calculate the foliar index (Deloire, Personal communication, 2009).

4.2.2.2 Cane characteristics at pruning

Cane mass of the experiment grapevines was weighed in each plot at pruning (June to August) by using a hanging balance. One cane per grapevine, on the second spur from the cordon split, was removed to determine the mean cane length, internode length and cane diameter. Cane length was determined by using a measuring tape. Cane diameter was determined by using a vernier caliper. Dorsal and ventral diameters were measured at the lower, middle and apical ends of each cane. Mean budding percentage was determined by counting the total number of buds awarded at winter pruning during the previous season as well as the number of buds which actually budded. Bud numbers were counted on all the grapevines per plot.

4.2.3 REPRODUCTIVE MEASUREMENTS

Grapes were harvested by hand when the sugar content was approximately 24ºB to 25ºB. All bunches on a plot were picked and counted using mechanical counters. The grapes were weighed to obtain the total mass per plot. Mean yield per grapevine was calculated and converted to tonnes per hectare. Bunch mass was determined by dividing total grape mass per plot by the number of bunches per plot. Number of bunches per grapevine were calculated by dividing the total number of bunches per plot by the number of experiment grapevines per plot. Fresh berry mass was determined in all the plots at harvest. Berry samples were obtained by picking 20 berries along the longitudinal axis from each of 10 bunches, i.e. 200 berries per plot. Berries were removed by cutting through the pedicle as close as possible to the berry using a small pair of scissors (Van Schalkwyk, 2004). The balance between vegetative and reproductive growth were estimated in each plot by using the ratio between the estimated CELAP and kg of grapes produced by a grapevine (Deloire, Personal communication, 2009).

4.2.4 STATISTICAL ANALYSES

Analysis of variance (ANOVA) was used to test the effects of locality, soil texture and irrigation strategy on reproductive measurements. Fisher least significant difference was calculated at the 95% confidence level to compare treatments. Version 9 of Statistica[®] was used. Relationships between variables were determined by means of linear regression at the 95% confidence level using Excell 2000[®]. Multiple linear regression models were calculated using Statgraphics[®].

4.3 RESULTS AND DISCUSSION

4.3.1 VEGETATIVE GROWTH

4.3.1.1 Canopy characteristics

At some localities, e.g. in the sandy soil at Kapel (P1), deficit irrigated grapevines already showed visual water stress symptoms, such as yellowing of basal leaves, before véraison in December 2006. Similarly, non-irrigated Tempranillo grapevines that were subjected to severe water deficits showed premature leaf senescence approximately three weeks before véraison (Lopes *et al.*, 2001). During both seasons, deficit irrigated grapevines in some of the sandy soils, e.g. P1 and P7, showed visual water stress symptoms such as yellowing of the older leaves and limited leaf shed at harvest (Fig. 4.1 & Fig. 4.2). Similar water deficit symptoms were described by Smart (2003). Grapevines in P1 and P7 received ca. 60% less water from flowering to harvest compared to the normal irrigated grapevines (Table 3.11). As a result of the deficit irrigation, mean soil water matric potential (Ψ_M) varied between -0.030 MPa and -0.050 MPa from flowering to harvest in these plots (Table 3.12). During berry ripening, mean Ψ_S in P1 and P7 grapevines was ca. -1.50 MPa during the 2006/07 and 2007/08 seasons (Table. 3.17 & Table. 3.19). At that stage, normal irrigated grapevines in the sandy soil at Kapel (P2) did not show any visual water stress symptoms. During the pre-véraison period, mean Ψ_M in P1 and P2 was approximately -0.030 MPa and -0.010 MPa, respectively (Table 3.12). In response to the Ψ_M difference, the predawn leaf water potential (Ψ_{PD}) was ca. -0.80 MPa and -0.40 MPa in the P1 and P2 grapevines, respectively (Table 3.15). During pre-véraison Ψ_{PD} values lower than -0.40 MPa place a constraint on vegetative and reproductive growth, and if Ψ_{PD} values are lower than -0.60 MPa, grapevines are under severe water stress (Deloire, *et al.*, 2004). The visual water stress symptoms that were observed, confirmed that Ψ_{PD} values of -0.60 MPa could be a threshold for the onset of severe water deficits in grapevines. The difference in Ψ_M also reflected in the midday Ψ_S values which were -1.48 MPa and -0.90 MPa for P1 and P2 grapevines, respectively.

No visual water stress symptoms were visible in grapevines in the heavier sandy loam soil at Kapel, although Ψ_{PD} values amounted to ca. -0.60 MPa and -0.50 MPa in P3 and P4, respectively. These values probably indicate towards an ideal situation in terms of regulating the vegetative and reproductive growth of the grapevine in the more fertile sandy loam soils, whereas -0.4 MPa could be the ideal for the sandy soils as discussed above. However, apart from the phenological stage during which water deficits occurred, the intensity as well as the duration of water stress is also important in determining the physiological response of the grapevine (A. Deloire, Personal communication, 2009).

Canopies of the normally irrigated grapevines did not show any visual water stress symptoms at harvest, irrespective of soil texture. During berry ripening stem water

potential in the normally irrigated grapevines varied between ca. -1.0 MPa and -1.10 MPa (Table 3.19 & Table 3.21). In fact, under the prevailing conditions, active shoot growth occurred until harvest in normal irrigated grapevines in P12 during both seasons. The Ψ_M values in this particular plot ranged between -0.010 MPa and -0.030 MPa from flowering to harvest (Table 3.12). Consequently, Ψ_{PD} was ca. -0.20 MPa to -0.30 MPa in the P12 grapevines from pea size to ripening during the 2006/07 season (Table 3.14, Table 3.15 & Table 3.16). As a result of the low Ψ_M, Ψ_S was ca. -0.70 MPa and -0.60 MPa during berry ripening during both seasons (Table 3.19 & Table 3.21). Active vegetative growth during berry ripening could be undesirable if it becomes a strong sink which competes with reproductive growth (Smart & Robinson, 1991).

Deficit irrigation tended to reduce the estimated CELAP of grapevines in the sandy soils during both seasons, (Table 4.1 & Table 4.2). In the sandy loam soils the CELAP of deficit irrigated grapevines were comparable to the normal irrigated ones. With the exception of P3 and P4, most of the plots did not achieve the minimum required CELAP value of 1.6 linear meter (A. Deloire, Personal communication, 2009). One of the strategies that could to be adopted to improve the CELAP value, particularly in the sandy soils, could be to increase the canopy height by allowing longer shoots on higher trellis systems.

Between plots there were big differences in terms of total leaf area per grapevine (Fig. 4.3). This could have been caused by the difference in soil texture and through that the regulation of water supply to the grapevine. Furthermore, the inherent mineral composition could also have played a role. Deficit irrigation tended to decrease total leaf area per grapevine (Fig. 4.3), but increased the foliar index, irrespective of soil texture (Fig. 4.4). With the exception of P7 during both seasons and P1 during the 2006/07 season, the foliar index of grapevines in most of the plots was below the optimum value of 0.7 to 0.8 (A. Deloire, Personal communication, 2009). These foliar surface grapevine drought indicators can be assessed reasonably easy, but must be used in conjunction with other indicators to determine grapevine water status (Deloire et al., 2004). Another consideration that should be kept in mind is the optimal value for, e.g. the foliar index, is according to European standards. Furthermore, number of laterals could also play an important role in the total leaf area of the grapevine. However, in the case P7 nearly no laterals were present (Table 4.3 & Table 4.4). The question that arises is: Could a foliar index of approximately 1, e.g. in the case of grapevines in P7, probably indicate too severe sun exposure of bunches under the warm South African conditions. However, the subject of the importance of laterals in terms of total leaf area and consequently the ratio between young leaves and adult leaves are beyond the scope of the study.

Leaf layer number (LLN) values of 2.0 to 2.5 at harvest are considered as the ideal under South Africa conditions (Archer, 1990). During the 2006/07 season, LLN of grapevines in P1, P2, P7, P9, P10 and P13 were lower than the ideal (Table 4.1). In the following season LLN values were lower than the ideal in P7, P8, P9, P10 and P13 (Table 4.2). Since low LLN can increase leaf and bunch exposure to direct sunlight, the grapes on grapevines in the sandy soils at Kapel and Vredendal, were probably over

exposed. However, for grapevines in plots at the coolest locality, i.e. at Koekenaap, relatively low LLN could be beneficial to aroma development (Smart & Robinson, 1991; Archer, 2002). During the 2007/08 season grapevine canopies in the sandy loam soil at Vredendal (P5 and P6) were probably too dense, i.e. approximately 40% shaded leaves and LLN higher than three (Table 4.2) (Hunter, 1992). Visual observation revealed that yellowing of leaves occurred inside the canopies of P5 and P6 grapevines. The yellow leaves were also shed earlier than was expected. At each of the four localities, grapevines in the heavier sandy loam soils tended to have more dense canopies compared to the ones in the sandy soils. Some of the variation in number of shaded leaves within the canopy at harvest could be explained by the silt content in the soils (R^2 = 0.4477; se = 5.6; p < 0.001). This suggested that inherent soil properties, such as silt content, could cause denser canopies in normal irrigated vineyards in the sandy loam soils compared to ones in the sandy soils.

Canopy score could be use to estimate potential wine grape quality of a vineyard before harvest (Smart & Robinson, 1991). In the sandy loam soils deficit irrigation tended to increase grapevine canopy score, but reduced the canopy score of grapevines in the sandy soils (Table 4.1 & Table 4.2). The consistently highest canopy score of grapevines in the sandy soil at Kapel (P2) compare well with the highest canopy score of 91% for Cabernet Sauvignon vineyards obtained in a field trial in the Stellenbosch region during the 1992/1993 season (Archer & Pienaar, 1993). In this study the vineyard with the highest canopy score, in combination with a good terroir, obtained a high wine quality score. Furthermore, it was showed that a suboptimal terroir could only partially be corrected in terms of wine quality by optimum canopy management practices.

4.3.1.2 Cane characteristics

Cane characteristics varied considerably between plots (Table 4.3 & Table 4.4). Consequently, substantial differences in pruning mass occurred between plots (Fig. 4.5). As expected, pruning mass increased with cane diameter (Fig. 4.6), cane length (Fig. 4.7) and lateral length per cane (R^2 = 0.4987; se = 1.4; p < 0.001). However, pruning mass did not correlated with budding percentage, internode length and number of lateral shoots per cane in any of the two seasons.

Pruning mass, tended to be higher during the 2007/08 season compared to the 2006/07 season, irrespective of soil texture or irrigation strategy (Fig. 4.5). Higher rainfall from October until January during the 2007/08 season probably contributed to the higher pruning masses compared to the first season (Fig. 3.12). Pruning mass of normal irrigated grapevines in the sandy soils was 60% lower compared to the heavier sandy loam soils during the 2006/07 season and 56% lower in 2007/08 (Fig. 4.8). On average, deficit irrigation reduced growth in the sandy soils by 32% and 31% during the 2006/07 and 2007/08 seasons, respectively (Fig. 4.9). However, water deficits had almost no effect on vegetative growth in the heavier sandy loam soils during the two seasons (Fig. 4.10).

From bud break to flowering, mean Ψ_M in the deficit irrigated plots were more or less comparable to the normal irrigated ones in the sandy as well as sandy loam soils (Table 3.12). The only exception occurred in P5 and P11 during the 2007/08 season when irrigation was cut off just after bud break in an effort to induce water deficits. Deficit irrigated grapevines tended to experience more water stress from flowering until harvest compared to the normal irrigated ones, irrespective of soil texture (Table 3.12). The increase in growth vigour with an increase in Ψ_M confirmed that grapevine growth responded positively to more frequent irrigation, particularly from flowering to véraison. A reduction in shoot growth is one of the first visible symptoms of grapevine water stress (Williams, 2000). Suboptimal irrigation, i.e. Ψ_M lower than -0.006 MPa during December and January (pre-véraison), reduced shoot growth of Bukettraube by approximately 50% in a sandy soil in the Lower Olifants River region (Conradie & Myburgh, 2000). This reduction in shoot growth is more pronounced compared to the ca. 30% reduction obtained with Cabernet Sauvignon in this study. However, the effect of water stress on shoot growth of a vigorous cultivar such as Cabernet Sauvignon could be less severe compared to Bukettraube (Goussard & Archer, 2003). It should be noted that rootstock could also have an influence on vegetative growth and eventually on pruning mass (Carstens et al., 1981).

The variation in pruning mass was positively related to soil carbon organic content (Fig. 4.11). The contribution of the soil C content is not a direct nutritional effect, but most probably serves as an indication of the soil fertility in terms of nitrogen (N) availability. Moderately bearing vineyards require only ca. 50 kg of N per hectare annually (Saayman, 1992). The medium textured soils in the coastal region of South Africa are able to supply this amount of N by means of the natural mineralization of organic material present in the soil. Consequently, only small amounts or no additional N should be added in the form of fertilizer. In Europe, balanced N nutrition is regarded to be of such importance that it is argued that the formal control of N fertilisation should enjoy serious consideration when rules of conduct are formulated by organisations wanting to control wine quality in the demarcated regions. However, 80 kg N per ha per year was insufficient for a Bukketraube vineyard in a sandy soil near Lutzville in the Lower Olifants River region (Conradie & Myburgh, 2000). In Bordeaux, France, it was shown that the vigour differences in Cabernet Sauvignon vineyards in different soils seems to be related to their nitrogen status rather than to their water status, which tended to be the comparable. It is logical and economically unwise to stimulate vigour early in the season by applying large amounts of N and then removing the surplus growth by summer pruning (Keller, 2005). Berries with high N and low phenol content on grapevines with vigorous, shaded canopies are more susceptible to sunburn.

In addition to organic soil C, pruning mass was also influenced by soil texture and water status. Approximately 79% of the variation in pruning mass (PM) could be explained by means of a multiple linear regression as indicated in the following equation:

PM = 0.771 + 4.73*C - 0.068*CS + 27.4*Ψ (R^2 = 0.7851; se = 0.2; p < 0.001)   (Eq. 4.1)

where C is soil organic carbon content (%), CS is the percentage coarse sand (%) and Ψ is the mean Ψ_M from September until December (MPa) in the wettest soil layer (data not shown). The negative correlation between pruning mass and the coarse sand fraction was probably caused by a decrease in plant available water as the coarse sand increased. Since pruning mass was not related to mean Ψ_M in the root zone, but to Ψ_M in the wettest layer, it appeared that the grapevine roots absorbed water more readily in the wettest soil layer, i.e. where the less energy is required. In Bordeaux in France pruning weight of Cabernet Sauvignon, Cabernet franc and Merlot grapevines were significantly affected by soil type (Van Leeuwen *et al.*, 2004). Total shoot length and growth cessation were strongly influenced by the vintage with growth cessation occurring earlier in dry vintages and on gravely and clayey soils where grapevines were subjected to water deficit. The difference in growth cessation in a dry and wet vintage was 52 days. Furthermore, pre-véraison water deficit provokes early shoot growth cessation. On the other hand, active growth in the post-véraison period could contribute positively to high pruning masses, e.g. in the case of normal irrigated grapevines in the loamy sand soil near Lutzville (P12).

In the case of deficit irrigation in the loamy sand soil near Lutville (P11), Ψ_M was ca. -0.070 MPa during ripening in the 2007/08 season. Although the soil was dry, it did not reflect in the relatively high mean Ψ_S value of -0.65 MPa. In the normal irrigated plot (P12) Ψ_M was substantially higher compared to P11 (Table 3.12). However, there was no difference in Ψ_S between the deficit irrigated and normal irrigated grapevines (Table 3.19). Visual observations revealed that shoot growth in P11 had stopped, but that the shoots in P12 continued to grow. Since the soil was dry to 900 mm depth, these results suggested that grapevines in P11 obtained water from another source. Due to the close proximity of the river to the vineyard (Fig. 3.32), a water table could have existed in soil layers deeper than 900 mm. Hence, it could be possible that grapevine roots absorbed water from these deep soil layers. This scenario showed the importance of using more than one parameter to manage irrigation in vineyards, e.g. measuring Ψ_M in the soil and Ψ_S in the grapevine, as well as visual monitoring of water stress symptoms.

4.3.2 YIELD AND ITS COMPONENTS

Berry mass varied considerably between plots during both seasons (Table 4.5 & Table 4.6). Deficit irrigation in the sandy soil at Kapel (P1) resulted in the smallest berries (ca. 0.80 g) which was considerably smaller compared to 1.29 g for Cabernet Sauvignon berries determined over a 10 year period in Stellenbosch, Robertson and Lutzville (Archer & Hunter, 2000 and references therein). However, grapevines in the sandy soil at Koekenaap (P13 and P14) produced berries in excess of 1.5 g which was slightly bigger than 1.29 g. With the exception of P5 and P6, deficit irrigation tended to reduce berry mass compared to normal irrigation in sandy as well as sandy loam soils during both seasons (Fig. 4.12 & Fig. 4.13). The higher water stress in the deficit irrigated grapevines, as induced by lower Ψ_M from flowering to harvest, could also have reduced berry size compared to the normal irrigated ones (Table 3.12). There is no explanation

for the seemingly inverse reaction of berry size to water deficits in the case of P5 and P6 during the 2007/08 season. At the beginning of berry development, the green active growing berries are extremely sensitive to water deficits (Van der Westhuizen, 1972; Williams, 2000). Cells divide for up to 40 days after fruit set and water deficits at this stage will influence berry size and bunch size that can not be corrected at a later stage. Irrigation at the beginning of berry development increased yield of potted grapevines compared to permanently dry soil conditions (Rühl & Alleweldt, 1985). Moderate to severe water deficits from flowering to véraison irreversibly modified the size of Shiraz berries, even if the berries received normal water from véraison to harvest (Ojeda *et al.*, 2001). Van Leeuwen *et al.* (2004) found that early, i.e. pre-véraison, water deficits reduced berry size. It was also shown that in the warmer inland regions of South Africa, water deficits during the early stages of berry development reduced berry size (Myburgh, 2006). Grapevine water status could also have an effect on berry growth during the period véraison to maturity (Ojeda *et al.*, 2001). However, it was also found that deficit irrigation (50% of full Etc) after véraison had no detrimental effect on berry size of Thompson Seedless grapes (Williams, 2000).

If localities are not considered, deficit irrigation reduced berry size significantly in the sandy as well as the heavier soils during the 2006/07 season (Fig. 4.14). However, during the 2007/08 season water deficits did not reduced berry size in the sandy loam soils (Fig. 4.15). The bigger berries produced by deficit irrigation in P5 compared to P6 in the 2007/08 season probably contributed to the lack of difference between the two irrigation strategies in the heavier soils.

At Kapel, berry mass obtained by deficit irrigation in the sandy soil (P1) and in the sandy loam soil (P3) were comparable during the 2006/07 season. From bud break to flowering Ψ_M in these two plots were comparable, but from flowering to véraison Ψ_M was considerably lower in P3 than in P1 (Table 3.12). The Ψ_M values in the sandy loam soil were comparable to the values obtained for the onset of water stress, i.e. of -0.064 MPa for Colombar grapes and -0.065 MPa for container-grown White Riesling grapevines (Myburgh, 2003 and references therein). This suggested that grapevines in the heavier sandy loam soils should be subjected to lower Ψ_M values to reduce berry mass to the same extent as in the sandy soils where Ψ_M was considerably higher.

Berry mass only correlated weakly with the number of bunches per grapevine ($R^2 = 0.3542$; se = 0.2; $p < 0.001$). Due to an incorrect mechanical counter, the bunch number determined in P9 during the 2006/07 season was considered to be incorrect and regarded as an outlier value. If the data for P9 is omitted from the regression equation, 55% of the variation in berry mass could be explained by the number of bunches per grapevine. This suggested that berry mass was to some extent reduced by a competition effect as the number of bunch per grapevine increased.

Similar to berry mass, bunch mass varied considerably between the plots (Table 4.5 & Table 4.6). Deficit irrigation in the sandy soil at Kapel (P1) also resulted in the smallest bunches (ca. 58 g) which was considerably smaller compared to 154 g per bunch for Cabernet Sauvignon bunches determined over a 10 year period in

Stellenbosch, Robertson and Lutzville (Archer & Hunter, 2000 and references therein). The biggest bunches weighted approximately 190 g. Smaller berries reflected in smaller bunch masses (R^2 = 0.5062, se = 23.2; p < 0.001). Bunch mass also increased as the number of berries per bunch increased (R^2 = 0.6560, se = 20.5; p < 0.001). Deficit irrigated grapevines in sandy soils tended to have less berries per bunch compared to the normal irrigated ones (Fig. 4.16). This trend was not so obvious in the heavier sandy loam soils (Fig. 4.17). This suggested that deficit irrigated grapevines in the sandy soils probably experienced early water deficits which could have reduced berry set (Van der Westhuizen, 1972). According to Hardie and Considine (1976) fresh fruit yield losses were the highest when water deficits were applied during the first three weeks after flowering and were primarily attributed to reduced fruit set. However, reduced fertility could also have been caused by other factors such as atmospheric conditions during differentiation of the inflorescences and floral meristems as well as the grapevine clone (Carey et al., 2008; Deloire, 2009). In a study with Cabernet Sauvignon grapevines in a sandy loam soil in Chile, berry size and number of berries per bunch were higher where no water deficits was applied (100% Etc), resulting in higher yields (Ferreyra *et al.*, 2004). Yield was primarily reduced when no water was applied from budburst to véraison. In addition to this, floral induction was affected by water stress in the following growing season.

Yield increased linearly as the bunch mass increased (Fig. 4.18). Consequently, the differences in bunch mass contributed to the yield variation between plots (Table 4.5, Table 4.6 & Fig. 4.19). In most plots, yields were comparable to values summarized for Cabernet Sauvignon by Archer & Hunter (2000), but grapevines in P5, P11 and P12 produced considerably more grapes. Deficit irrigation reduced mean yield, expressed as kilogram per spur, of grapevines in the sandy soils by 29% and 33% during the 2006/07 and 2007/08 seasons, respectively, compared to the normal irrigated ones (Fig. 4.20). Yield of grapevines in the heavier soils were 15% lower during both seasons (Fig. 4.21). The foregoing indicated that reproductive growth of grapevines in the sandy soils was more sensitive to water deficits compared to the ones in the heavier soils (Fig. 4.22). Furthermore, grapevine yield in sandy soils tended to be lower compared to the ones in the sandy loam soils (Fig.4.22). During the 2006/07 season the yield reduction of grapevines in the sandy soils was induced by applying ca. 50% and 66% less water from flowering to véraison and from véraison to harvest, respectively (Table 3.11). During the 2007/08 season ca. 40% and 72% less water was applied during the two respective periods. During the 2006/07 season the yield reduction of grapevines in the sandy loam soils was induced by applying ca. 83% and 96% less water from flowering to véraison and from véraison to harvest, respectively. During the 2007/08 season ca. 83% and 88% less water was applied during the two respective periods. Similarly, yields in Saint-Emilion vineyards located in France were affected by soil type via water regulation to the grapevine (Van Leeuwen *et al.*, 2004). In the sandy soils in Bordeaux the presence of a water table could have supplied water to grapevine roots. Consequently, the grapevines did not experience water deficits, even in a dry season.

According to European standards, grapevines in this study in the Lower Olifants River region did not have the optimal CELAP to kilogram of grape ratio of 0.8 to 1.2, which indicate balanced grapevines, in any of the plots (A. Deloire, Personal communication, 2009). It should be noted that the CELAP to kilogram of grape ratio is only one of the physiological indicators that could be used to estimate the balance of a grapevine. Furthermore, the CELAP to kilogram of grape ratio does not consider the ratio between the primary and secondary shoots of a grapevine. Deficit irrigation tended to increase the CELAP to kilogram of grape ratio, irrespective of soil texture (Fig. 4.23). The only exception was P5 and P6 with a seemingly inverse reaction. However, it appeared that by inducing moderate water deficits, the balance between vegetative and reproductive growth in grapevines could be improved. A possible option to improve grapevine balance would be to physically reduce bunches to one bunch per primary shoot.

4.4   CONCLUSIONS

Vegetative growth of normal irrigated grapevines, as quantified by the pruning mass, was approximately 60% lower in sandy soils compared to the heavier sandy loam soils. Deficit irrigation reduced vegetative growth in sandy soils by ca. 30% compared to little or no growth reduction in sandy loam soils. However, there were indications that severe water deficits in sandy soils could be detrimental to grapevine canopy quality. Deficit irrigation could improve the canopy quality of grapevines in sandy loam soils, i.e. the canopy score and CELAP value, but the latter was limited in terms of canopy height. In order to achieve more balanced grapevines in the Lower Olifants River region, alternative trellis systems which allow higher canopies should be a considered. Since grapevines in the sandy loam soils tended to have too dense canopies, nitrogen fertilizer should be applied judicially. The possibility to adapt grapevine balance standards for South African conditions, particularly for the Lower Olifants River region, should be investigated.

Deficit irrigation tended to reduced berry size, irrespective of soil texture. Deficit irrigation that was applied to grapevines in the sandy soils too early, i.e. during flowering, seemed to decrease the number of berries per bunch. Some of the variation in yield could be related to the variation in bunch mass. Deficit irrigation reduced yield of grapevines in the sandy soils by ca. 30%, whereas yield of grapevines in the heavier soils was only ca. 15% lower. Hence, deficit irrigation could be a means of decreasing berries size in sandy loam soils without effecting yield too much and at same time have the beneficial effect of smaller berries on wine quality.

Although distinct climatic zones exist in the Lower Olifants River region, there seemed to be no definite climatic effect on vegetative growth and yield of Cabernet Sauvignon grapevines. The main driver for differences in vegetative growth and yield seemed to be the difference in soil texture which, in turn, played an important role in the regulation of water supply to the grapevine. Since water deficits affected vegetative and

reproductive growth of grapevines in sandy soils, it could be use as a tool to manipulate the grapevine. On the other hand, intensive canopy management practices would also play an important role to improve wine quality in Cabernet Sauvignon grapevines in the sandy loam soils. The first step would be to manipulate the canopy by irrigation. Before applying addtional intensive canopy management practices, such as leaf removal or removal of laterals to improve canopy quality, costing should be carried out to establish if the additional practices would be economically viable in terms of improved wine quality.

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Table 4.1 Canopy characteristics in 16 plots representing different localities, soil texture and irrigation strategies in Cabernet Sauvignon vineyards as determined at harvest during the 2006/07 season in the Lower Olifants River region.

Plot no[1]	Locality	Soil texture	Irrigation strategy	Canopy dimensions		Canopy external leaf area perimeter (linear meter)	Canopy gaps (%)	Leaf layer number	Shaded leaves (%)	Shaded bunches (%)	Canopy score (%)
				Height (m)	Width (m)						
P1	Kapel	Sand	Deficit irrigation	0.81	0.32	1.06	10	1.3	10.8	25.0	71.4
P2			Normal	0.96	0.39	1.26	0	1.9	22.1	50.0	84.3
P3		Sandy loam	Deficit irrigation	1.30	0.46	1.70	0	2.2	27.9	56.8	81.4
P4			Normal	1.23	0.55	1.67	0	2.4	32.8	64.6	78.6
P5	Vredendal	Sandy loam	Deficit irrigation	0.75	0.90	1.32	0	2.4	31.2	65.0	72.9
P6			Normal	0.68	0.94	1.26	2	2.7	35.0	65.2	72.9
P7		Sand	Deficit irrigation	0.59	0.30	0.89	2	1.8	18.5	46.7	68.6
P8			Normal	0.80	0.35	1.17	2	2.6	30.0	75.0	81.4
P9	Lutzville	Sand	Deficit irrigation	0.87	0.37	1.27	6	1.5	13.2	22.2	68.6
P10			Normal	1.14	0.34	1.57	6	1.7	16.5	40.6	75.7
P11		Loamy sand	Deficit irrigation	1.04	0.52	1.56	0	2.3	30.0	45.2	84.3
P12			Normal	0.98	0.51	1.48	0	2.2	29.7	43.3	74.3
P13	Koekenaap	Sand	Deficit irrigation	0.87	0.43	1.18	6	1.8	23.1	40.7	64.3
P14			Normal	0.95	0.59	1.36	2	2.3	26.6	60.9	77.1
P15		Sandy loam	Deficit irrigation	0.96	0.32	1.34	2	2.2	24.3	47.4	87.1
P16			Normal	0.97	0.37	1.39	0	2.2	29.1	30.4	87.1

[1] Refer to Table 3.1 for description of the plots

Table 4.2 Canopy characteristics in 16 plots representing different localities, soil texture and irrigation strategies in Cabernet Sauvignon vineyards as determined at harvest during the 2007/08 season in the Lower Olifants River region.

Plot no[1]	Locality	Soil texture	Irrigation strategy	Canopy dimensions		Canopy external leaf area perimeter (linear meter)	Canopy gaps (%)	Leaf layer number	Shaded leaves (%)	Shaded bunches (%)	Canopy score (%)
				Height (m)	Width (m)						
P1	Kapel	Sand	Deficit irrigation	0.88	0.30	1.13	0	2.1	18.1	50.0	91.4
P2			Normal	0.92	0.44	1.25	0	2.3	24.4	67.6	95.7
P3		Sandy loam	Deficit irrigation	1.16	0.54	1.59	0	2.6	31.3	65.2	81.4
P4			Normal	1.15	0.61	1.62	4	2.3	30.1	46.7	78.6
P5	Vredendal	Sandy loam	Deficit irrigation	0.82	0.69	1.28	0	3.1	41.2	64.3	65.7
P6			Normal	0.74	0.97	1.34	0	3.1	40.8	81.8	57.1
P7		Sand	Deficit irrigation	0.69	0.36	1.04	4	1.8	18.7	45.8	67.1
P8			Normal	0.82	0.39	1.22	2	1.9	24.7	34.5	84.3
P9	Lutzville	Sand	Deficit irrigation	0.98	0.35	1.39	2	1.8	14.6	50.0	87.1
P10			Normal	0.97	0.40	1.40	0	1.8	17.4	46.9	84.3
P11		Loamy sand	Deficit irrigation	1.06	0.44	1.54	2	2.2	27.8	51.4	80.0
P12			Normal	0.97	0.45	1.43	0	2.3	28.1	48.3	80.0
P13	Koekenaap	Sand	Deficit irrigation	0.99	0.44	1.32	6	1.8	22.8	42.1	80.0
P14			Normal	1.08	0.50	1.45	0	2.7	33.3	71.4	84.3
P15		Sandy loam	Deficit irrigation	0.92	0.41	1.35	2	2.2	25.5	50.0	78.6
P16			Normal	0.93	0.37	1.34	0	2.1	21.4	44.8	87.1

[1] Refer to Table 3.1 for description of the plots.

Table 4.3 Cane characteristics in 16 plots representing different localities, soil texture and irrigation strategies in Cabernet Sauvignon vineyards as determined during the 2006/07 season in the Lower Olifants River region.

Plot no[1]	Locality	Soil texture	Irrigation strategy	Budding percentage (%)	Cane length (m)	Internode length (mm)	Number of lateral shoots per cane	Laterals length (mm)	Cane diameter (mm)
P1	Kapel	Sand	Deficit irrigation	83.9	0.7	53.3	2	24.3	6.1
P2			Normal	83.0	0.8	60.3	5	27.4	7.0
P3		Sandy loam	Deficit irrigation	77.6	1.1	61.1	4	167.4	7.6
P4			Normal	84.3	1.3	59.7	4	115.5	7.6
P5	Vredendal	Sandy loam	Deficit irrigation	83.3	0.9	61.2	4	65.6	7.9
P6			Normal	82.0	1.2	55.5	2	52.8	7.6
P7		Sand	Deficit irrigation	84.2	0.3	41.5	0	/	4.6
P8			Normal	82.6	0.3	47.5	2	195.4	5.8
P9	Lutzville	Sand	Deficit irrigation	82.9	0.8	49.5	2	43.1	6.0
P10			Normal	81.7	0.8	50.4	4	101.9	6.6
P11		Loamy sand	Deficit irrigation	87.0	1.0	56.4	4	228.6	8.2
P12			Normal	84.8	1.0	59.5	5	146.6	8.3
P13	Koekenaap	Sand	Deficit irrigation	82.4	0.6	52.5	3	32.3	7.1
P14			Normal	87.5	0.8	52.6	5	69.9	7.5
P15		Sandy loam	Deficit irrigation	90.1	1.3	54.2	4	60.0	7.0
P16			Normal	91.9	1.5	55.0	5	34.3	6.9

[1] Refer to Table 3.1 for description of the plots.

Table 4.4 Cane characteristics in 16 plots representing different localities, soil texture and irrigation strategies in Cabernet Sauvignon vineyards as determined during the 2007/08 season in the Lower Olifants River region.

Plot no[1]	Locality	Soil form	Irrigation strategy	Budding percentage (%)	Cane length (m)	Internode length (mm)	Number of lateral shoots per cane	Laterals length (mm)	Cane diameter (mm)
P1	Kapel	Sand	Deficit irrigation	88.6	0.7	46.4	1	11.3	5.7
P2			Normal	87.1	1.1	47.2	2	41.0	6.5
P3		Sandy loam	Deficit irrigation	82.3	1.2	58.2	2	139.3	7.1
P4			Normal	76.9	1.1	55.5	2	78.6	7.1
P5	Vredendal	Sandy loam	Deficit irrigation	85.0	1.6	56.3	3	142.0	7.4
P6			Normal	84.4	2.0	57.3	2	141.5	7.4
P7		Sand	Deficit irrigation	91.7	0.4	38.6	2	14.8	5.1
P8			Normal	83.9	0.6	41.7	2	119.3	5.9
P9	Lutzville	Sand	Deficit irrigation	84.4	0.8	46.3	3	93.9	6.3
P10			Normal	88.1	1.3	45.2	1	42.4	6.8
P11		Loamy sand	Deficit irrigation	86.7	1.1	58.2	5	204.9	8.8
P12			Normal	85.1	1.2	58.6	4	192.4	8.0
P13	Koekenaap	Sand	Deficit irrigation	91.0	0.9	49.8	4	44.1	7.4
P14			Normal	91.4	0.6	51.6	3	162.7	7.3
P15		Sandy loam	Deficit irrigation	88.4	[2]	[2]	[2]	[2]	[2]
P16			Normal	86.0	[2]	[2]	[2]	[2]	[2]

[1] Refer to Table 3.1 for description of the plots.

[2] Vineyards were pre-pruned before measurements could have been taken.

Table 4.5 Yield and its components as determined for Cabernet Sauvignon in 16 plots representing different localities, soil texture and irrigation strategies in the Lower Olifants River region during the 2006/07 season.

Plot no[1]	Locality	Soil texture	Irrigation strategy	Berry mass	Number of bunches		Bunch mass	Yield	
				(g)	(per grapevine)	(per meter)	(g)	(kg per grapevine)	(kg per meter)
P1	Kapel	Sand	Deficit irrigation	0.82	50.6	33.7	58.89	3.04	2.03
P2			Normal	0.93	55.9	37.0	84.62	4.81	3.19
P3		Sandy loam	Deficit irrigation	0.84	46.4	31.6	89.87	4.26	2.90
P4			Normal	1.01	45.2	31.0	105.86	4.89	3.35
P5	Vredendal	Sandy loam	Deficit irrigation	1.32	37.0	30.6	168.23	6.22	5.14
P6			Normal	1.38	31.9	26.1	163.64	5.22	4.28
P7		Sand	Deficit irrigation	1.15	44.0	29.9	94.79	4.17	2.84
P8			Normal	1.24	44.9	31.0	115.21	5.18	3.57
P9	Lutzville	Sand	Deficit irrigation	0.98	23.1	15.3	81.78	2.30	1.52
P10			Normal	1.11	34.7	24.8	123.05	4.58	3.27
P11		Loamy sand	Deficit irrigation	1.17	37.8	25.9	183.17	7.34	5.03
P12			Normal	1.37	34.1	23.9	195.61	7.66	5.35
P13	Koekenaap	Sand	Deficit irrigation	1.52	29.5	20.5	133.76	4.17	2.89
P14			Normal	1.53	30.8	21.8	138.62	4.55	3.23
P15		Sandy loam	Deficit irrigation	1.34	31.3	20.0	131.98	4.43	2.84
P16			Normal	1.47	33.7	23.4	159.57	5.74	3.99

[1] Refer to Table 3.1 for description of the plots.

Table 4.6 Yield and its components as determined for Cabernet Sauvignon in 16 plots representing different localities, soil texture and irrigation strategies in the Lower Olifants River region during the 2007/08 season.

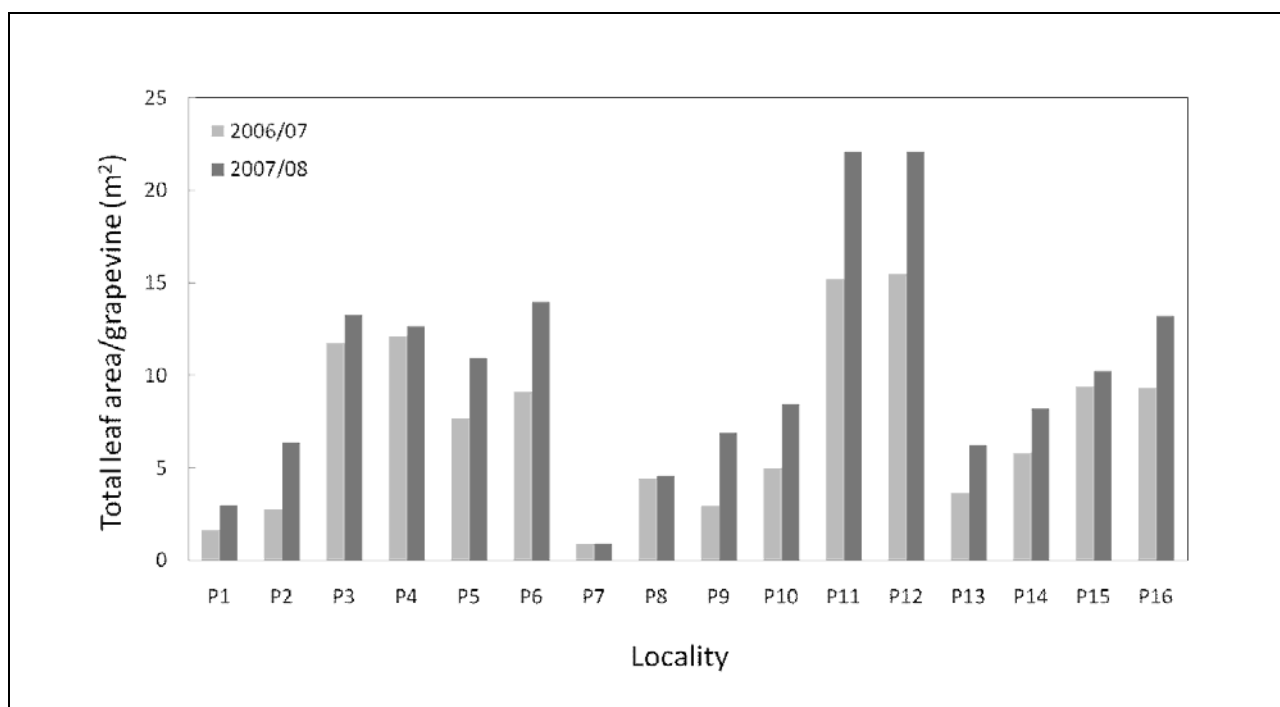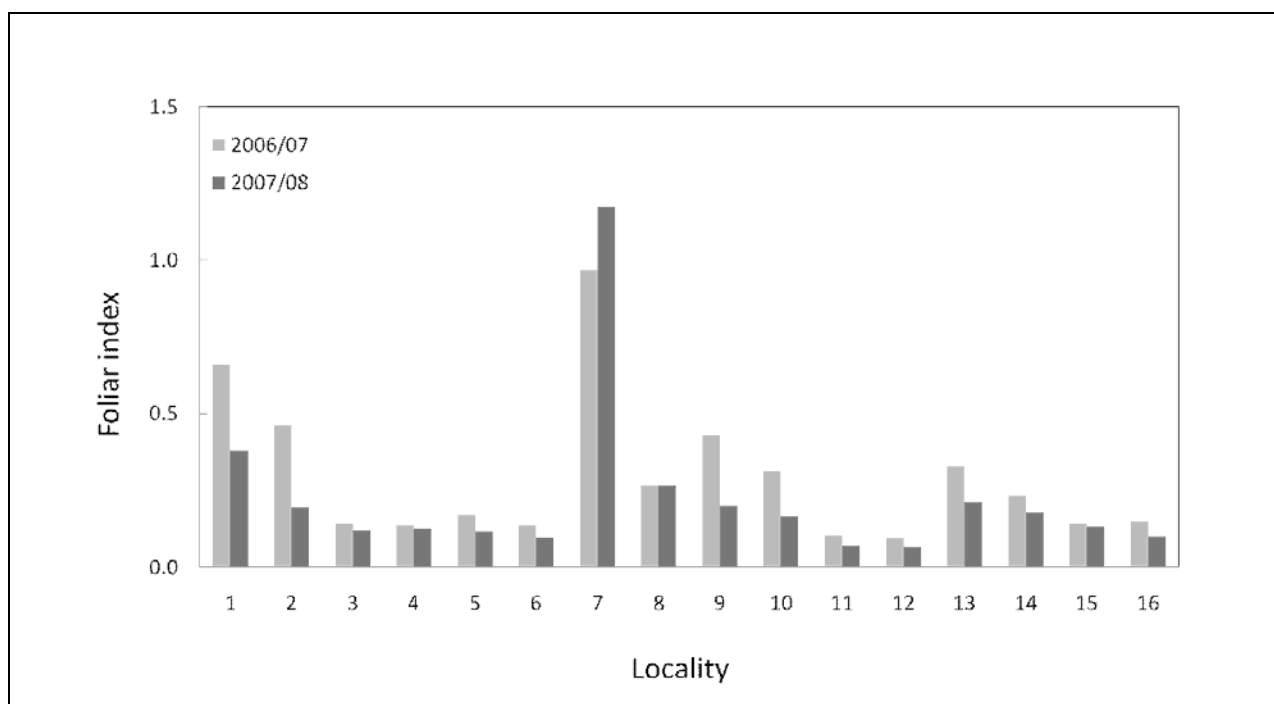| Plot no[1]	Locality	Soil texture	Irrigation strategy	Berry mass	Number of bunches		Bunch mass	Yield	
				(g)	(per grapevine)	(per meter)	(g)	(kg per grapevine)	(kg per meter)
P1	Kapel	Sand	Deficit irrigation	0.78	42.6	28.4	57.34	2.54	1.69
P2			Normal	1.03	49.0	32.5	90.35	4.67	3.10
P3		Sandy loam	Deficit irrigation	0.95	35.1	23.9	120.90	4.44	3.02
P4			Normal	1.02	42.1	28.8	117.42	5.23	3.59
P5	Vredendal	Sandy loam	Deficit irrigation	1.45	34.4	28.4	133.17	5.03	4.15
P6			Normal	1.39	32.0	26.2	135.94	4.80	3.94
P7		Sand	Deficit irrigation	0.90	44.8	30.4	62.01	3.01	2.05
P8			Normal	1.12	42.6	29.4	121.51	5.58	3.85
P9	Lutzville	Sand	Deficit irrigation	1.05	42.8	28.3	86.16	3.93	2.61
P10			Normal	1.33	45.6	32.6	107.68	5.22	3.73
P11		Loamy sand	Deficit irrigation	1.29	42.3	29.0	109.25	4.92	3.37
P12			Normal	1.32	35.6	24.9	120.37	4.58	3.21
P13	Koekenaap	Sand	Deficit irrigation	1.25	39.9	27.7	123.80	5.20	3.61
P14			Normal	1.38	37.0	26.2	150.56	5.95	4.22
P15		Sandy loam	Deficit irrigation	1.24	35.4	22.7	108.23	4.07	2.61
P16			Normal	1.40	34.5	23.9	156.20	5.81	4.03

[1] Refer to Table 3.1 for description of the plots.

Figure 4.1 Water stress symptoms, i.e. yellowing of basal leaves, in deficit irrigated Cabernet Sauvignon in a sandy soil at Kapel (P1) in the Lower Olifants River region.

Figure 4.2   water stress symptoms, i.e. yellowing and limited shedding of basal leaves, in deficit irrigated grapevines in a sandy soil at Vredendal (P7) in the Lower Olifants River region.
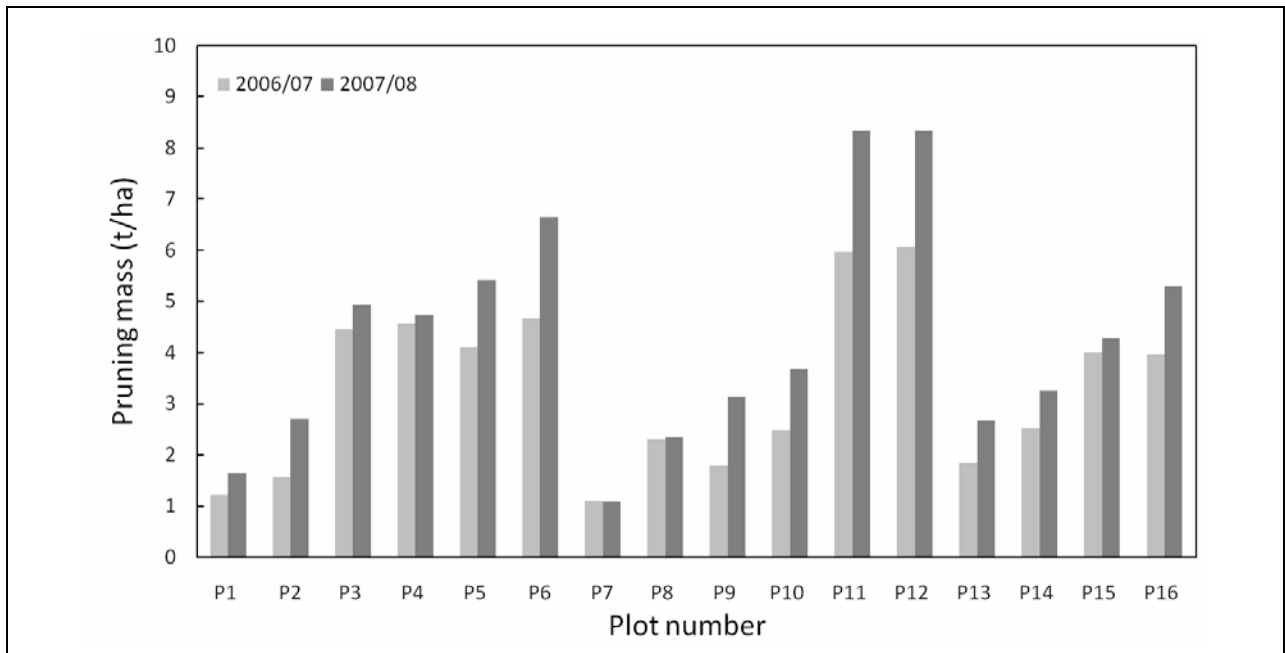
Figure 4.3   The estimated total leaf area per grapevine in 16 Cabernet Sauvignon plots representing different localities, soil texture and irrigation strategies in the Lower Olifants River region where soil and grapevine water status were monitored during the 2006/07 and 2007/08 seasons.


Figure 4.4   The foliar index in 16 Cabernet Sauvignon plots representing different localities, soil texture and irrigation strategies in the Lower Olifants River region where soil and grapevine water status were monitored during the 2006/07 and 2007/08 seasons.
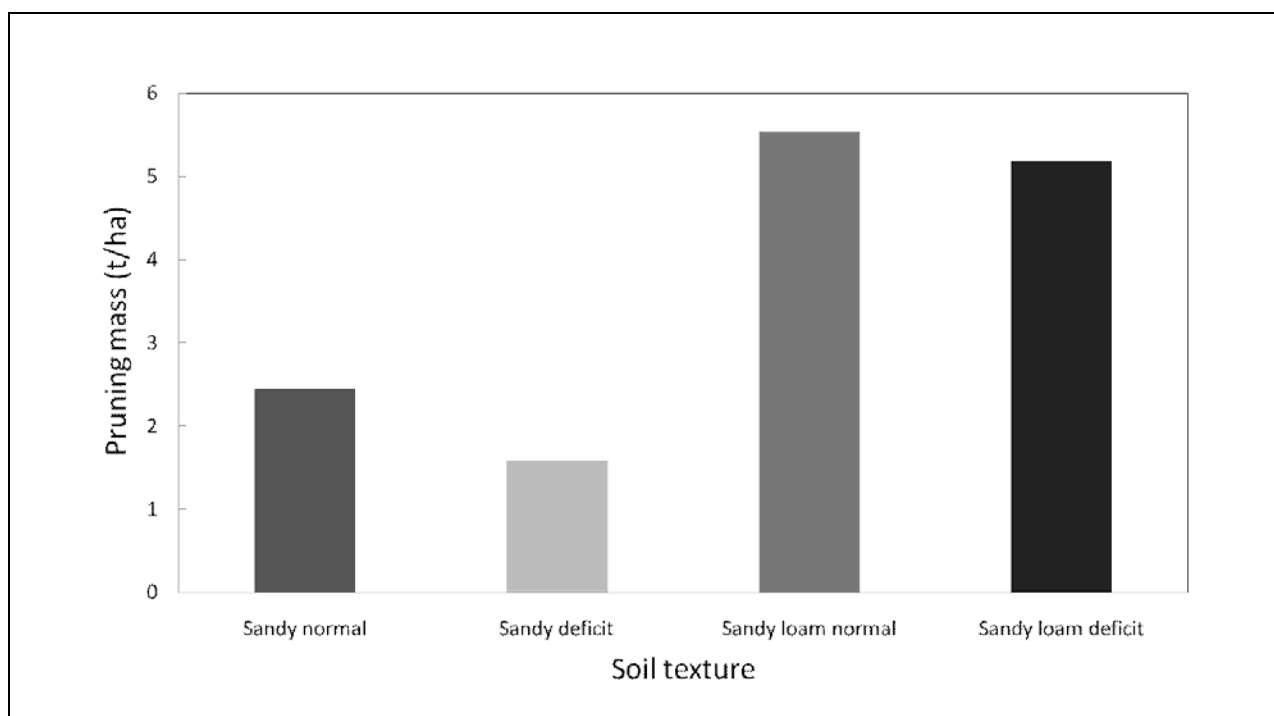
Figure 4.5 Pruning mass in 16 Cabernet Sauvignon plots representing different localities, soil texture and irrigation strategies in the Lower Olifants River region where soil and grapevine water status were monitored during the 2006/07 and 2007/08 seasons.
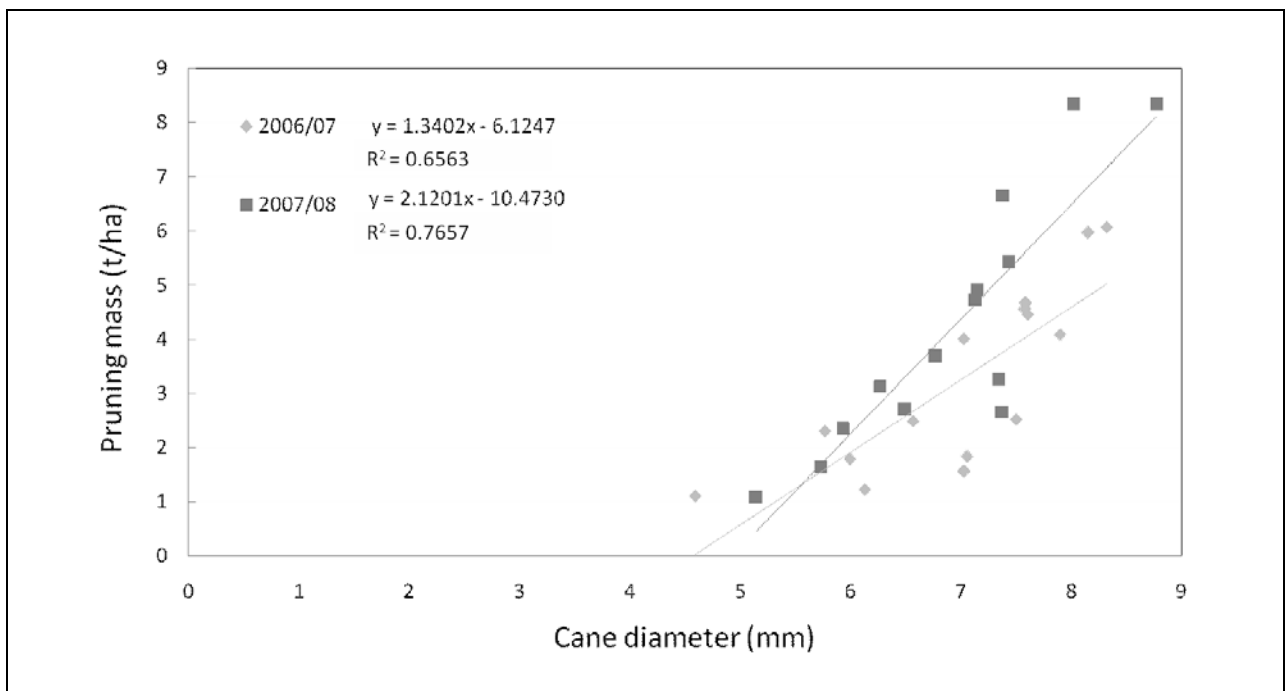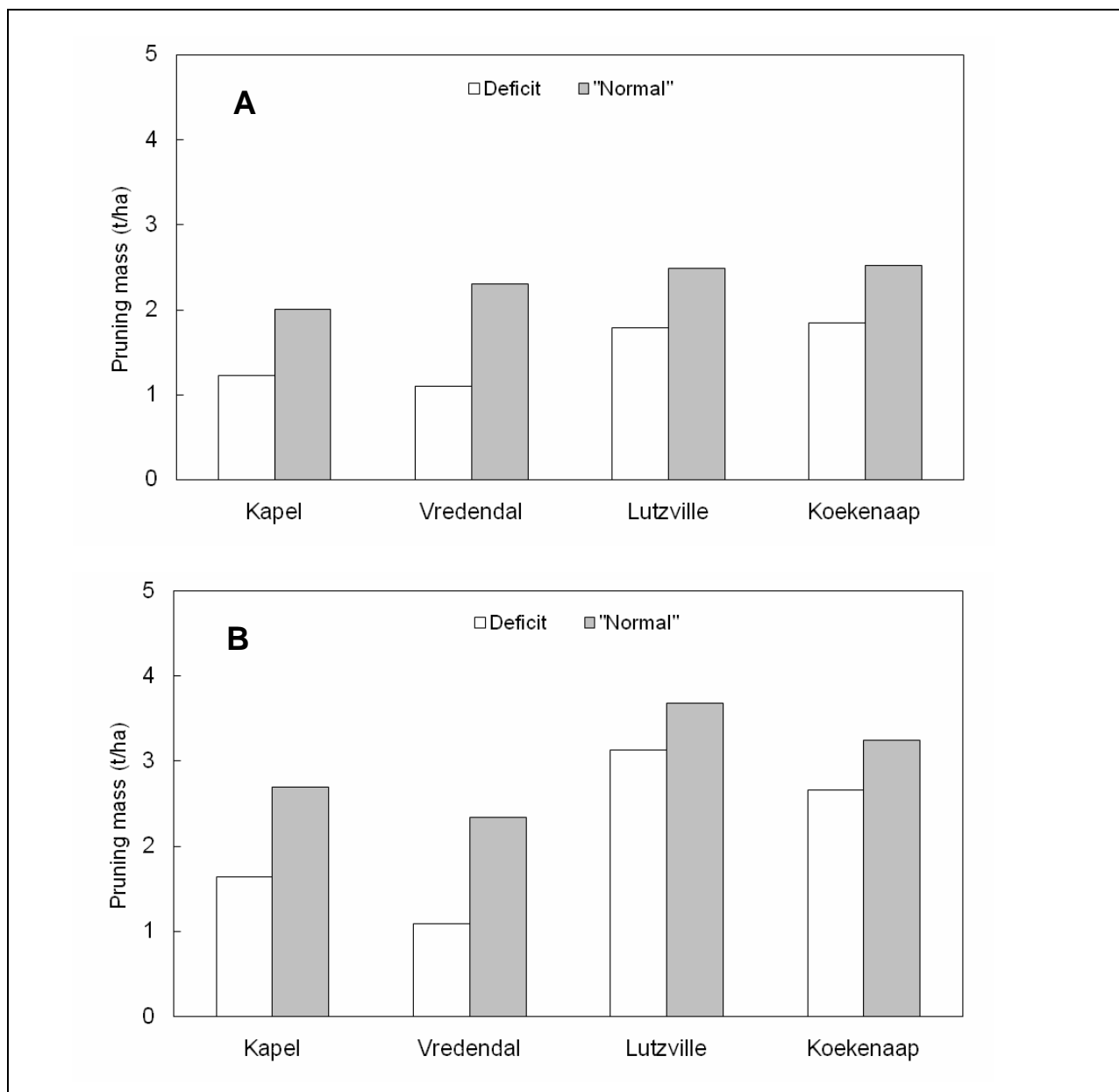

Figure 4.6 The relationship between pruning mass and cane diameter of Cabernet Sauvignon grapevines in the Lower Olifants River region as determined during the 2006/07 and 2007/08 seasons.
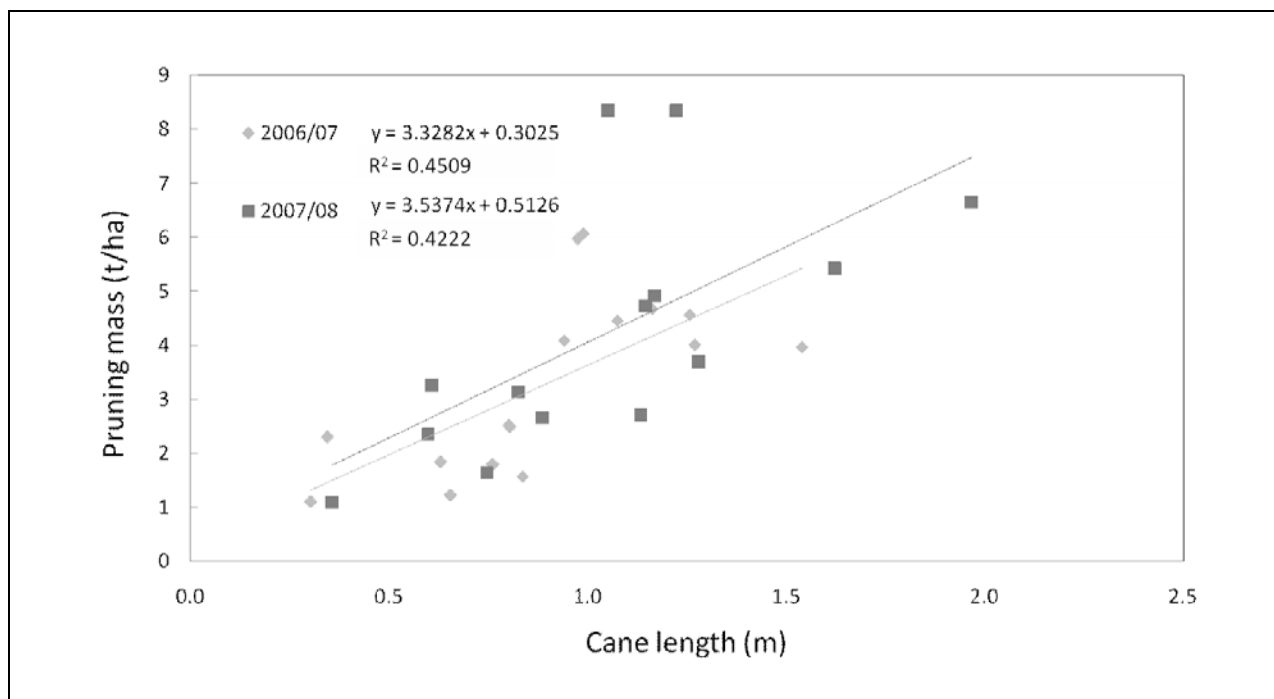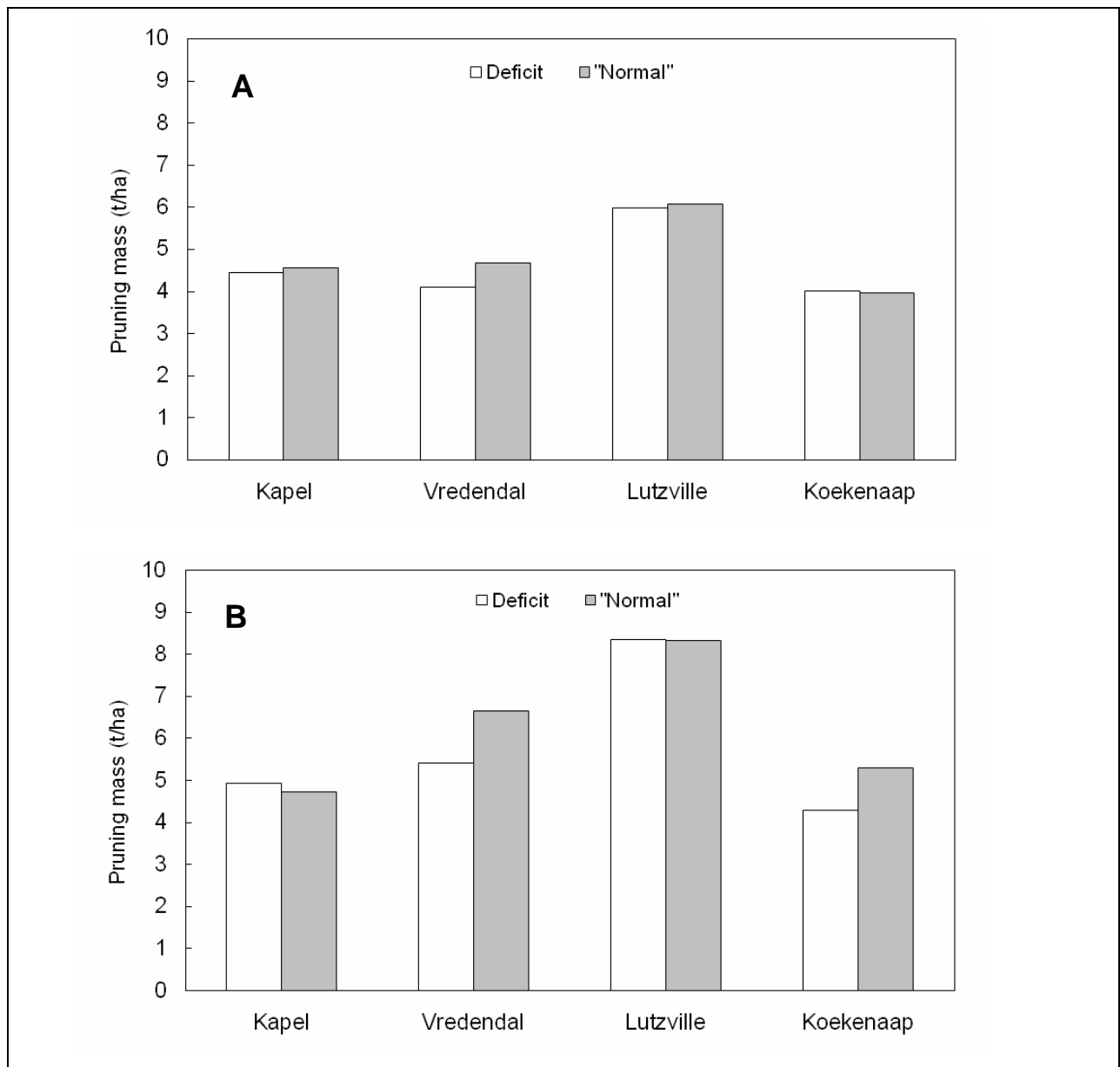
Figure 4.7   The relationship between pruning mass and cane length of Cabernet Sauvignon grapevines in the Lower Olifants River region as determined during the 2006/07 and 2007/08 seasons.
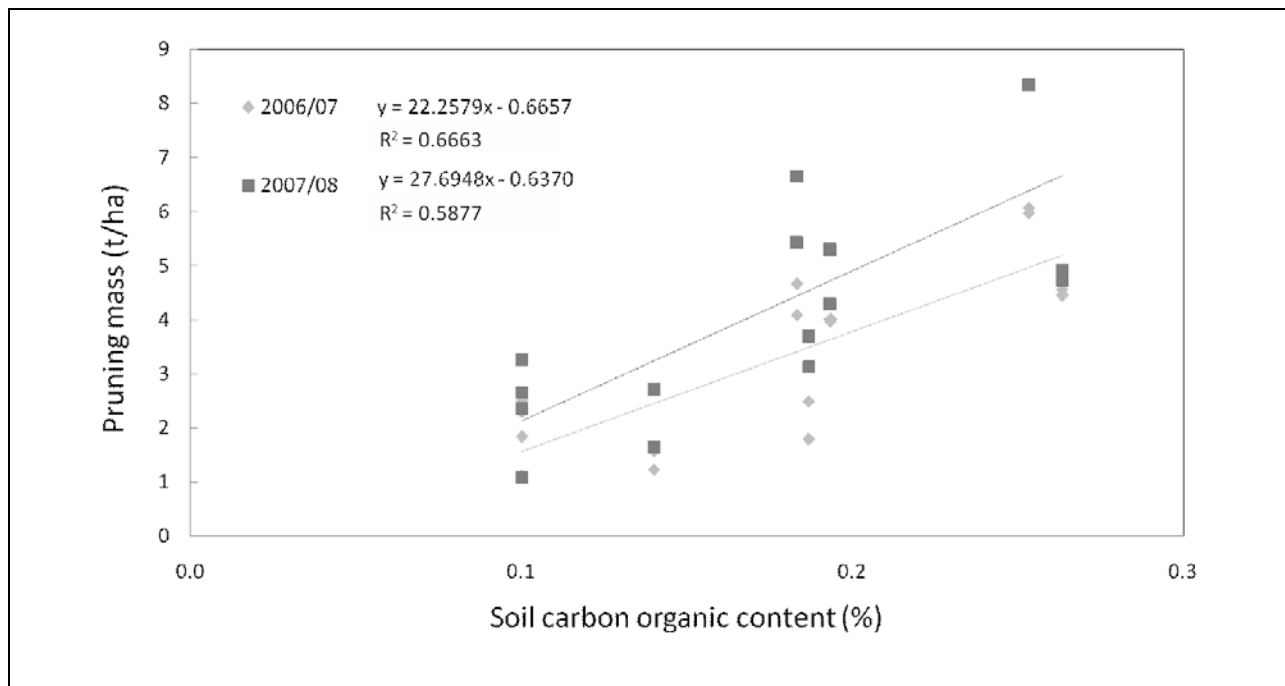

Figure 4.8   Trends in pruning mass of Cabernet Sauvignon in relation to soil texture and irrigation strategy in the Lower Olifants River region during the 2006/07 and 2007/08 seasons.
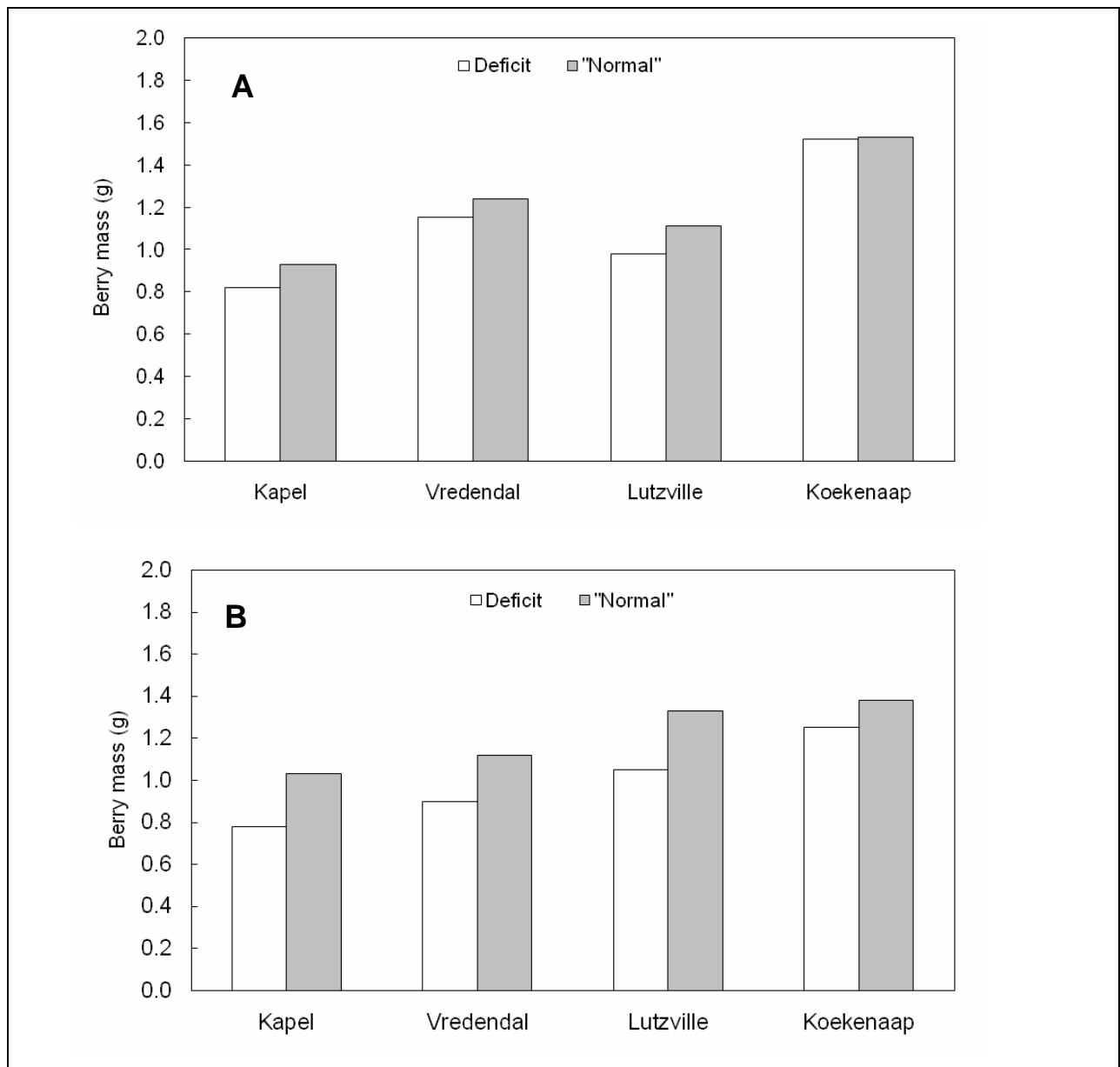
Figure 4.9 Trends in the pruning mass of Cabernet Sauvignon in sandy soils at four localities in relation to deficit and normal irrigation strategies in the Lower Olifants River region as measured during (A) the 2006/07 season and (B) the 2007/08 season.

Figure 4.10 Trends in the pruning mass of Cabernet Sauvignon in sandy loam soils at four localities in relation to deficit and normal irrigation strategies in the Lower Olifants River region as measured during (A) the 2006/07 season and (B) the 2007/08 season.

Figure 4.11 the relationship between the pruning mass of Cabernet Sauvignon grapevines and soil carbon organic content as determined in the Lower Olifants River region during the 2006/07 and 2007/08 seasons.

Figure 4.12 **Trends in the berry mass of Cabernet Sauvignon in sandy soils at four localities in relation to deficit and normal irrigation strategies in the Lower Olifants River region as measured during (A) the 2006/07 season and (B) the 2007/08 season.**
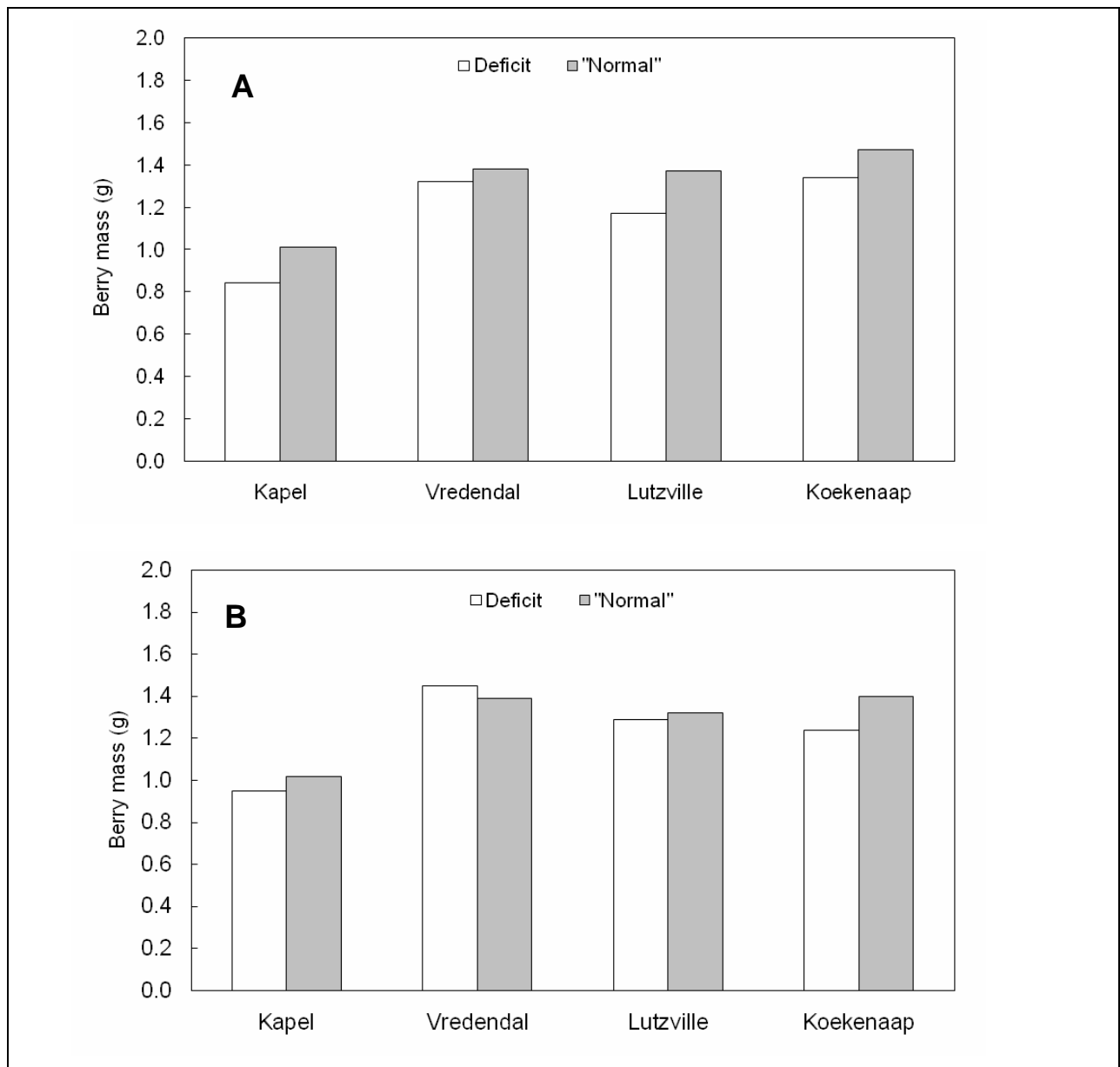
Figure 4.13   Trends in the berry mass of Cabernet Sauvignon in sandy loam soils at four localities in relation to deficit and normal irrigation strategies in the Lower Olifants River region as measured during (A) the 2006/07 season and (B) the 2007/08 season.
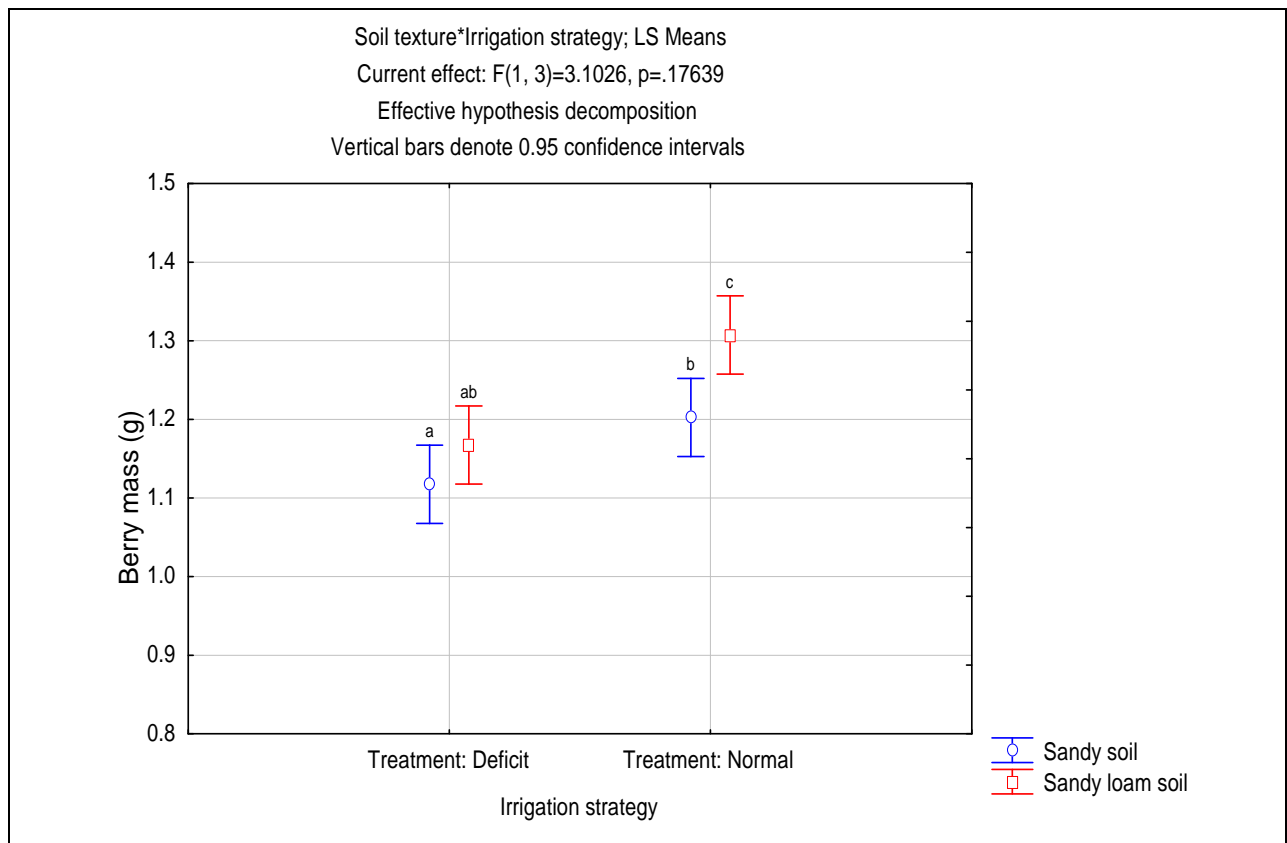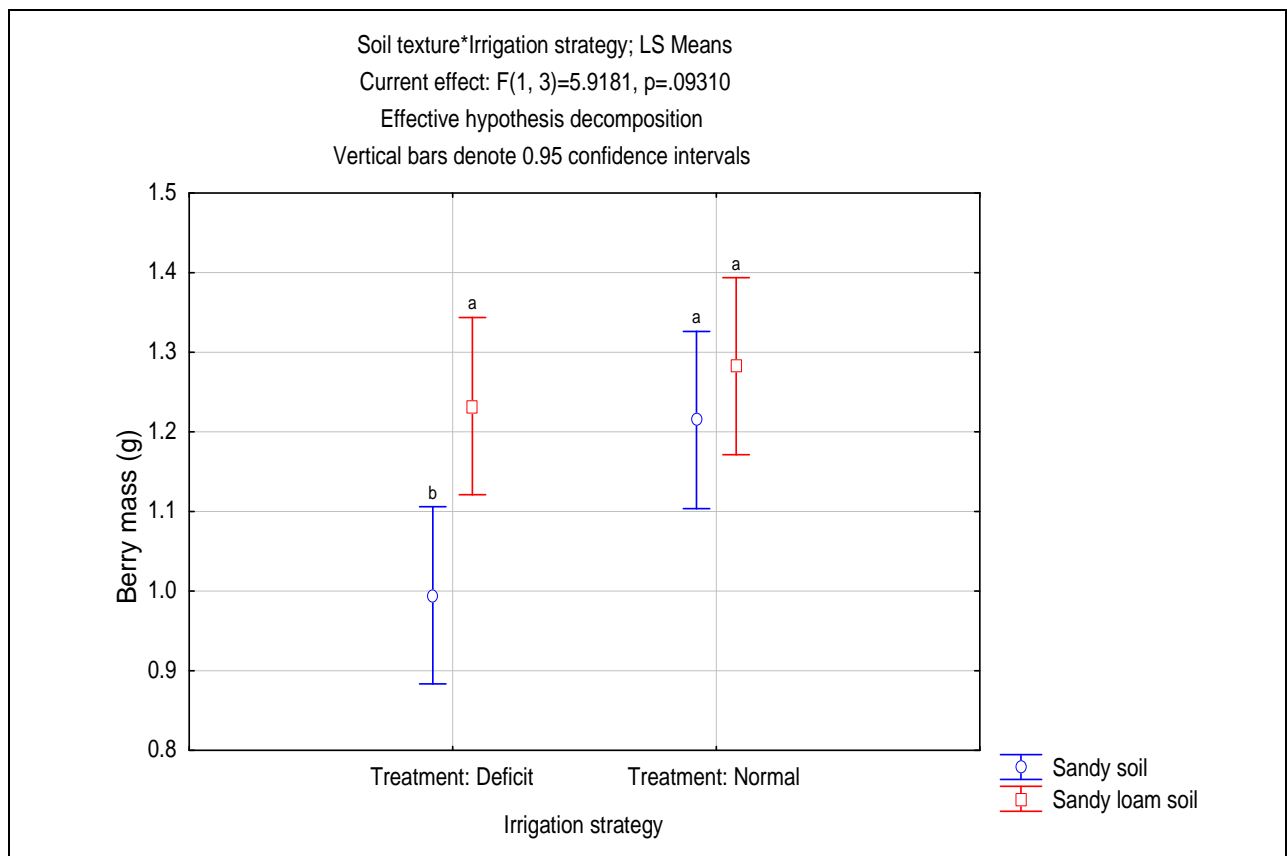
Figure 4.14 The effect of deficit irrigation and soil texture on berry mass of Cabernet Sauvignon in the Lower Olifants River region as measured during the 2006/07 season.

Figure 4.15 The effect of deficit irrigation and soil texture on berry mass of Cabernet Sauvignon in the Lower Olifants River region as measured during the 2007/08 season.

Figure 4.16 Trends in the number of berries per bunch of Cabernet Sauvignon in sandy soils at four localities in relation to deficit and normal irrigation strategies in the Lower Olifants River region as measured during (A) the 2006/07 season and (B) the 2007/08 season.
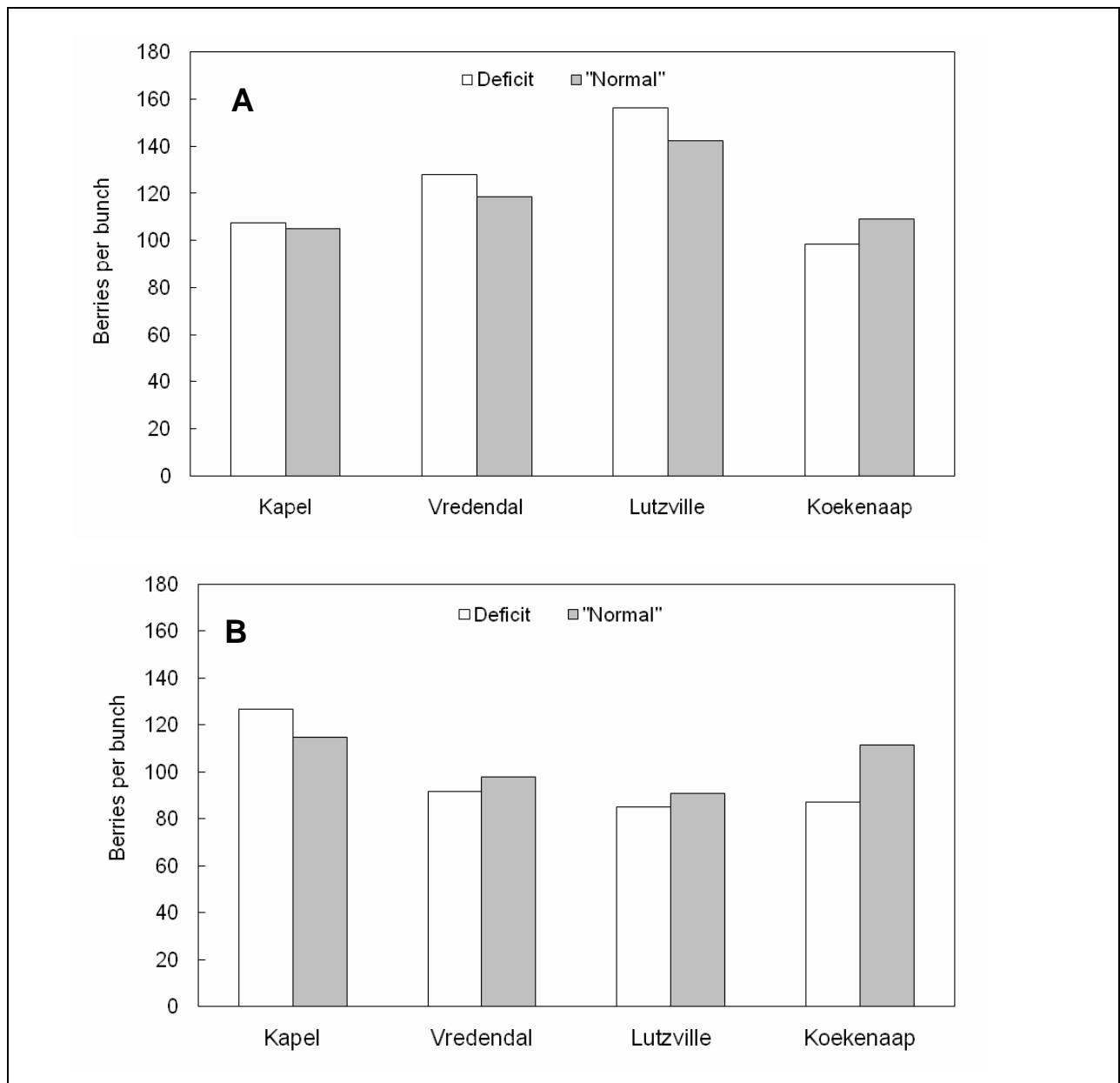
Figure 4.17 Trends in the number of berries per bunch of Cabernet Sauvignon in sandy loam soils at four localities in relation to deficit and normal irrigation strategies in the Lower Olifants River region as measured during (A) the 2006/07 season and (B) the 2007/08 season.
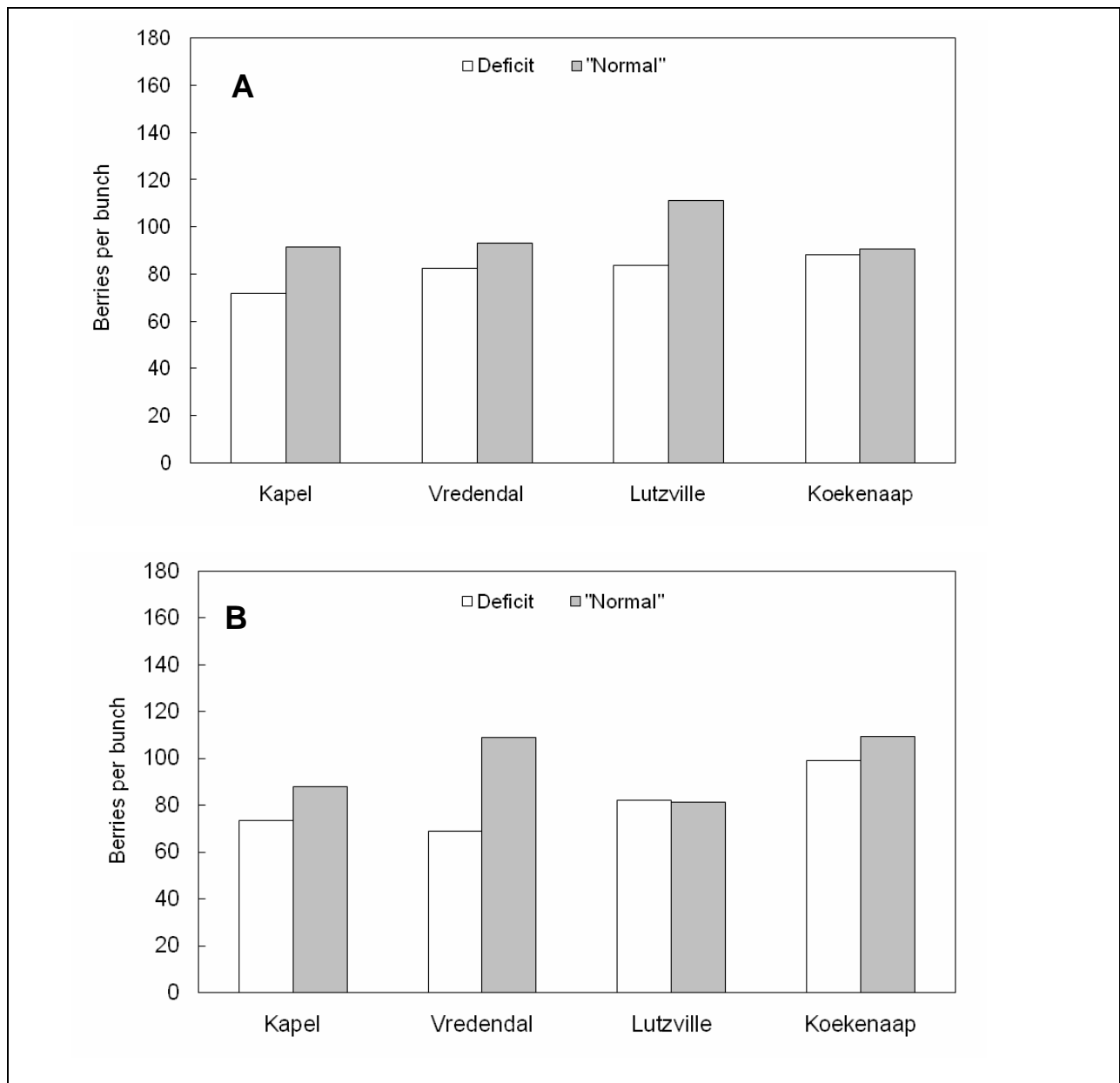
Figure 4.18   The relationship between yield and bunch mass of Cabernet Sauvignon grapevines in the Lower Olifants River region as measured during the 2006/07 and 2007/08 seasons.

Figure 4.19 Yield in 16 Cabernet Sauvignon plots representing different localities, soil texture and irrigation strategies in the Lower Olifants River region where soil and grapevine water status were monitored during the 2006/07 and 2007/08 seasons.

Figure 4.20 Trends in the yield per spur of Cabernet Sauvignon in sandy soils at four localities in relation to deficit and normal irrigation strategies in the Lower Olifants River region as measured during (A) the 2006/07 season and (B) the 2007/08 season.
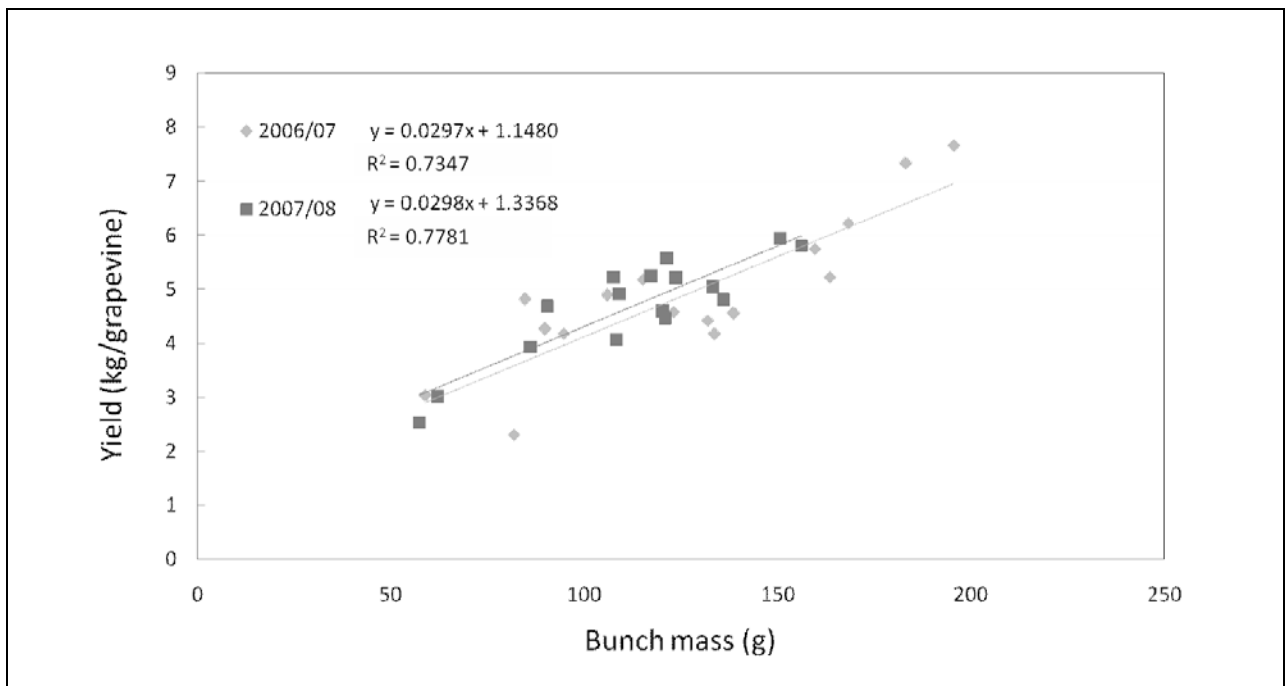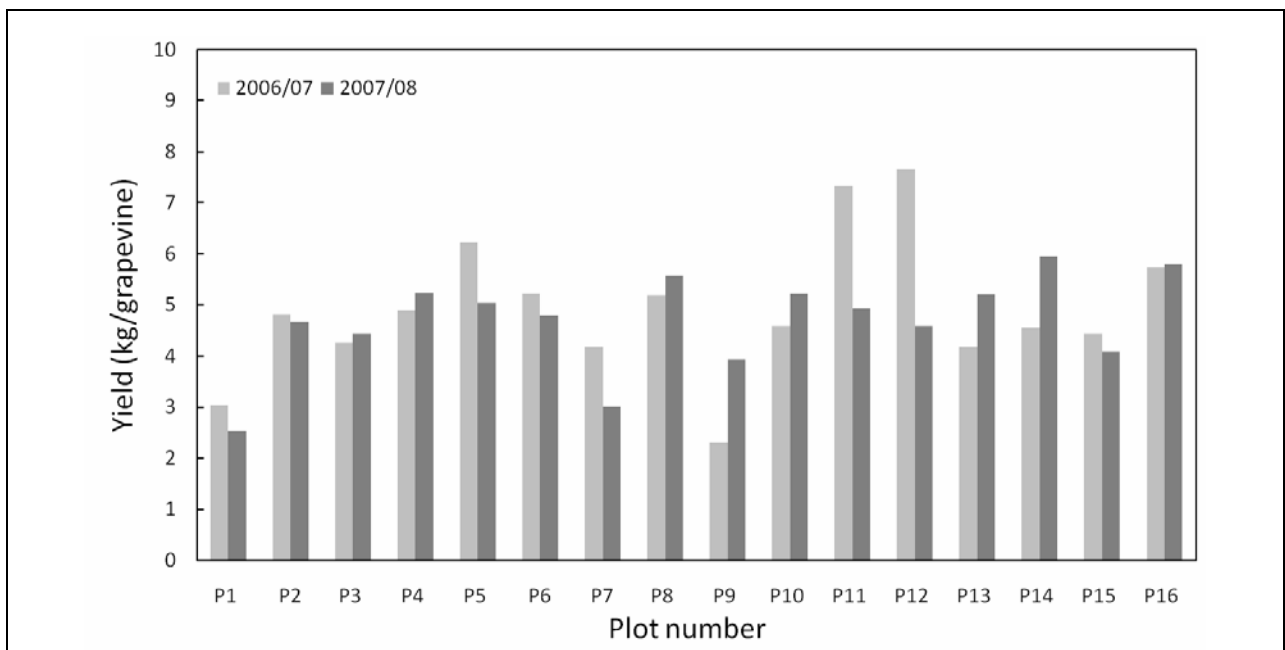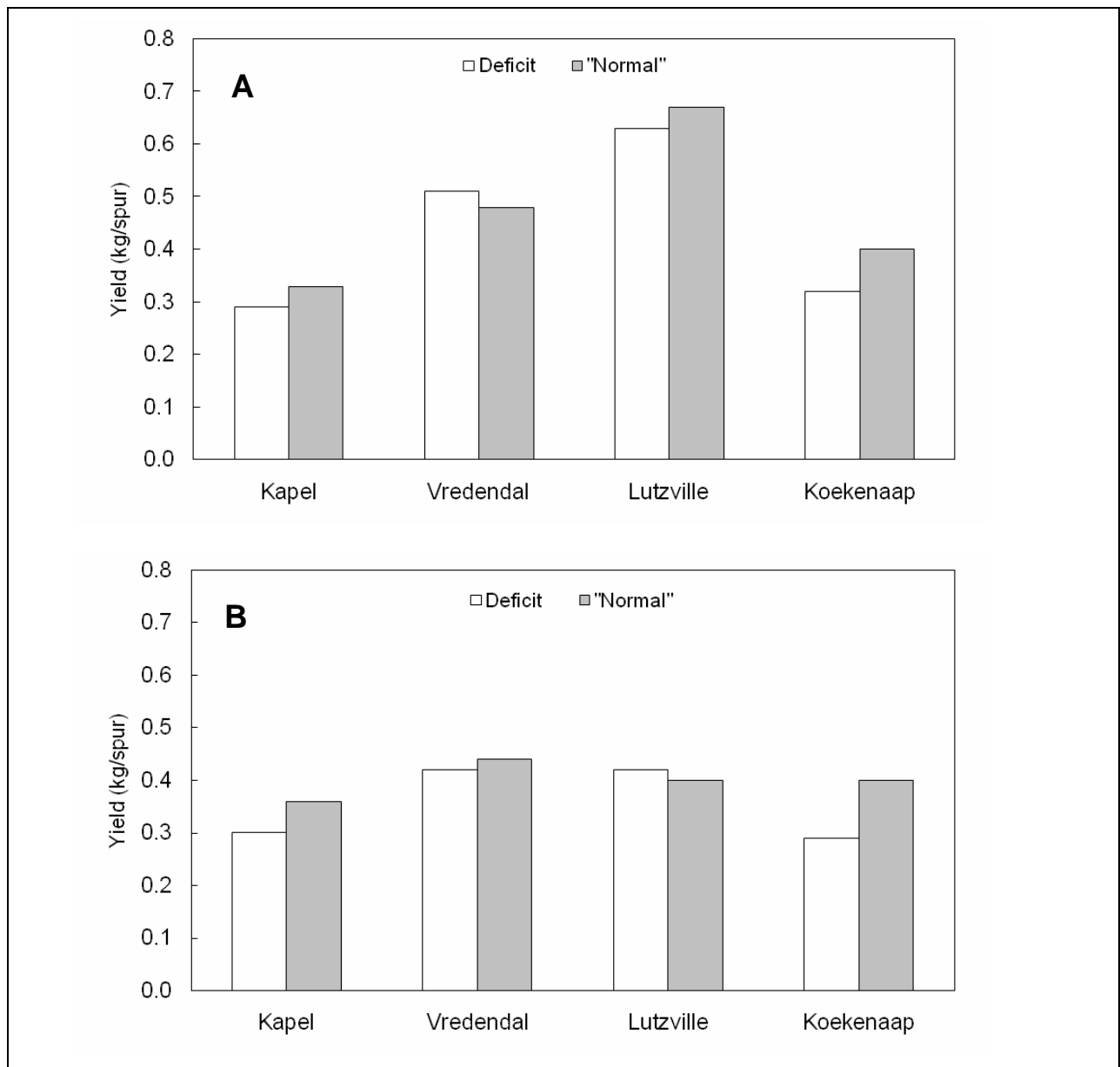
Figure 4.21   Trends in the yield per spur of Cabernet Sauvignon in sandy loam soils at four localities in relation to deficit and normal irrigation strategies in the Lower Olifants River region as measured during (A) the 2006/07 season and (B) the 2007/08 season.
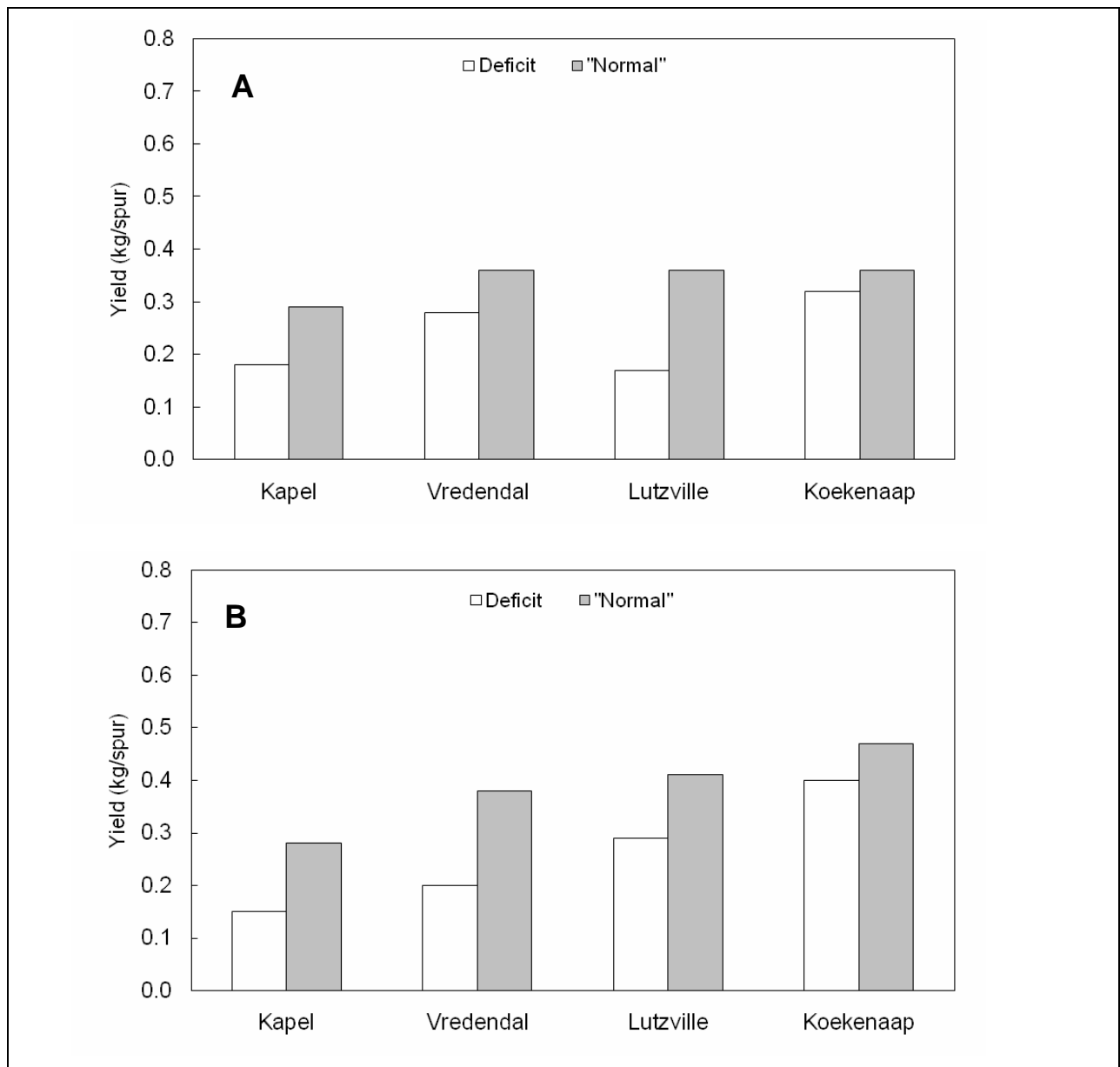
Figure 4.22 Trends in the yield of Cabernet Sauvignon in relation to soil texture and irrigation strategy in the Lower Olifants River region during the 2006/07 and 2007/08 seasons.

Figure 4.23 The CELAP to kilogram of grape ratio in 16 Cabernet Sauvignon plots representing different localities, soil texture and irrigation strategies in the Lower Olifants River region where soil and grapevine water status were monitored during the 2006/07 and 2007/08 seasons.
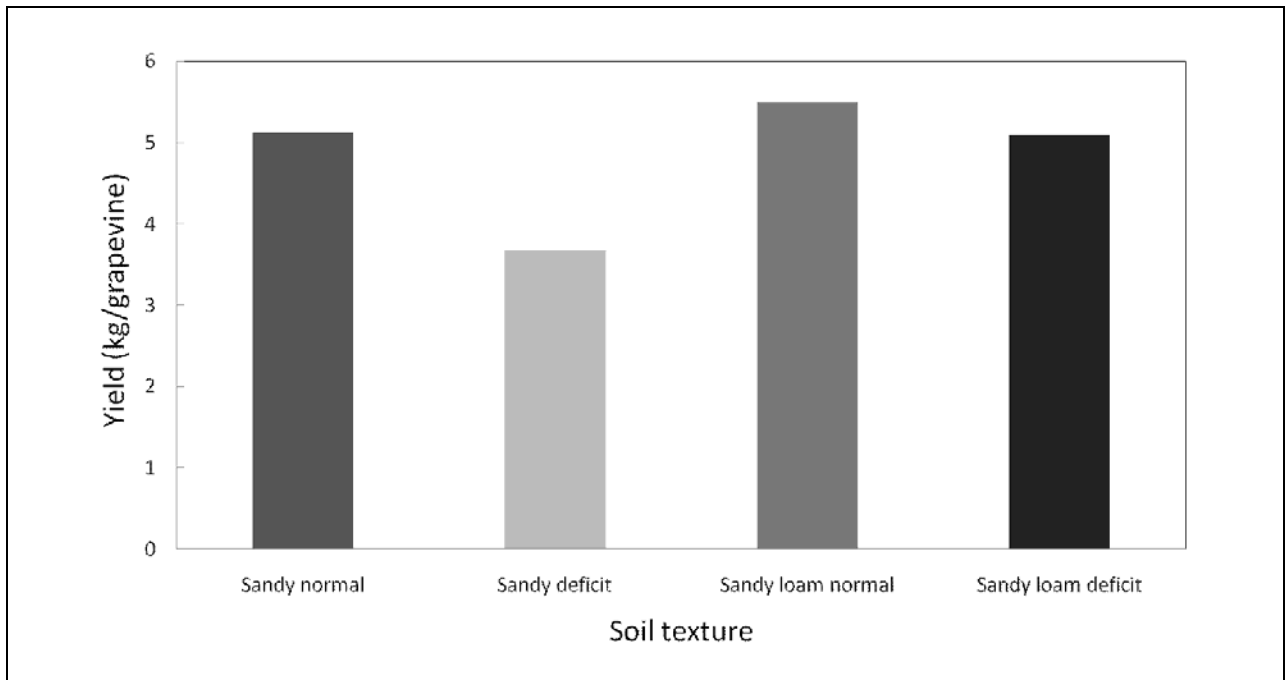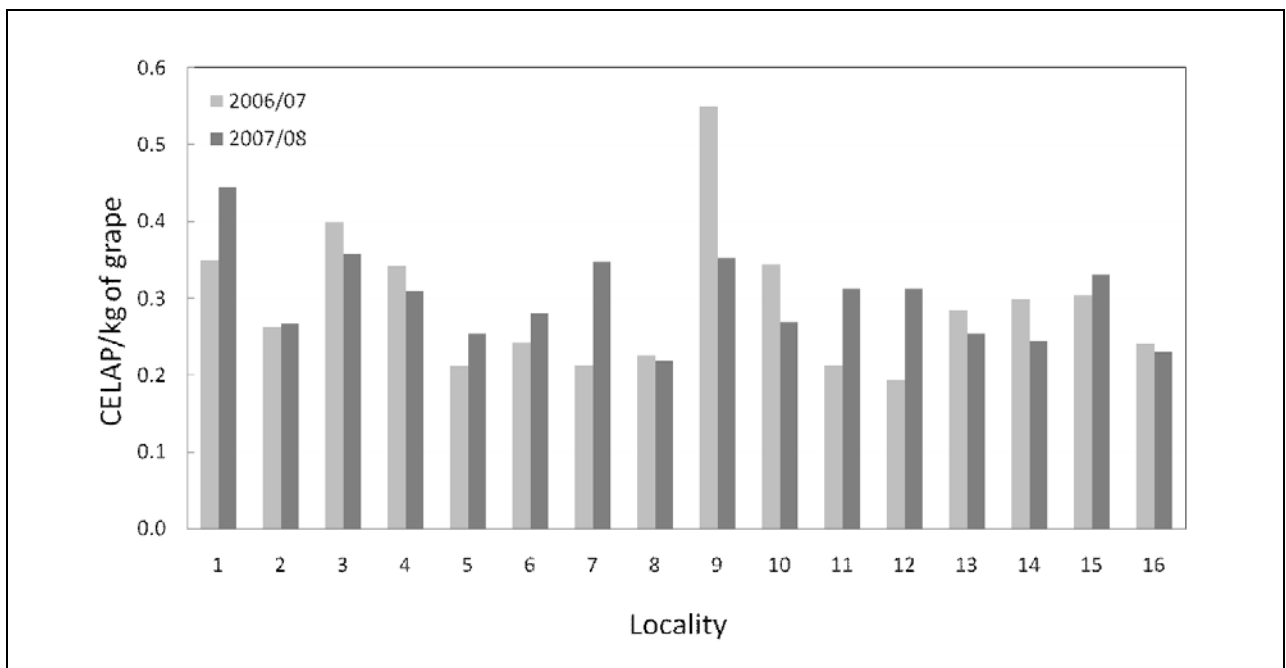
Chapter 5

RESEARCH RESULTS

The effect of climate, soil and irrigation on juice composition and wine quality

THE EFFECT OF CLIMATE, SOIL AND IRRIGATION ON JUICE COMPOSITION AND WINE QUALITY

5.1 INTRODUCTION

Wine needs to fulfill certain quality specifications in terms of, e.g. wine colour, wine chemistry and sensorial characteristics for wineries to compete internationally at a specific price point. Climate and its components such as temperature, plays an important role in determining wine quality (Le Roux, 1974; de Villiers *et al.*, 1996; Marais & Fourie, 1997). The mean February temperature (MFT), Winkler index, Huglin heliotermic index (HI) and Cool night index (CI) are some of the climatic variables or indices used to demarcate the most suitable locality for a specific grape cultivar (Le Roux, 1974; De Villiers *et al.*, 1996; Tonietto & Carbonneau, 2004). It was estimated that the MFT in the Western Cape Coastal region of South Africa increased by ca. 0.6ºC per 10 km increase in distance from the ocean (Myburgh, 2005 and references therein). Furthermore, the Atlantic Ocean had a significant influence on MFT in excess of 60 km inland, and it seemed that the air flow or land sea breeze circulation occurred in a westerly direction. These results suggested that the proximity of the Atlantic Ocean influenced MFT over longer distances, compared to the 35 km reported for sea breezes around False Bay (Bonnardot *et al.* 2003). According to Gladstones (1992) the grape ripening phase is arguably the most important period for determining grape and potential wine quality, and any detailed comparison of viticultural environments needs to include direct comparisons for it.

It was shown that day temperatures of 20ºC promoted colour development (anthocyanins) in Cabernet Sauvignon compared to temperatures of 30ºC (Buttrose *et al.*, 1971). At 25ºC day temperature, night temperature of 30ºC reduced anthocyanin levels in Cabernet Sauvignon compared to 15ºC, 20ºC or 25ºC night temperature (Kliewer & Torres, 1972). Berries that were subjected to continuous low day temperatures of 20ºC during berry development, had a greater concentration of malic acid (MA) than any of the berries that was subjected for a part, or the whole of the study period, to day temperatures of 30ºC. Furthermore, Buttrose *et al.* (1971) also found that proline concentrations in Cabernet Sauvignon berries were considerably lower at 20ºC compared to 30ºC.

It is accepted that climate will have a dominant effect on wine character in the warm wine producing regions of the world (Winkler *et al.*, 1974). In the Stellenbosch and Durbanville areas in the Western Cape, temperature and rainfall had a pronounced effect on Sauvignon blanc wine style (Bonnardot *et al.*, 2000). In Cabernet Sauvignon vineyards in the Stellenbosch and Drakenstein areas of South Africa, the terroir effect on wine style was evident, although seasonal variation in climate was observed (Carey, 2002).

According to Fregoni (1977) the effect of the soil on the quality of the harvest could be due to physical characteristics, particularly soil texture. The colour, chemico-physical

composition, pH and the mineral composition of the soil also play a role. According to Saayman (1972) it was only the nitrogen (N) and potassium (K) content in the soil that have a definite effect on wine quality. Excessive N has a direct negative effect on wine quality. However, indirectly N causes more serious negative effects by stimulating unwanted vegetative growth. This creates grapevines that are not only more susceptible to disease, but also causes herbaceous unbalanced wines. Furthermore, carbohydrates are utilized for grapevine vegetative growth at the cost of sugar accumulation. The foregoing are the primary reasons why soils rich in organic material, and consequently high N supplying capacities, are not selected for quality wine production.

Previous research indicted that the effect of soil type on Cabernet Sauvignon wine style was moderated, but not entirely eliminated by accurate irrigation scheduling (Olivier and Conradie, 2008). It has been noted by Noble *et al.* (1995) that there was an association between the vegetative notes in Cabernet Sauvignon wines and the deep clay-rich soils that are nutrient-rich and have a high water holding capacity. It was found in Bordeaux that grapevines in well drained soils had a faster decline in methoxypyrazine levels than in poorly drained soils (Winter & Hand, 2003).

Different irrigation strategies could cause aroma and flavour differences in Cabernet Sauvignon wines (Oliviera *et al.*, 2003; Ferreyra *et al.*, 2004; Chapman *et al.*, 2005). Irrigation can also cause indirect effects on juice composition, and wine quality can be reduced by the negative effect of excessive grapevine vigour (Noble *et al.*, 1995; Choné *et al.*, 2001; Neira-Pena *et al.*, 2004) and yield (Ahlgren *et al.*, 2002). It was shown that viticultural practices, which were applied to control yield, were more important than the actual yield per se in determining the eventual sensory characteristics in the wines (Chapman *et al.*, 2005).

The aim of this study was to determine the effect of climate, soil and irrigation on juice composition and wine quality potential in drip irrigated Cabernet Sauvignon vineyards in the Lower Olifants River region.

5.2 MATERIALS AND METHODS

5.2.1 EXPERIMENT LAYOUT

The study was carried out in eight commercial drip irrigated Cabernet Sauvignon vineyards in the Lower Olifants River region. Refer to Chapter 3 for the details of the vineyards and the experiment layout.

5.2.2 JUICE ANALYSES

During the 2006/07 season (26 January) as well as during the 2007/08 season (24 January and 1 February), total soluble solids (TSS), pH and total acid (TA) in grapes from all the plots were measured on the same day. Five randomly picked bunches were sampled per plot. The samples were homogenised for 30 seconds, using a stick blender (Braun 400 Watt MR4050CA, Spain) and centrifuged (Hermle 5000 rpm/rcf Z200a) for

two minutes. Following this, the samples were scanned using a Winescan FT120 instrument (Software 2.3.0) equipped with a purpose built Michelson interferometer (FOSS Electric A/A Hillerød, Denmark). The FT-IR spectra were captured, however, the analyses and interpretation of the spectral data were beyond the scope of the study. The above mentioned analyses were carried out at the laboratory of Namaqua Wines at Vredendal according to their standard procedures.

Grape samples were also collected when a specific plot was harvested. The target sugar content for harvesting was 24°B to 25°B. After the grapes had been crushed and pressed, a sample of the juice was taken for analyses. The total soluble solids (TSS), pH and titatable acids (TA) in the juice was determined according to the standard procedures of the Infruitec-Nietvoorbij Institute of the Agricultural Research Council (ARC) at Stellenbosch. The sodium (Na), potassium (K), calcium (Ca) and manganese (Mg) as well as the phosphorus (P) and total nitrogen (N) contents in the juice were determined by a commercial laboratory (BEMLAB, Strand).

During the 2006/2007 season the photosynthetic carbon isotope composition (δ^{13}C) in the sugars (‰) (Gaudillère et al., 2002) in grapes from all 16 plots was determined at harvest. Analyses were carried out at the Stable Light Isotope Laboratory of the Department of Archaeology at University of Cape Town. Samples were analysed by combustion in a Thermo 1112 Elemental Analyser coupled via a Thermo Conflo III to a Thermo Delta XP stable light isotope mass spectrometer.

5.2.3 WINE SENSORIAL EVALUATION

Forty kilograms of grapes were picked from the experiment grapevines at each plot. The grapes were micro-vinified at the experiment winery of the Infruitec-Nietvoorbij at Stellenbosch according to their procedures for red wine (Anonymous, 2008). After crushing, 50 mg/kg SO_2 was added to the grapes. Skin contact was allowed for at least one hour before the grapes were inoculated with rehydrated pure yeast (VIN 13) at a concentration of 30 g/hL. Furthermore, an addition of 50 g/hL diammonium phosphate (DAP) was made. Fermentation was conducted on the skins at a fermentation temperature of 25°C and the cap was punched down three times a day. The must was fermented down to between 0°B and 5°B. Following this, the juice and skins were separated, pressed at two bars and the pressed wine was added to the free run-off wine and then fermented at 25°C until dry. As soon as fermentation was completed, the wine was racked, the SO_2 adjusted to a total of 85 mg/L SO_2 (in accordance with the analysis) and cold stabilised at 0°C for at least two weeks. After cold stabilisation the wine was filtered by using sterile mats (K900 and EK), as well as a 0.45μm membrane and bottled into nitrogen filled bottles at room temperature. The total SO_2 was adapted during bottling to ensure that it is not less than 85 mg/L. A maximum of 10 bottles were bottled. After bottling, wines were stored at 14°C until it was evaluated.

Wines were subjected to sensorial evaluation by a panel of at least 12 experienced wine tasters from the South African wine industry. The evaluation was carried out approximately six months after harvest during August. Wine characteristics were scored

by means of a 100 mm long unstructured line scale. The descriptor on the left hand side of the scale was "None", i.e. meaning that the attribute was not recognisable in the wine, and on the right hand side "Prominent" was the descriptor. The primary sensorial wine characteristics were colour, flavour, taste and overall wine quality. The flavour characteristics consisted of (i) fresh vegetative aroma, i.e. herbaceous, fresh cut grass, green pepper, eucalyptus, mint, green beans, asparagus and olives, (ii) dry vegetative aroma, i.e. hay or straw, tea and tobacco, (iii) berry intensity, i.e. blackberry, raspberry, strawberry and black currant and (iv) spicy aroma, i.e. liquorice, anise, black pepper and cloves. The taste characteristics were acidity, fullness (body) and astringency. The character and quality potential of the experimental wines was divided into the following classes: (i) > 70% = high, (ii) $\geq$ 60% = medium to high, (iii) $\leq$ 50% = medium to low and (iv) $\leq$ 40% = low (P.A. Myburgh, Personal communication, 2009).

Following the sensorial evaluation, wines were analysed by a commercial laboratory (Integral Laboratories, Paarl). Residual sugar (RS), volatile acidity (VA), total acid (TA), malic acid (MA), pH, alcohol and potassium (K) contents were determined in the wine. Wine colour absorbance at A420nm, A520nm and A620nm was determined at the Namaqua Wines laboratory at Vredendal using a spectrophotometer (Cecil 1011, 1000 Series, LASEC, Cape Town) with 1 mm wavelength (Starna Scientific Ltd., Merc, Cape Town). The FT-IR spectra in the wines from all plots were carried out by using a Winescan FT120 instrument. However, the analyses and interpretation of the FT-IR spectral data were beyond the scope of the study.

5.2.4 STATISTICAL ANALYSES

Analysis of variance (ANOVA) was used to test the effects of locality, soil texture and irrigation strategy on sensorial wine characteristics. Fisher's least significant difference was calculated at the 95% confidence level to compare treatments. Version 9 of Statistica® was used. Relationships between variables were determined by means of linear regression at the 95% confidence level using Excell 2000®.

5.3   RESULTS AND DISCUSSION

5.3.1 JUICE COMPOSITION

During both seasons, the rate of berry ripening varied to such an extent between plots that harvest extended over a two month period (Fig. 5.1). On 26 January 2007 and 24 January 2008, i.e. when grapes were sampled from all plots, the TSS in the juice related positively to the distance from the Atlantic Ocean (Table 5.1 & Fig. 5.2). The higher maturation rate further inland was probably caused by the difference in climatic zones within the region (Fig. 3.6 & Fig. 3.7). A similar "advancing" influence of high air temperature on Pinot noir maturation rate was found in Burgundy in France (Bonnardot, 1997). However, in another study it was concluded that sugar accumulation in Cabernet Sauvignon was not significantly influenced by temperature and that it was probably a

varietal characteristic (Buttrose *et al.*, 1971). According to Winkler *et al.* (1974), seasonal conditions, particularly temperature in terms of heat summation, markedly influence the rate of the grapevine development and that the seasonal influences are identical to those displayed between hot and cool regions. Warmer atmospheric conditions during the 2007/08 season probably caused the more rapid rate of ripening compared to 2006/07. As the distance to the Atlantic Ocean decreased, the effect of cooler atmospheric conditions on TSS seemed to retard sugar accumulation. High yields could also slow down sugar accumulation (Winkler & Williams, 1939; Winkler *et al.*, 1974; Kliewer & Dokoozlian, 2005; Van Schalkwyk & Archer, 2008). However, under the conditions of this study, grapevine yield expressed in terms of kg per spur did not have a prominent influence on the rate of sugar accumulation (R^2 = 0.2505; se = 3.1; p < 0.005).

Due to logistic constraints, it was not possible to pick the grapes for winemaking in some of the plots at the target sugar content of 24°B to 25°B (Table 5.2). Under the given conditions, acceptable juice pH values were obtained from grapevines in most plots (Table 5.2). However, in some plots juice pH at harvest was higher than 3.4, i.e. the ideal pH for red must, and even as high as 3.8 (Anonymous, date unknown; J. Weidemann, Personal communication, 2009). High pH in grape juice often results in unstable musts and wines that are more susceptible to oxidative and microbiological spoilage (Conde *et al.*, 2007 and references therein). Must with pH values above 3.6 could be prone growth of spoilage organisms. Furthermore, higher pH in the must requires more additions of chemical substance, such as tartaric acid, in an attempt to the lower the pH (Anonymous, date unknown). The TA in the juice at harvest was surprisingly high given the relatively warm atmospheric conditions (Fig. 3.9), and the fact that grapevines in 50% of the plots were subjected to water deficits (Table 5.2). At the same TSS, the TA tended to be lower during the 2007/08 season compared to the 2006/07 season. This could have probably been caused by warmer atmospheric conditions during the 2007/08 season. Tartaric and malic acids were reduced via respiration and grapes grown in warmer climates typically had lower acidity than those grown in cooler climates (Pandell, 1999). However, the lower TA could also have been caused by more intense water deficits. Since pH is a measure of "active" acidity, pH will decrease with an increase in acidity. Due to this, juice TA correlated negatively with pH at harvest (R^2 = 0.5035; se = 0.1; p < 0.001).

During both seasons the locality, soil texture and irrigation strategy did not seem to affect the juice Na content at harvest (Table 5.3 & Table 5.4). The Na content in the juice from P11 was exceptionally high during the 2006/07 season. The high Na contents could not be explained by any of the measured variables. However, the high values could have been caused by sample contamination or laboratory error (W.J. Conradie, Personal communication, 2007). The high juice Na content in grapes from P15 and P16 during the 2006/07 season could probably be related to the relatively high Na content in the soil (Table 3.7). Since the soil Na did not reflect in the juice during the second

season, it could be that the high concentrations in the first season were probably also caused by sample contamination or laboratory error.

Juice K contents at harvest did not show any trends with respect to the locality, soil texture and irrigation strategy during the two seasons (Table 5.3 & Table 5.4). Potassium is the most abundant cation in must (Blouin & Cruège, 2003). The K content in the juice of grapes produced in most plots was higher than 900 mg/L. Potassium contents in the juice were exceptionally high in grapes from P4, P9 and P13 during the 2006/07 season (Table 5.3). In the 2007/08 season juice from P6 and P7 had exceptionally high K contents. The high K contents could not be explained by any of the measured variables. However, the high values could have been caused by sample contamination or laboratory error. Juice Ca, Mg, P and N contents at harvest did not show any trends with respect to the locality, soil texture and irrigation strategy during the two seasons (Table 5.3 & Table 5.4). The juice Ca content was relatively high (Blouin & Cruège, 2003), i.e. higher than 80 mg/L, during the 2006/07 season in grapes from P8 and P9 and in grapes from P2 during the 2007/08 season. The high Ca could also not be explained by any of the measured variables. As in the case of Na and K, sample contamination or laboratory error could have caused the high concentrations.

During the 2006/07 season juice N in grapes from P5 and P13 as well as in grapes from P4 in the following season, was lower than 150 mg/L (Table 5.3 & Table 5.4). These relatively low N concentrations could have caused problems during winemaking. Slow fermentation is caused by N deficiencies and can be predicted by estimating the assimilable N concentration in must (Blateyron *et al.*, 2003). According to Aggenbach (1977), yeast cells require ca. 130 mg/L of assimilable amino N in must to sustain fermentation through to dryness. It was also found that assimilable N levels of 120 mg/L to 150 mg/L were needed to sustain fermentation through to dryness in white grapes (Holzapfel & Treeby, 2007). When fermentable N is below 150 mg/L to 200 mg/L, ammonium in the form of phosphate, sulphate of sulphite salts is added to the must to avoid stuck fermentation as well as the formation of hydrogen sulphide and other sulphur odours (Kunkee, 1991; Jiranek *et al.*, 1995). The mean N contents of the juice in this study were approximately 255 mg/L and 276 mg/L during the 2006/07 and 2007/08 seasons, respectively. These values were relatively high compared to the HPLC-derived assimilable nitrogen concentrations of ca. 165 mg/L in samples collected from 10 year-old Cabernet Sauvignon vineyards grown in north-western Virginia (Gump *et al.*, 2002).

With the exception of P5, the photosynthetic carbon isotope composition ($\delta^{13}C$) of the juice sugar in fresh berries was consistently higher where grapes were subjected to water deficits compared to the normal irrigated ones during the 2006/07 season (Table 5.3). When stomata are closed due to water deficits, carbon isotope discrimination is reduced. As a result the $\delta^{13}C$ in primary products of photosynthesis, i.e. sugar in grapevines, bears the signature of the intensity of the water deficits during the ripening period (Deloire *et al.*, 2005 and references therein). Water stress could reduce the activity of both the sugar transporters and the enzyme involved in the process of sugar

phloem unloading in ripening berries thus leading to a reduction in sugar unloading in the ripening berry. This method of measuring water deficits in grapevines has the advantage that it integrates the effects of water deficits over a longer period and that it does not require field measurements. Sugar $\delta^{13}C$ values were comparable to -20‰ for severely water stressed grapevines and -27‰ for the ones that were not subjected to any water stress (Deloire *et al.* and references therein, 2005). In a study carried out in Bordeaux in France in rain-fed vineyards it was found that the $\delta^{13}C$ in sugars of Merlot, Cabernet Sauvignon and Cabernet franc at harvest could be applied to compare the capacities of vineyard soils and canopy management to induce mild water stress in order to produce premium wines (Gaudillère *et al.*, 2002). The data which were collected over four seasons in various locations showed a range in sugar $\delta^{13}C$ between -20‰ and -26‰. Differences in water availability between years and soils clearly and consistently reflected in sugar $\delta^{13}C$ measured at harvest. Berry sugar $\delta^{13}C$ correlated well with grapevine water status during summer. It integrates conditions during the ripening stage and allows a precise comparison of mild water stress conditions. Leaf water potential (Ψ_L) also correlated reasonably well with $\delta^{13}C$ in rain-fed and irrigated Sauvignon blanc vineyards in the Stellenbosch region (Van Zyl & Carey, 2008). The reported $\delta^{13}C$ values varied between -24‰ and -28‰. Although this method could be a reliable indicator to differentiate between the cumulative water stress experienced by grapevines for research purposes, the method have practical constraints in terms of analyses (A. Strever, Personal communication, 2009). A high level of technical ability is required (Deloire *et al.*, 2004). Furthermore, the method of analyses has constraints when measuring at the beginning of the ripening period. Consequently, it would be impractical to use $\delta^{13}C$ as a monitoring tool in irrigation management during the season.

5.3.2 WINE COMPOSITION

Wine alcohol, TA, MA, RS, VA and anthocyanin contents did not show any trends with respect to the locality, soil texture and irrigation strategy during the two seasons (Table 5.5 & Table 5.6). The VA in wine from P11 was higher than 1.0 mg/L during the 2007/08 season. Although it was still lower than the legal limit of 1.2 mg/L for bottled wines in South Africa, it could be an indication of acetic deterioration (Cullinan, 2009).

There was no relationship between pruning mass and pH or K concentration in the juice at harvest. However, K concentration in the wine increased with an increase in pruning mass (R^2 = 0.5769; se = 364.7; p < 0.001). Furthermore, wine colour hue (A420nm/A520nm) tended to increase as the K concentration in the wine increased (R^2 = 0.4896; se = 0.1; p < 0.001). The colour hue of the wines from grapevines in the sandy loam soils tended to be higher compared to the ones in sandy soils. The colour hue of a wine is an indication of the wine's dominant pigment concentration. The optical density of wine at A420nm is sometimes a useful indicator of browning and therefore, related to oxidation of wine (Anonymous, 2009). This could be an indirect effect due to shading and unfavourable canopy microclimate of grapevines in the sandy loam soils, i.e. grapevines with the higher pruning masses. The negative effect on wine colour

could be due to the effect of K on wine pH which, in turn, affects the properties of anthocyanins in wine (Conde *et al.*, 2007 and references therein). During both seasons wines from P11 and P12 tended to contain the highest colour hue (i.e. > 0.9), which could be an indication of high brown/yellow pigment concentrations (Table 5.5 & Table 5.6). High colour hues in particularly young wines would be undesirable and could be an indication of poor ageing potential. The foregoing results suggested that canopy management practices in sandy loam soils could be important for wine quality in terms of wine colour.

Deficit irrigation tended to increase wine colour intensity during both seasons, irrespective of soil texture (Fig. 5.3 & Fig. 5.4). This could have been caused by the reduction of vegetative growth via water deficits which improved canopy microclimate. Anthocyanin synthesis is promoted by light, particularly in the shorter wavelength range (Bidwell, 1974). Water deficits can also produce smaller berries which can increase the solute to solvent ratio (Conde *et al.*, 2007 and references therein). However, the effect of grapevine water status on the concentration of anthocyanins could also be due to the differential growth response of the skin and inner mesocarp tissue to water deficits or direct stimulation of phenolic biosynthesis (Conde *et al.*, 2007 and references therein). Furthermore, grapevine nitrogen status has a direct effect on synthesis of pigments in grape skins in addition to the indirect effects caused by modifications of vigour and fruit set (Keller, 2005). Where grapes ripen in full sunlight on grapevines with a relatively low N status the wine will be deeply coloured showing a well balanced crimson to purple hue. A decrease in total pigment content and a colour shift toward red might be expected in wine made from grapes that experienced excessive N and poor light conditions (Keller, 2005). Colour is among the quality attributes most easily influenced by N availability, but is also linked to water supply. Poor N management in vineyards cannot be corrected by other practices, e.g. canopy management. Severe water deficits in grapevines in the sandy soil at Vredendal (P7) during the 2006/07 season could have had a detrimental effect on colour intensity (Fig. 5.3), either by direct or indirect effects.

Colour intensity of the wines tended to be lower during the 2007/08 season compared to the 2006/07season (Table 5.5 & Table 5.6). Stronger vegetative growth, i.e. more dense canopies, during the 2007/08 season than in 2006/07 could have contributed to the lower colour intensity (Fig. 4.3). The red pigments in the wines (A520nm) decreased as the pruning mass, i.e. vegetative growth, increased during both seasons (R^2 = 0.5597; se = 1.1; p < 0.001). Where pruning masses were higher, less red pigments could have been formed due to unfavourable bunch microclimate. It was shown that shading can reduce the skin colour (A520nm) of Cabernet Sauvignon berries (Archer & Strauss, 1989). Cluster shading also reduced anthocyanins in grape berries (Morrison & Noble, 1990). Poor colouring of grapes could eventually have negative effects on overall wine quality (Marais, 2005). However, grape colour can not be exclusively used as a quality parameter, since too many additional factors come into play during ripening. During the two seasons wines from P1 tended to have the highest colour intensity, followed by P13 (Table 5.5 & Table 5.6). This trend is in agreement with

previous results which showed that controlled or restricted irrigation could be desirable for wine colour development where grapes are produced under irrigation (Rankine *et al.*, 1971).

5.3.3 WINE SENSORIAL CHARACTERISTICS

Overall sensorial wine quality potential, based on certain characteristics, varied considerably between plots (Fig. 5.5). Within a specific locality, grapevines in the sandy soils, e.g. P1 & P2 tended to produce wines with a higher quality potential compared to those in the more fertile sandy loam soils, e.g. P3 & P4. Rankine *et al.* (1971) concluded that soil type influences the amounts of certain components in grapes and wine, but had no effects on wine quality. The soil depth, drainage and water holding capacity appeared to play a more important role than the composition of the soil. According to Olivier & Conradie (2008) irrigation did not eliminate soil-induced differences in aroma intensity, berry character and overall quality of Cabernet Sauvignon wines in the Breede River Valley, South Africa.

Normal irrigated grapevines in the sandy soil at Kapel (P2) consistently produced wines of medium to high quality potential, i.e. a mean wine quality of ca. 66% (Fig. 5.5). This wine quality potential was obtained where mean Ψ_M for the two seasons was relatively high, i.e. -0.005 MPa from bud break to flowering, -0.010 MPa from flowering to véraison and -0.018 MPa from véraison to harvest. In response to the soil water status, mean total diurnal leaf water potential (Ψ_{LT}) was 20 MPa^2 from pea size to harvest during the 2006/07 season. Mean predawn leaf water potential (Ψ_{PD}) was -0.40 MPa (Table 3.14 to Table 3.17). During berry ripening Ψ_S was approximately -1.10 MPa in both seasons (Table 3.19 & Table 3.21). These grapevine water status levels resulted in a mean leaf layer number of 2, canopy score of 90%, cane length of 1 m, cane diameter of 6.8 mm and pruning mass of 2.13 t/ha during the two seasons (Table 4.1 to Table 4.4 & Fig. 4.5). The wine quality potential was also related to a mean berry mass of 1.0 g, bunch mass of 87.5 g and yield of 4.7 kg/grapevine during the two seasons (Table 4.5, Table 4.6 & Fig. 4.19). Visually, shoot growth and yield of grapevines in this particular plot appeared to be in balance (Fig. 5.6). However, the canopy external leaf area perimeter to kilogram grape ratio was suboptimal, i.e. ca. 0.27 (Fig. 4.23) (A. Deloire, Personal communication, 2009). It is important to note that, under the given conditions, the four wines which had wine quality potentials of 60% and higher, were produced from grapevines where the canopy external leaf area perimeter to kilogram grape ratio ranged between 0.23 and 0.45.

In contrast to the sandy soil at Kapel (P2), the normal irrigated grapevines in the loamy sand soil at Lutzville (P12) consistently produced wines of low quality potential, i.e. mean wine quality was ca. 41%. The low wine quality potential was obtained where mean Ψ_M for the two seasons was relatively high, i.e. -0.010 MPa from bud break to flowering, -0.018 kPa from flowering to véraison and -0.018 MPa from véraison to harvest. In response to the soil water status, Ψ_{LT} from pea size to harvest ranged between 14 MPa^2 and 16 MPa^2, whereas Ψ_{PD} ranged between -0.32 MPa and -0.18

MPa in the 2006/07 season (Table 3.14 to Table 3.17). During berry ripening Ψ_S was approximately -0.65 MPa in both seasons (Table 3.1 & Table 3.21). These grapevine water status levels resulted in a mean canopy score of 77%, cane length of 1.10 m, cane diameter of 8.2 mm and pruning mass of 7.20 t/ha during the two seasons (Table 4.1 to Table 4.4 & Fig. 4.5). The low wine quality potential was also related to a berry mass of ca. 1.35 g, a bunch mass of ca. 157.99 g and a yield of ca. 6.12 kg/grapevine (Table 4.5, Table 4.6 & Fig. 4.19). Visually, excessive grapevine shoot growth occurred in P12 (Fig. 5.7). Similar to the grapevines in P2, the canopy external leaf area perimeter to kilogram grape ratio, was suboptimal, i.e. ca. 0.25 (Fig. 4.23) (Deloire, Personal communication, 2009). This illustrated that guidelines could be given, but a single indicator could not be used to estimate grapevine balance, and wine quality potential. It also possibly suggest that other grapevine parameters, e.g. number of laterals per grapevine or the ratio of adult leaves to young leaves could also play a role in determining grapevine balance. The terroir, of which soil texture and climate are important components, also plays a role in eventual wine style and quality potential.

During the 2007/08 season deficit irrigated grapevines in the sandy soil at Kapel (P1) produced wine of medium to low quality potential compared to the 2006/07 season when the wine quality potential was medium to high. During the 2006/07 season, mean Ψ_M was -0.031 MPa in P1 compared to -0.053 MPa in 2007/08 (Table 3.12). In response to these Ψ_M levels, Ψ_S was -1.47 MPa and -1.58 MPa in 2006/07 and 2007/08, respectively (Table 3.19 & Table 3.21). The low Ψ_S values during berry ripening in 2007/08 indicated that the grapevines were subjected to a high degree of water stress, which could have reduced the wine quality potential. Similarly, deficit irrigated grapevines in the sandy soil at Vredendal (P7) which experienced severe water stress during both seasons, produced wine of inferior quality compared to those that received normal irrigation (P8). From bud break to flowering Ψ_M was comparable in P7 and P8, i.e. -0.012 MPa (Table 3.12). However, from flowering to véraison Ψ_M was -0.030 MPa and from véraison to harvest Ψ_M -0.045 MPa in P7, whereas mean Ψ_M in P8 was approximately -0.012 MPa throughout the season. Mean Ψ_S in the deficit irrigated grapevines was -1.36 MPa and -1.47 MPa during berry ripening in the 2006/07 and 2007/08 seasons, respectively. The normal irrigated grapevines in P8 experienced substantially less water stress, i.e. mean Ψ_S was -1.04 MPa and -1.11 MPa during the respective seasons. According to Conradie (2002) water stress will be the most important factor that could reduce wine quality in rain-fed or low frequency irrigated vineyards in sandy soils.

During the 2007/08 season deficit irrigated grapevines in the sandy soil at Lutzville (P9) produced wine of medium to high quality potential compared to the 2006/07 season when the wine quality potential was medium to low. During the 2006/07 season, mean Ψ_M was -0.060 MPa during berry ripening in P9 compared to -0.039 MPa in 2007/08 (Table 3.12). In response to these Ψ_M levels, Ψ_S was -1.37 MPa and -1.25 MPa in 2006/07 and 2007/08, respectively (Table 3.19 & Table 3.21). The low Ψ_S values during berry ripening in 2006/07 indicated that the grapevines were subjected to some

degree of water stress, which could have reduced the wine quality potential compared to the 2007/08 season. This result was similar to the positive response of wine quality potential to less water stress which occurred in the deficit irrigated plot in the sandy soil at Kapel (P1) as discussed above. Due to less water stress in grapevines in P9, the wine quality potential was comparable to the normal irrigated plot in the sandy soil at Kapel (P2) in 2007/08 (Fig. 5.5). Although Ψ_M was lower from flowering to harvest in P9 compared to the normal irrigated P2, Ψ_S did not differ substantially (Table 3.12). This suggested that grapevines in the deep, red sandy soil with no restrictive dorbank within 900 mm depth in P9 were more buffered against water deficits compared to the ones in P2 (Table 3.21, Fig. 3.33 & Fig. 3.37).

Although the deficit irrigated grapevines in the shallow sandy soil at Koekenaap (P13) only received 15% of the water that was applied to normal irrigated ones (P14), mean Ψ_M was -0.027 MPa during berry ripening (Table 3.12). This was substantially higher compared to Ψ_M in the deficit irrigation plots in the shallow sandy soils at some of the other localities further inland as discussed above. Koekenaap was cooler and more humid and the potential evaporation was lower compared to the other localities (Table 3.4 Table 3.5 & Table 3.6). Under the relatively cool atmospheric conditions grapevines probably used less water which caused the higher Ψ_M compared to the warmer localities. Due to the high Ψ_M and the cooler atmospheric conditions, mean Ψ_S in the deficit irrigated grapevine was only -1.17 MPa. This level of water stress was comparable to the levels in grapevines in P2 and P8 which produced wines of high quality potential. However, grapevines in P13 only produced wine of medium quality potential in both seasons (Fig. 5.5). This indicated that the cooler conditions at Koekenaap probably could have limited wine quality potential of Cabernet Sauvignon.

Within a specific locality, deficit irrigated grapevines in the heavier sandy loam soils, e.g. in P11 & P15, tended to produce wines with higher quality potential compared to the normal irrigated ones (Fig. 5.8 & Fig. 5.9). A similar trend was observed in the sandy soils, but too severe water deficits reduced wine quality potential, e.g. in the case of P1 and P7 as discussed above. Overall sensorial wine quality potential increased with an increase in fullness of the wine (Fig. 5.10). Severe water deficits in sandy soils decreased wine fullness, e.g. in P1 and P7 during the 2007/08 season (Fig. 5.11). On the other hand, wine fullness of deficit irrigated grapevines in sandy loam soils tended to increase compared to the normal irrigated ones (Fig. 5.12). This was in particular the case in the sandy loam soils further away from the river (P3 & P15). Wine quality also increased with an increase in sensorial wine colour (R^2 = 0.4640; se = 5.9; p < 0.001) and berry character (R^2 = 0.4267; se = 6.1; p < 0.001). Sensorial wine colour observed by the judges correlated well with wine colour intensity (A420nm + A520nm + A620nm) (Fig. 5.13).

Berry character tended to be stronger in wines produced from grapevines in the sandy soils compared to the ones in the sandy loam soils (Fig. 5.14 & Fig. 5.15). Furthermore, deficit irrigation of grapevines in sandy loam soils tended to increase the berry character in Cabernet Sauvignon wines (Fig. 5.15). These trends could have been

due to the indirect effects of less vigorous vegetative growth of grapevines in the sandy soils and deficit irrigation in the sandy loam soils which improved canopy microclimate. However, the difference in berry character could also have been caused by chemical breakdown or formation of berry flavours due to grapevine water status (Conde *et al.*, 2007 and references therein). The positive effect of less vegetative growth on berry character was in contrast with previous results obtained in the Western Cape (Conradie, 2002). Where Cabernet Sauvignon grapevines in a drier Sterkspruit soil near Durbanville were subjected to more water stress, wine with a stronger vegetative character was produced, whereas grapevines in the wetter Oakleaf soil produced wines with stronger berry character with a subordinate spicy character. In the Robertson area Cabernet Sauvignon grapevines in a heavier clayey Tukulu soil produced more full bodied wines with higher berry and spice aroma intensity, whereas grapevines in the sandier Fernwood soil produced a light, atypical Cabernet Sauvignon style wine (Conradie, 2002). On the other hand it was shown that grapevines which experienced water deficits produced wines with more fruity and less vegetative aromas and flavours than ones with a high water status (Chapman *et al.*, 2005). Similarly, it was found that water deficits increased grapevine water stress, reduced vegetative growth and increased the berry character in Merlot near Wellington (Myburgh, 2006). In other field experiments water deficits also reduced vegetative growth and increased the berry character in Cabernet Sauvignon, Shiraz and Merlot wines produced in different soils and localities (P.A. Myburgh, Personal communication, 2009).

Berry character in wines produced from normal irrigated grapevines in the sandy soils tended to decrease as distance to the ocean decreased (Fig. 5.16). The breakdown of methoxypyrazines, the dominant component in Cabernet Sauvignon wines, is higher under warmer conditions (Winter & Hand, 2003). Hence, higher temperatures inland probably contributed to methoxypyrazine breakdown compared to localities closer to the ocean (Fig. 3.6 & Fig. 3.7). Furthermore, stimulation of the biosynthesis of other "fruity" aromas, e.g. certain C_{13}-norisoprenoids, could have been promoted by warmer atmospheric conditions (Bindon *et al.*, 2007 and references therein). The trend did not occur in the heavier sandy loam soils (Fig. 5.17). Due to denser canopies, berries were probably less exposed to the sun and the breakdown of methoxypyrazines did not occur to the same extent as in grapes produced in the sandy soils. Water deficits probably had a stronger influence on berry character in wine produced from grapevines in sandy loam soils than climate.

There was no linear relationship between yield and overall sensorial potential quality of Cabernet Sauvignon wines in the Lower Olifants River region (R^2 = 0.1636; se = 7.4; p < 0.001). Perceptions exist that there is a linear relationship between grape yield and wine quality, i.e. an increase in quality as yield decreases (Keller, 2005). However, lower yields were to a lesser extent associated with more intense berry character (R^2 = 0.3660; se = 10.1; p < 0.001). The positive response was probably an indirect effect caused by differences in soil texture and irrigation strategy which regulated vegetative growth and yield. These results were in contrast with earlier reports

that "low yielding" vineyards produce Cabernet Sauvignon wines higher in vegetative aroma and flavour, bell pepper aroma, bitterness and astringency compared to "high-yielding" vineyards (Chapman *et al.*, 2004). Fruity attributes increased in intensity as bud number and yield increased and when yield is altered early in fruit development berry character intensity is increased (Chapman *et al.*, 2004). However, they concluded that the effects of yield control practices on the grapevine were more important than the actual yield in determining the sensorial wine characteristics.

5.4   CONCLUSIONS

Macro climate had an influence on the phenological stages of the grapevine, i.e. the physiology of the grapevine was primarily driven by temperature. Therefore, harvest date and the rate of sugar accumulation would be influenced by the proximity to the Atlantic Ocean.

Under the conditions in the Lower Olifants River region, Cabernet Sauvignon grapevines nearer to the ocean did not seem to produce grapes with higher potential for wine quality, i.e. higher TA and lower pH. However, grapevines in the sandy soils tended to produce wines with higher berry character compared to those in the sandy loam soils. Deficit irrigation in sandy loam soils could enhance the berry character in Cabernet Sauvignon wines. Berry character in wines produced from normal irrigated grapevines in the sandy soils tended to increase as distance from the Atlantic Ocean increased, probably due to warmer climatic conditions. Furthermore, deficit irrigation tended to increase wine colour intensity (A420nm +A520nm +A620nm), irrespective of soil texture. Deficit irrigation in sandy loam soils also tended to increase wine fullness. In heavier soils deficit irrigation could enhance quality potential of Cabernet Sauvignon wines, but too severe water stress on the sandier soils could produce wines of low quality potential. Soil texture had an influence on wine style and quality despite the given climatic variation in the region and intensive irrigation in some vineyards. This effect was probably achieved indirectly through the regulation of water supply which, in turn, controlled grapevine vegetative growth and created a more favourable canopy microclimate. However, the effect of water supply on other processes such as anthocyanin and berry flavour breakdown or biosynthesis could also have played a role.

Irrigation strategies for grapevines in the sandy soils should be adapted according to soil depth. (i) In the shallow sandy soils Ψ_M should be ca. -0.005 to -0.010 MPa (no water deficits) from bud break to flowering, ca. -0.010 MPa; from flowering to véraison and ca. -0.015 to -0.020 MPa (mild water deficits) from véraison to harvest. Mean Ψ_M lower than -0.030 MPa from flowering to harvest in the shallow sandy soils could be too low and probably would have detrimental effects on reproductive and vegetative growth of grapevines. (ii) In the deep, red sandy soils Ψ_M should be ca. -0.005 to -0.010 MPa (no water deficits) from bud break to flowering, ca. -0.040 MPa from flowering to véraison and ca. -0.040 MPa (moderate water deficits) from véraison to harvest. Lower mean Ψ_M values during the flowering to harvest stage could be allowed in the deep

sands compared to the shallow red sands. These two strategies would probably control the vegetative growth, possibly stimulate anthocyanin synthesis, the concentration of metabolites and increase the skin to flesh ratio.

It seemed that irrigation strategies for grapevines in the heavier sandy loam soils should be adapted according to the distance from the main course of the river. (i) In the sandy loam soil further away from the river Ψ_M should be ca. -0.010 MPa from bud break to flowering (no water deficits), ca. -0.050 MPa from flowering to véraison and ca. -0.070 MPa from véraison to harvest. (ii) In the sandy loam soils on the banks of the river where water tables could have formed when the vineyards were submerged during the winter Ψ_M should be ca. -0.030 MPa from bud break to flowering, ca. -0.050 MPa from flowering to véraison and ca. -0.070 MPa from véraison to harvest. The objective of the latter strategy is to impose higher water deficits early in the season in an attempt to control vegetative growth since the deeper roots, i.e. deeper than 1.5 m, will supply the grapevine with water from the water table.

Predawn leaf water potential values of ca. -0.4 MPa in grapevines in sandy soils were probably the ideal in terms of balancing the vegetative and reproductive growth pea size and ripening to achieve high wine quality potential. Predawn leaf water potential values of ca. -0.6 MPa seemed to be a threshold between moderate constraints and severe water stress in the sandy soils. In the heavier sandy loam soils Ψ_{PD} values of ca. -0.5 MPa were probably the ideal in terms of balancing the vegetative and reproductive growth from pea size to ripening.

Further research is necessary to differentiate on cultivar basis what the effect of soil texture in the Lower Olifants River region would be on wine style and quality potential.

5.5   LITERATURE CITED

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Table 5.1 Total soluble solids (TSS), pH and total acid (TA) measured on the same day in Cabernet Sauvignon juice from 16 plots representing different localities, soil texture and irrigation strategies in the Lower Olifants River region during the 2006/07 and 2007/08 seasons.

Plot no[1]	Locality	Soil texture	Irrigation strategy	TSS (ºB)			pH			TA (g/L)		
				26/01/2007	24/01/2008	01/02/2008	26/01/2007	24/01/2008	01/02/2008	26/01/2007	24/01/2008	01/02/2008
P1	Kapel	Sand	Deficit irrigation	26.4	23.8	25.6	4.2	4.0	4.4	5.5	5.9	5.3
P2			Normal	24.9	20.4	25.0	3.8	3.7	3.9	6.7	7.2	5.9
P3		Sandy loam	Deficit irrigation	25.4	20.9	26.2	4.1	3.8	4.2	6.8	7.2	6.1
P4			Normal	23.4	20.3	24.9	4.1	3.8	4.2	6.9	8.1	5.8
P5	Vredendal	Sandy loam	Deficit irrigation	18.4	17.1	18.8	3.4	3.5	3.8	8.6	11.9	8.2
P6			Normal	18.2	17.7	19.4	3.5	3.6	3.8	8.4	10.6	7.7
P7		Sand	Deficit irrigation	20.2	16.9	19.6	3.7	3.6	4.1	8.1	8.9	6.6
P8			Normal	17.1	18.7	19.2	3.5	3.7	3.8	9.8	9.0	7.9
P9	Lutzville	Sand	Deficit irrigation	23.2	18.4	20.3	3.8	3.6	3.9	6.8	9.5	6.8
P10			Normal	22.5	18.1	22.4	3.8	3.6	4.0	7.5	9.7	6.4
P11		Loamy sand	Deficit irrigation	17.6	16.2	18.9	3.8	3.6	4.0	10.3	12.3	8.2
P12			Normal	16.2	16.0	18.1	3.6	3.6	3.9	11.1	12.9	8.9
P13	Koekenaap	Sand	Deficit irrigation	17.6	16.3	19.2	3.3	3.2	3.5	10.1	13.2	8.7
P14			Normal	18.3	16.5	19.2	3.3	3.2	3.5	12.8	15.9	8.7
P15		Sandy loam	Deficit irrigation	16.4	13.3	15.7	3.3	3.1	3.4	13.7	18.6	12.1
P16			Normal	15.6	11.4	15.5	3.4	3.0	3.5	12.4	24.1	12.5

[1] Refer to Table 3.1 for description of the plots.

Table 5.2 Harvest date as well as total soluble solids (TSS), pH and total acid (TA) at harvest in Cabernet Sauvignon juice from 16 plots representing different localities, soil texture and irrigation strategies in the Lower Olifants River region during the 2006/07 and 2007/08 seasons.

Plot no[1]	Locality	Soil texture	Irrigation strategy	Harvest date		Juice analyses at harvest					
						TSS (ºB)		pH		TA (g/L)	
				2006/07	2007/08	2006/07	2007/08	2006/07	2007/08	2006/07	2007/08
P1	Kapel	Sand	Deficit irrigation	30/01/07	05/02/08	25.6	23.7	3.4	3.8	7.4	6.2
P2			Normal	30/01/07	05/02/08	23.9	23.9	3.2	3.6	8.6	6.0
P3		Sandy loam	Deficit irrigation	30/01/07	01/02/08	24.5	25.2	3.2	3.7	9.5	8.4
P4			Normal	30/01/07	13/02/08	22.6	24.2	3.2	3.5	9.0	7.4
P5	Vredendal	Sandy loam	Deficit irrigation	07/03/07	11/03/08	24.0	24.1	3.5	3.6	6.7	6.6
P6			Normal	14/03/07	11/03/08	26.0	24.0	3.5	3.7	6.8	6.9
P7		Sand	Deficit irrigation	07/03/07	11/03/08	25.4	23.8	3.5	3.8	6.8	5.6
P8			Normal	14/03/07	07/03/08	27.1	25.4	3.5	3.6	7.8	6.6
P9	Lutzville	Sand	Deficit irrigation	01/03/07	07/03/08	25.8	24.4	3.5	3.6	5.9	6.1
P10			Normal	07/03/07	07/03/08	24.5	25.3	3.5	3.6	7.0	6.5
P11		Loamy sand	Deficit irrigation	21/03/07	19/03/08	25.0	25.3	3.7	3.7	6.5	6.6
P12			Normal	05/04/07	27/03/08	23.7	25.6	3.7	3.8	7.4	6.5
P13	Koekenaap	Sand	Deficit irrigation	14/03/07	11/03/08	24.6	25.1	3.3	3.4	7.4	7.6
P14			Normal	29/03/07	19/03/08	24.2	24.6	3.2	3.4	9.2	8.2
P15		Sandy loam	Deficit irrigation	21/03/07	19/03/08	28.1	25.9	3.4	3.5	7.4	7.2
P16			Normal	21/03/07	27/03/08	25.8	23.9	3.4	3.5	7.5	6.9

[1] Refer to Table 3.1 for description of the plots.

Table 5.3 Cations, phosphorus (P) and total nitrogen (N) contents as well as carbon discrimination at harvest in Cabernet Sauvignon juice from 16 plots representing different localities, soil texture and irrigation strategies in the Lower Olifants River region during the 2006/07 season.

Plot no[1]	Locality	Soil texture	Irrigation strategy	Na (mg/L)	K (mg/L)	Ca (mg/L)	Mg (mg/L)	P (mg/L)	N (mg/L)	Carbon discrimination (‰)
P1	Kapel	Sand	Deficit irrigation	21.6	1320.0	71.2	148.9	139.6	210	-24.13
P2			Normal	20.6	1176.1	57.5	123.4	104.5	254	-25.35
P3		Sandy loam	Deficit irrigation	20.0	1463.3	51.1	103.1	92.9	443	-25.62
P4			Normal	18.4	3228.6	43.1	100.2	105.3	441	-25.71
P5	Vredendal	Sandy loam	Deficit irrigation	23.7	1378.4	59.7	132.8	133.2	130	-26.70
P6			Normal	13.8	1865.7	61.0	113.6	189.7	199	-26.58
P7		Sand	Deficit irrigation	47.4	1495.7	83.5	194.9	129.0	183	-24.94
P8			Normal	43.3	1739.7	111.4	196.3	241.8	171	-25.05
P9	Lutzville	Sand	Deficit irrigation	74.8	3243.6	111.7	199.2	214.3	173	-23.76
P10			Normal	40.2	1627.7	59.4	147.9	148.8	236	-25.21
P11		Loamy sand	Deficit irrigation	844.5	914.4	22.2	36.4	80.1	321	-26.50
P12			Normal	52.3	2196.2	79.6	113.2	187.8	209	-26.68
P13	Koekenaap	Sand	Deficit irrigation	52.8	4981.9	67.8	154.0	141.7	130	-23.69
P14			Normal	47.4	1164.4	83.9	165.4	145.9	282	-27.01
P15		Sandy loam	Deficit irrigation	287.3	1314.4	38.2	78.8	109.0	346	-24.62
P16			Normal	169.1	819.6	32.8	60.1	97.0	358	-25.97

[1] Refer to Table 3.1 for description of the plots.

Table 5.4 Cations, phosphorus (P) and total nitrogen (N) contents at harvest in Cabernet Sauvignon juice from 16 plots representing different localities, soil texture and irrigation strategies in the Lower Olifants River region during the 2007/08 season.

Plot no[1]	Locality	Soil texture	Irrigation strategy	Na (mg/L)	K (mg/L)	Ca (mg/L)	Mg (mg/L)	P (mg/L)	N (mg/L)
P1	Kapel	Sand	Deficit irrigation	10.2	1428.0	70.4	133.0	50.7	243
P2			Normal	45.7	987.3	292.8	104.8	108.7	297
P3		Sandy loam	Deficit irrigation	77.7	1698.8	61.3	126.4	102.6	430
P4			Normal	13.0	1426.4	50.1	121.9	49.5	76
P5	Vredendal	Sandy loam	Deficit irrigation	7.7	2180.2	34.8	95.8	127.3	256
P6			Normal	6.7	11458.0	35.3	86.7	138.2	158
P7		Sand	Deficit irrigation	17.4	7942.6	79.6	144.0	157.8	373
P8			Normal	23.4	915.7	35.7	88.9	126.2	319
P9	Lutzville	Sand	Deficit irrigation	20.9	948.6	36.4	94.3	140.7	340
P10			Normal	17.5	1133.3	59.1	130.1	148.3	308
P11		Loamy sand	Deficit irrigation	33.7	2911.2	85.7	169.6	269.5	307
P12			Normal	18.3	1887.0	48.8	101.1	236.4	339
P13	Koekenaap	Sand	Deficit irrigation	19.5	2439.7	56.2	134.6	203.3	276
P14			Normal	30.0	2068.3	71.9	134.1	179.2	257
P15		Sandy loam	Deficit irrigation	29.2	2891.5	83.1	162.8	214.3	198
P16			Normal	22.5	1313.8	37.1	111.7	162.8	241

[1] Refer to Table 3.1 for description of the plots.

Table 5.5 Alcohol, pH, total acid (TA), malic acid (MA), residual sugar (RS), volatile acid (VA), potassium (K), anthocyanins and wine colour in Cabernet Sauvignon wines from 16 plots representing different localities, soil texture and irrigation strategies in the Lower Olifants River region during the 2006/07 season.

Plot no[1]	Locality	Soil texture	Irrigation strategy	Alcohol (%)	pH	TA (g/L)	MA (g/L)	RS (g/L)	VA (g/L)	K (mg/L)	Anthocyanins (mg/L)	Wine colour 420 nm	520 nm	620 nm
P1	Kapel	Sand	Deficit irrigation	15.65	3.72	5.81	2.08	4.80	0.23	1505	223	5.54	8.87	2.05
P2			Normal	14.74	3.56	5.85	1.57	4.24	0.23	831	231	3.65	5.46	1.30
P3		Sandy loam	Deficit irrigation	14.49	4.30	4.73	0.92	3.24	0.29	1743	205	3.15	3.76	1.13
P4			Normal	13.06	4.30	4.51	0.92	2.60	0.34	1783	218	2.37	2.84	0.80
P5	Vredendal	Sandy loam	Deficit irrigation	15.32	4.09	5.22	1.77	3.71	0.17	2150	195	2.97	3.68	0.93
P6			Normal	15.68	4.23	5.35	1.56	4.50	0.18	2435	186	2.74	3.3	0.88
P7		Sand	Deficit irrigation	15.00	3.95	5.25	0.78	3.91	0.14	1525	213	3.49	4.52	1.15
P8			Normal	16.00	4.27	5.12	0.78	4.68	0.27	1910	186	4.37	5.38	1.59
P9	Lutzville	Sand	Deficit irrigation	15.28	3.88	6.04	2.16	6.07	0.16	1223	217	4.30	6.01	1.39
P10			Normal	14.26	3.95	5.13	0.81	4.54	0.14	1243	216	2.97	4.06	1.01
P11		Loamy sand	Deficit irrigation	14.44	4.73	4.45	1.07	3.97	0.20	2188	170	2.6	2.89	0.98
P12			Normal	13.22	5.09	4.79	1.07	6.37	0.39	2970	187	2.43	2.47	0.82
P13	Koekenaap	Sand	Deficit irrigation	15.30	3.64	6.26	2.56	1.66	0.16	1670	296	4.55	7.64	1.55
P14			Normal	14.66	3.86	5.72	2.01	1.39	0.31	1745	219	2.76	3.97	0.85
P15		Sandy loam	Deficit irrigation	17.66	4.21	5.42	2.43	2.48	0.35	2115	190	4.71	6.24	1.64
P16			Normal	15.03	4.09	5.51	2.91	1.60	0.24	2385	196	2.28	2.83	0.71

[1] Refer to Table 3.1 for description of the plots.

Table 5.6 Alcohol, pH, total acid (TA), malic acid (MA), residual sugar (RS), volatile acid (VA), potassium (K), anthocyanins and wine colour in Cabernet Sauvignon wines from 16 plots representing different localities, soil texture and irrigation strategies in the Lower Olifants River region during the 2007/08 season.

Plot no[1]	Locality	Soil texture	Irrigation strategy	Alcohol (%)	pH	TA (g/L)	MA (g/L)	RS (g/L)	VA (g/L)	K (mg/L)	Anthocyanins (mg/L)	Wine colour 420 nm	520 nm	620 nm
P1	Kapel	Sand	Deficit irrigation	13.16	3.72	5.01	1.78	1.26	0.20	1680	288	3.55	4.88	1.31
P2			Normal	14.83	3.62	5.88	2.13	1.26	0.16	981	325	3.21	4.70	1.03
P3		Sandy loam	Deficit irrigation	14.19	3.75	5.46	2.45	1.43	0.27	1720	292	2.88	3.49	0.85
P4			Normal	13.85	3.74	5.30	2.06	1.39	0.13	1745	271	2.47	2.76	0.69
P5	Vredendal	Sandy loam	Deficit irrigation	14.39	3.82	4.71	1.92	1.46	0.24	2085	283	2.21	2.59	0.71
P6			Normal	13.92	3.81	4.83	2.09	1.63	0.24	2470	213	1.73	1.81	0.49
P7		Sand	Deficit irrigation	13.91	3.80	4.47	1.24	1.63	0.21	2010	246	4.28	5.90	1.65
P8			Normal	14.65	3.83	4.51	0.86	1.36	0.21	1950	238	3.76	4.88	1.40
P9	Lutzville	Sand	Deficit irrigation	13.94	3.88	5.23	0.73	1.43	0.63	2445	196	4.24	5.05	1.53
P10			Normal	14.59	3.72	4.95	1.58	1.49	0.36	1640	235	2.49	2.68	0.77
P11		Loamy sand	Deficit irrigation	15.37	4.00	6.67	1.54	2.21	1.05	2950	141	2.67	2.77	0.94
P12			Normal	15.05	4.07	5.30	1.34	1.39	0.38	3380	153	2.47	2.70	0.86
P13	Koekenaap	Sand	Deficit irrigation	15.07	3.64	5.71	2.17	1.60	0.15	1540	263	3.82	5.90	1.30
P14			Normal	14.58	3.72	4.76	0.77	1.53	0.24	1745	227	3.63	4.81	1.23
P15		Sandy loam	Deficit irrigation	15.54	3.80	4.92	0.70	1.46	0.54	1885	136	3.09	3.71	0.99
P16			Normal	13.30	3.79	4.63	1.15	1.09	0.38	2040	223	2.53	3.29	0.95

[1] Refer to Table 3.1 for description of the plots.

Table 5.7 Colour, acidity, fullness (body) and astringency in Cabernet Sauvignon wines from 16 plots representing different localities, soil texture and irrigation strategies in the Lower Olifants River region during the 2006/07 and 2007/08 seasons.

Plot no[1]	Locality	Soil texture	Irrigation strategy	Wine colour (%)		Acidity (%)		Fullness (%)		Astringency (%)	
				2006/07	2007/08	2006/07	2007/08	2006/07	2007/08	2006/07	2007/08
P1	Kapel	Sand	Deficit irrigation	88.65	76.73	53.99	52.08	59.85	45.08	56.81	37.67
P2			Normal	86.47	70.00	65.19	56.00	62.05	62.67	40.30	34.75
P3		Sandy loam	Deficit irrigation	62.31	67.17	57.82	56.75	34.76	48.58	36.73	28.18
P4			Normal	55.30	59.25	54.13	52.64	22.49	45.92	38.42	31.91
P5	Vredendal	Sandy loam	Deficit irrigation	67.66	52.82	52.94	50.00	43.56	42.50	36.04	26.17
P6			Normal	71.95	61.45	57.16	47.75	43.89	43.25	32.12	32.00
P7		Sand	Deficit irrigation	74.06	91.44	62.11	48.50	49.72	59.90	46.63	28.67
P8			Normal	79.60	84.83	49.31	51.75	54.35	64.58	44.95	31.75
P9	Lutzville	Sand	Deficit irrigation	78.09	71.08	55.51	60.55	50.83	58.75	50.69	32.80
P10			Normal	63.17	58.73	44.65	49.10	40.72	52.42	35.97	28.50
P11		Loamy sand	Deficit irrigation	46.53	60.09	54.65	49.10	37.18	44.70	34.32	26.27
P12			Normal	48.09	55.36	44.16	51.08	35.77	43.17	35.45	32.64
P13	Koekenaap	Sand	Deficit irrigation	84.88	87.09	67.99	58.58	53.69	61.27	45.15	38.00
P14			Normal	65.48	72.64	64.21	55.82	50.61	46.17	49.50	39.73
P15		Sandy loam	Deficit irrigation	78.68	64.50	57.23	58.33	58.04	51.08	50.20	27.42
P16			Normal	48.58	75.45	54.32	46.17	30.57	43.58	23.87	36.73

[1] Refer to Table 3.1 for description of the plots.

Table 5.8 Vegetative fresh, vegetative dry, berry and spicy flavour in Cabernet Sauvignon wines from 16 plots representing different localities, soil texture and irrigation strategies in the Lower Olifants River region during the 2006/07 and 2007/08 seasons.

Plot no[1]	Locality	Soil texture	Irrigation strategy	Vegetative fresh (%)		Vegetative dry (%)		Berry (%)		Spicy (%)	
				2006/07	2007/08	2006/07	2007/08	2006/07	2007/08	2006/07	2007/08
P1	Kapel	Sand	Deficit irrigation	25.66	47.60	26.68	40.92	75.25	57.92	36.39	41.42
P2			Normal	42.57	50.45	13.86	30.36	63.52	58.92	29.88	30.82
P3		Sandy loam	Deficit irrigation	47.60	47.00	37.06	43.40	47.34	52.18	23.17	34.20
P4			Normal	56.66	37.25	16.39	29.44	30.46	44.27	0.88	34.82
P5	Vredendal	Sandy loam	Deficit irrigation	36.85	40.64	21.78	28.67	31.30	41.67	27.23	27.09
P6			Normal	43.49	46.42	29.04	44.36	38.84	30.67	26.40	23.18
P7		Sand	Deficit irrigation	41.51	54.64	31.02	31.27	39.60	63.27	24.83	29.64
P8			Normal	37.09	48.50	12.75	31.92	55.60	61.50	44.91	32.82
P9	Lutzville	Sand	Deficit irrigation	51.87	44.20	18.92	36.00	42.75	47.17	33.17	30.20
P10			Normal	45.40	52.67	12.38	27.40	54.13	41.50	27.90	28.00
P11		Loamy sand	Deficit irrigation	64.58	34.91	47.38	47.10	24.92	58.18	18.90	26.27
P12			Normal	53.68	31.30	65.54	36.18	12.10	46.92	16.04	19.63
P13	Koekenaap	Sand	Deficit irrigation	64.65	50.45	22.11	44.64	50.72	39.00	31.11	22.40
P14			Normal	53.47	56.90	16.96	37.42	51.32	41.30	28.08	24.82
P15		Sandy loam	Deficit irrigation	34.24	53.33	20.54	37.70	46.38	42.92	40.59	30.70
P16			Normal	40.24	38.42	20.92	35.22	40.92	45.25	23.40	31.80

[1] Refer to Table 3.1 for description of the plots.
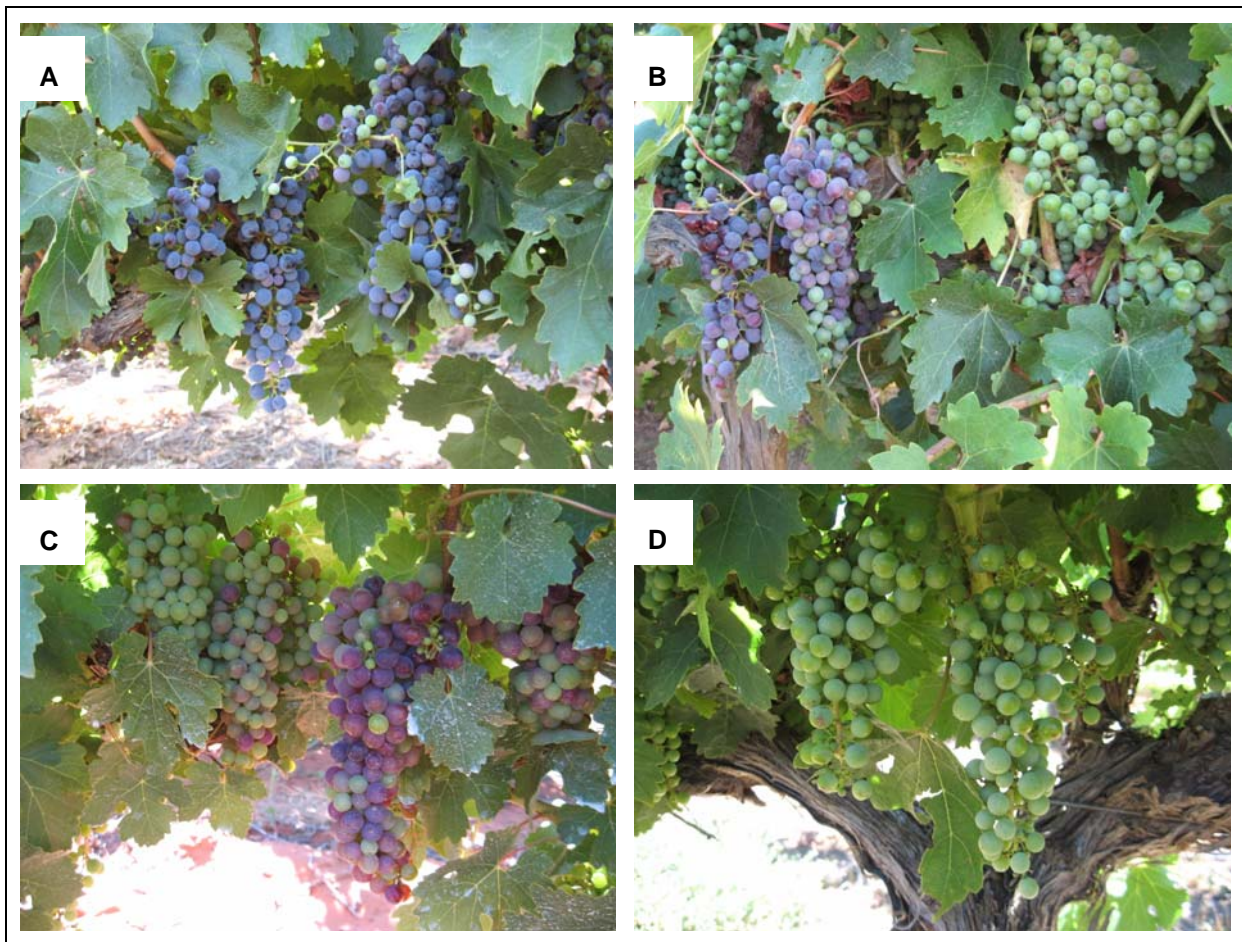
Figure 5.1   Visual differences in berry ripeness in Cabernet Sauvignon vineyards on 9 January 2008 at (A) Kapel (P3), (B) Vredendal (P5), (C) Lutzville (P11) and (D) Koekenaap (P15).
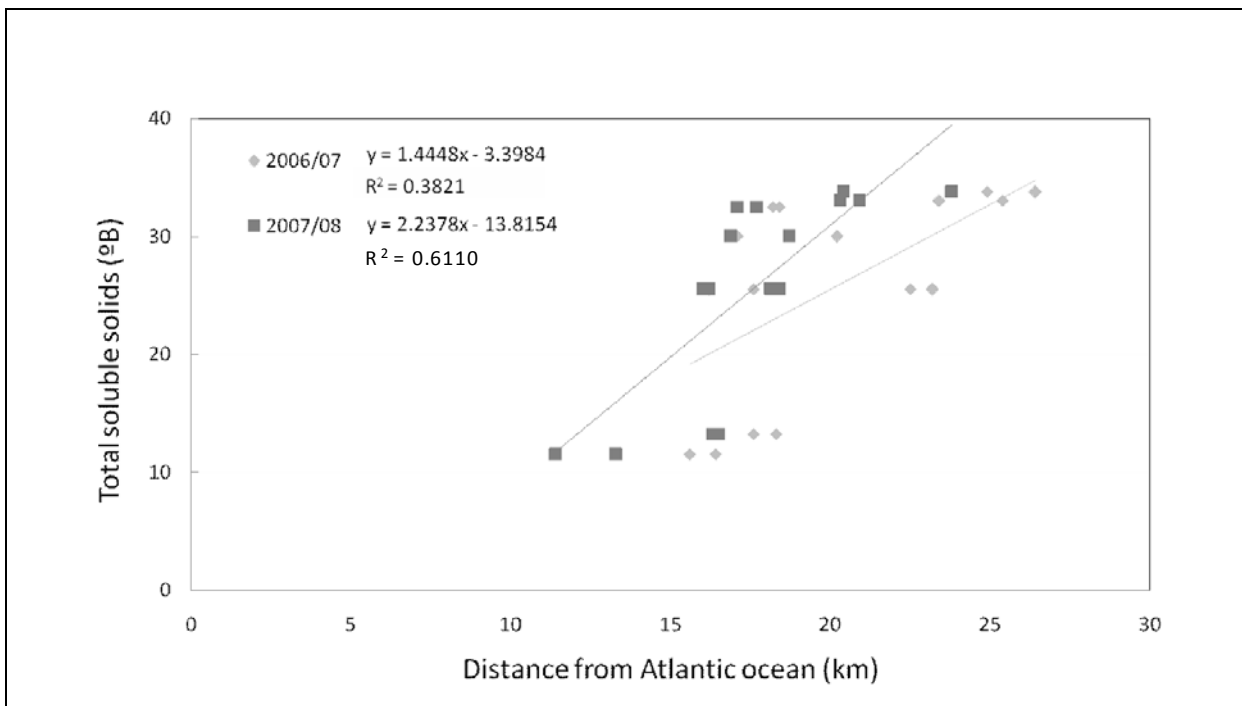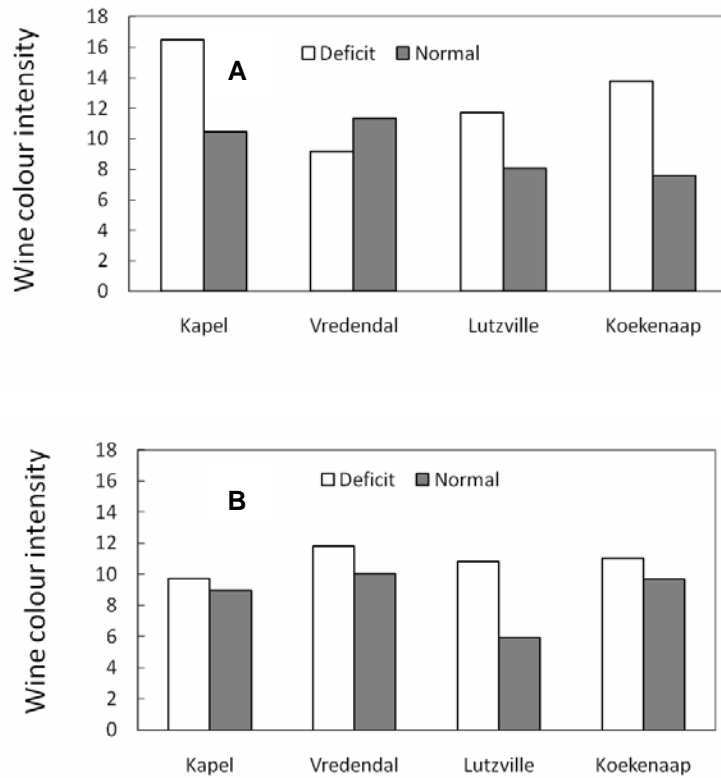

Figure 5.2   The relationship between total soluble solids and distance from the Atlantic Ocean as determined on 26 January 2007 and 24 January 2008, respectively, in the Lower Olifants River region.

Figure 5.3   Trends in wine colour intensity (A420 + A520 + A620) of Cabernet Sauvignon in sandy soils at four localities in relation to deficit and normal irrigation strategies in the Lower Olifants River region as measured during (A) the 2006/07 season and (B) the 2007/08 season.
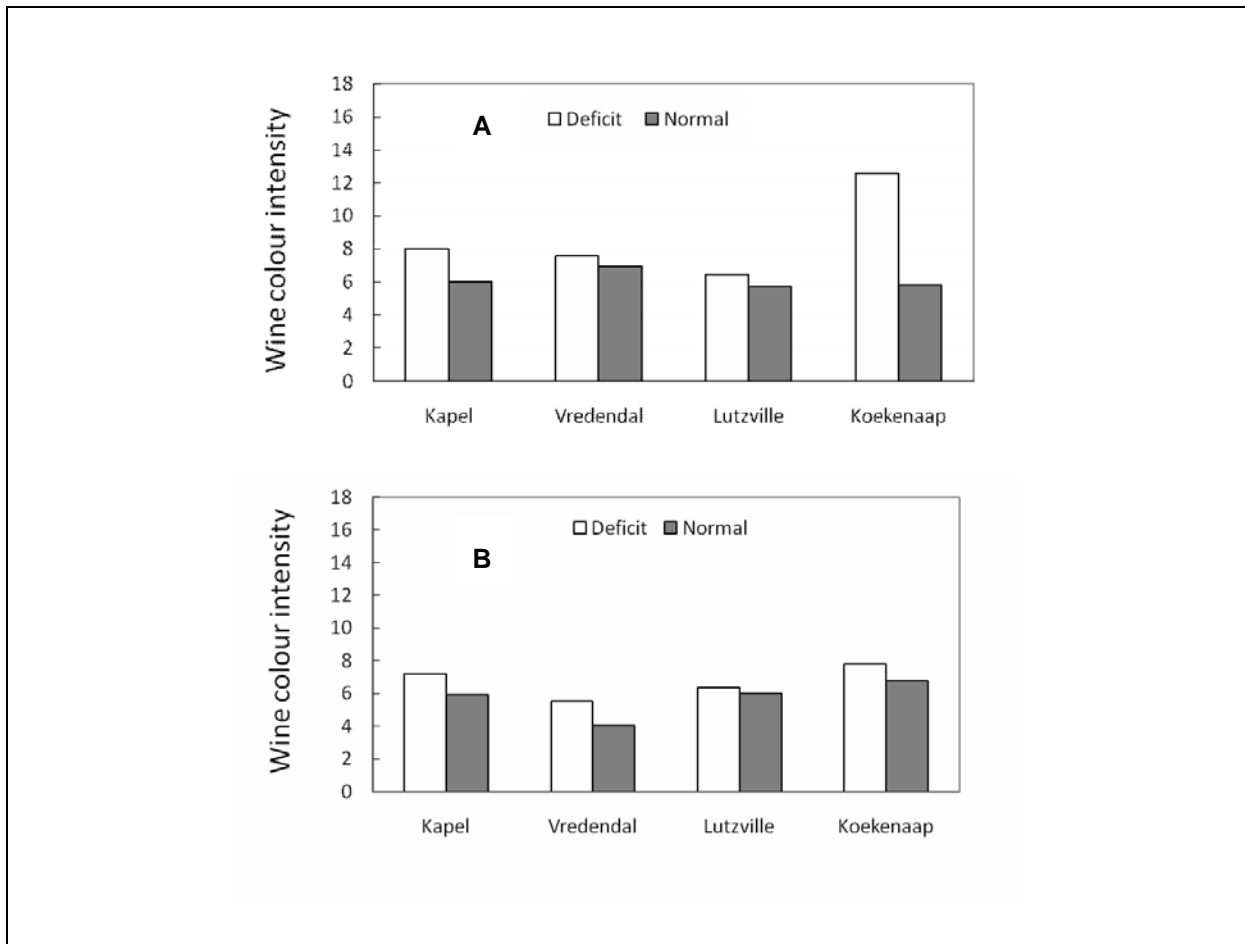
Figure 5.4 Trends in wine colour intensity (A420 + A520 + A620) of Cabernet Sauvignon in sandy loam soils at four localities in relation to deficit and normal irrigation strategies in the Lower Olifants River region as measured during (A) the 2006/07 season and (B) the 2007/08 season.
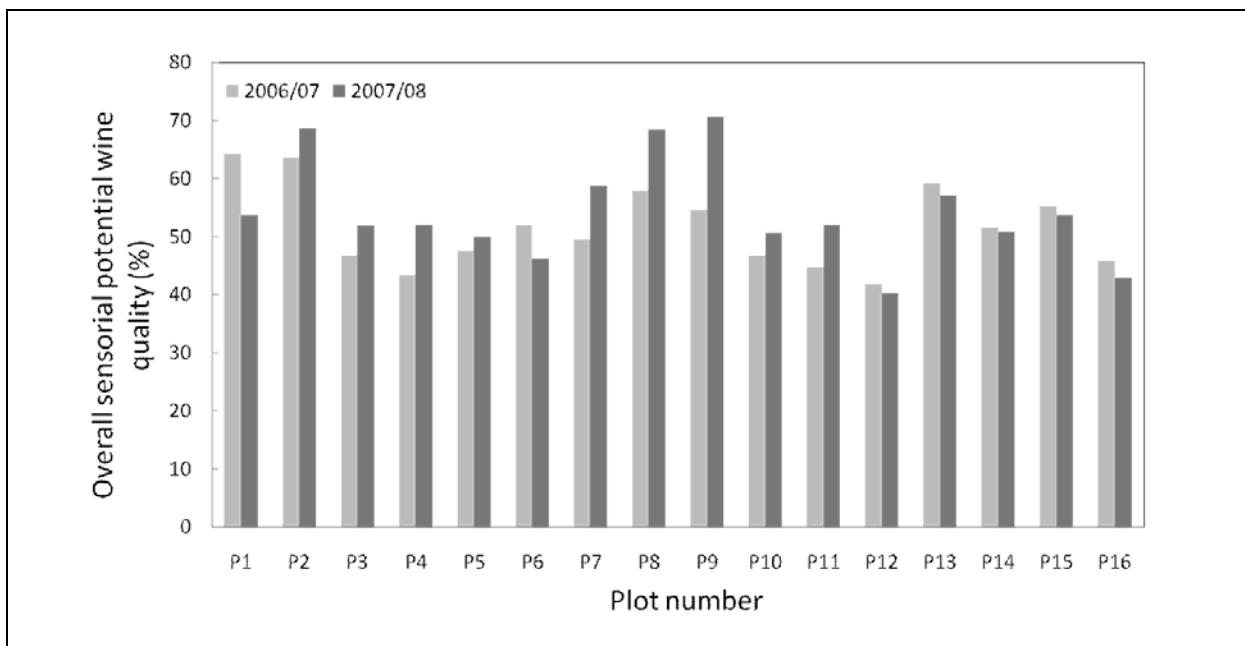

Figure 5.5 Overall sensorial potential wine quality of Cabernet Sauvignon grapevines in the Lower Olifants River region where soil and grapevine water status were monitored during the 2006/07 and 2007/08 seasons.

Figure 5.6 Normal irrigated Cabernet Sauvignon grapevines in a sandy soil at Kapel (P2) just before harvest.

Figure 5.7 Normal irrigated Cabernet Sauvignon grapevines in a sandy soil at Lutzville (P12) just before harvest.
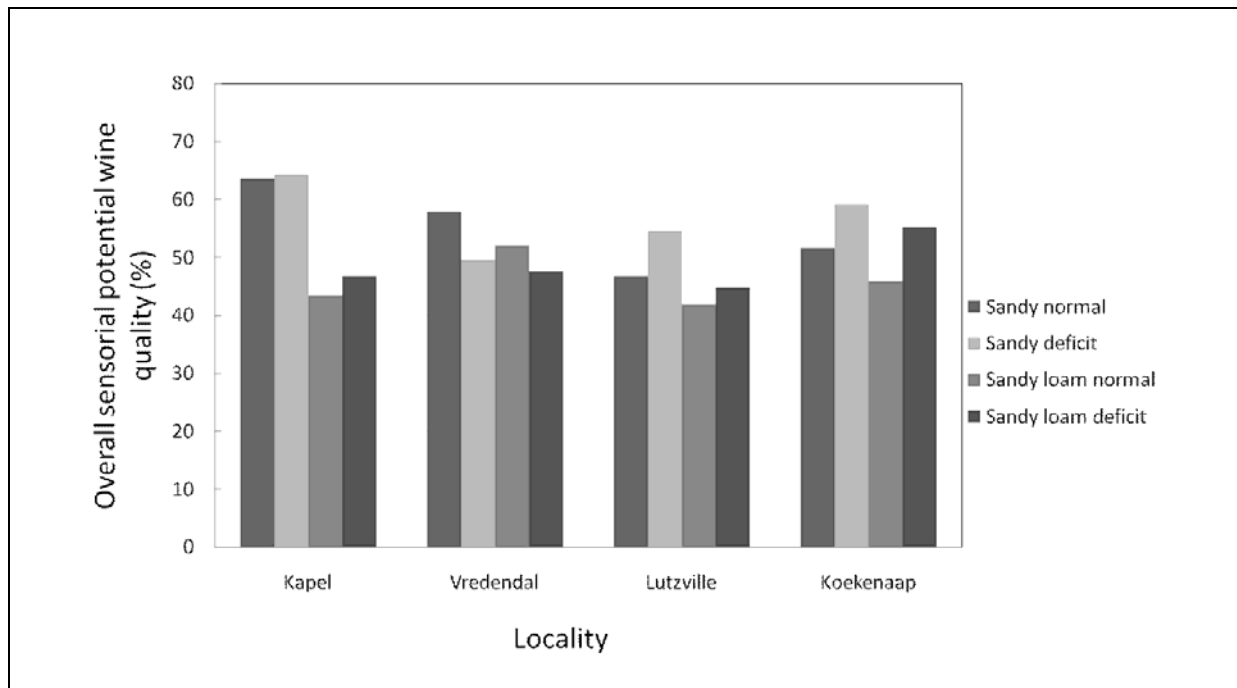
Figure 5.8 Trends in sensorial wine quality of Cabernet Sauvignon in sandy loam soils at four localities in relation to soil texture as well as deficit and normal irrigation strategies in the Lower Olifants River region as measured during the 2006/07 season.
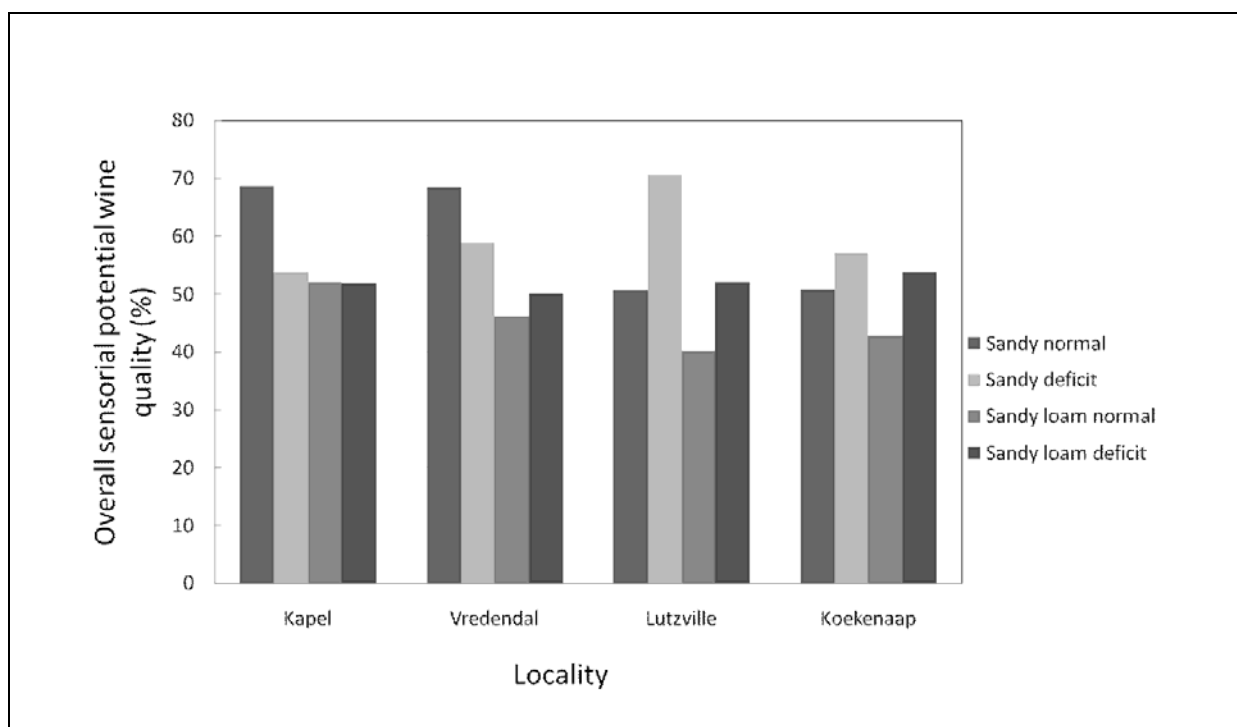
Figure 5.9 Trends in sensorial wine quality of Cabernet Sauvignon in sandy loam soils at four localities in relation to soil texture as well as deficit and normal irrigation strategies in the Lower Olifants River region as measured during the 2007/08 season.
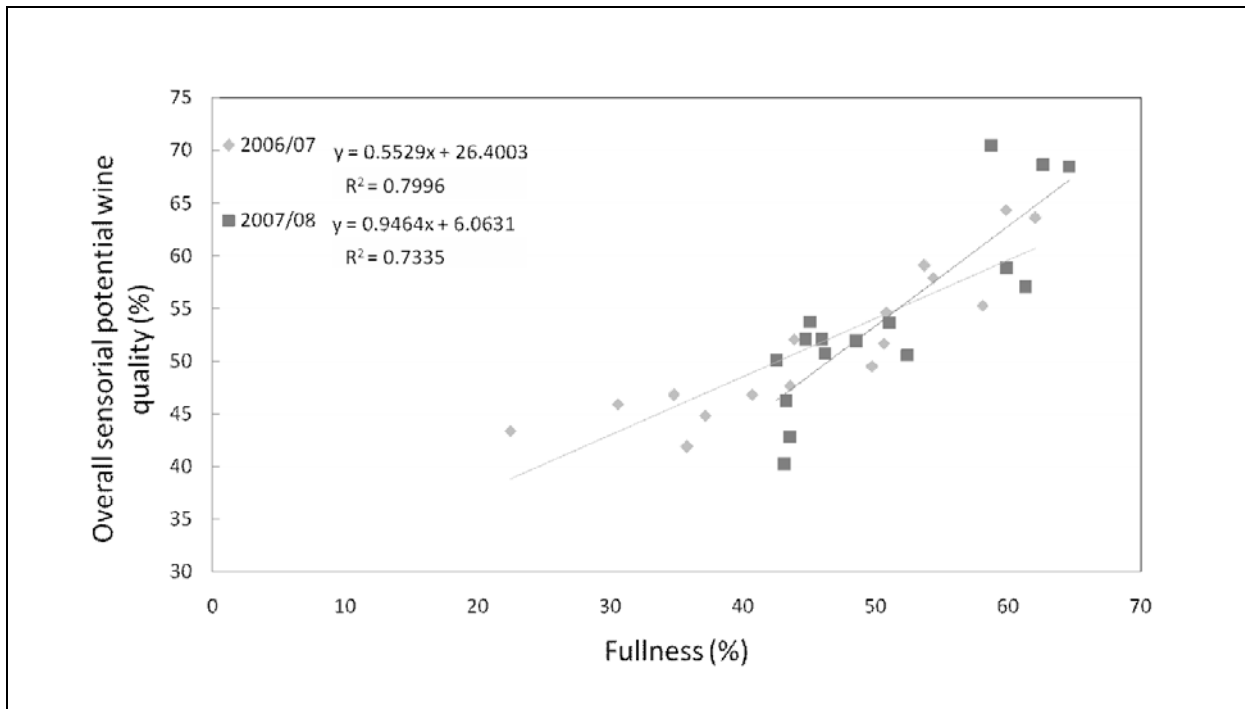
Figure 5.10 Relationship between sensorial quality and fullness (body) in Cabernet Sauvignon wines in the Lower Olifants River region during the 2006/07 and 2007/08 seasons, respectively,
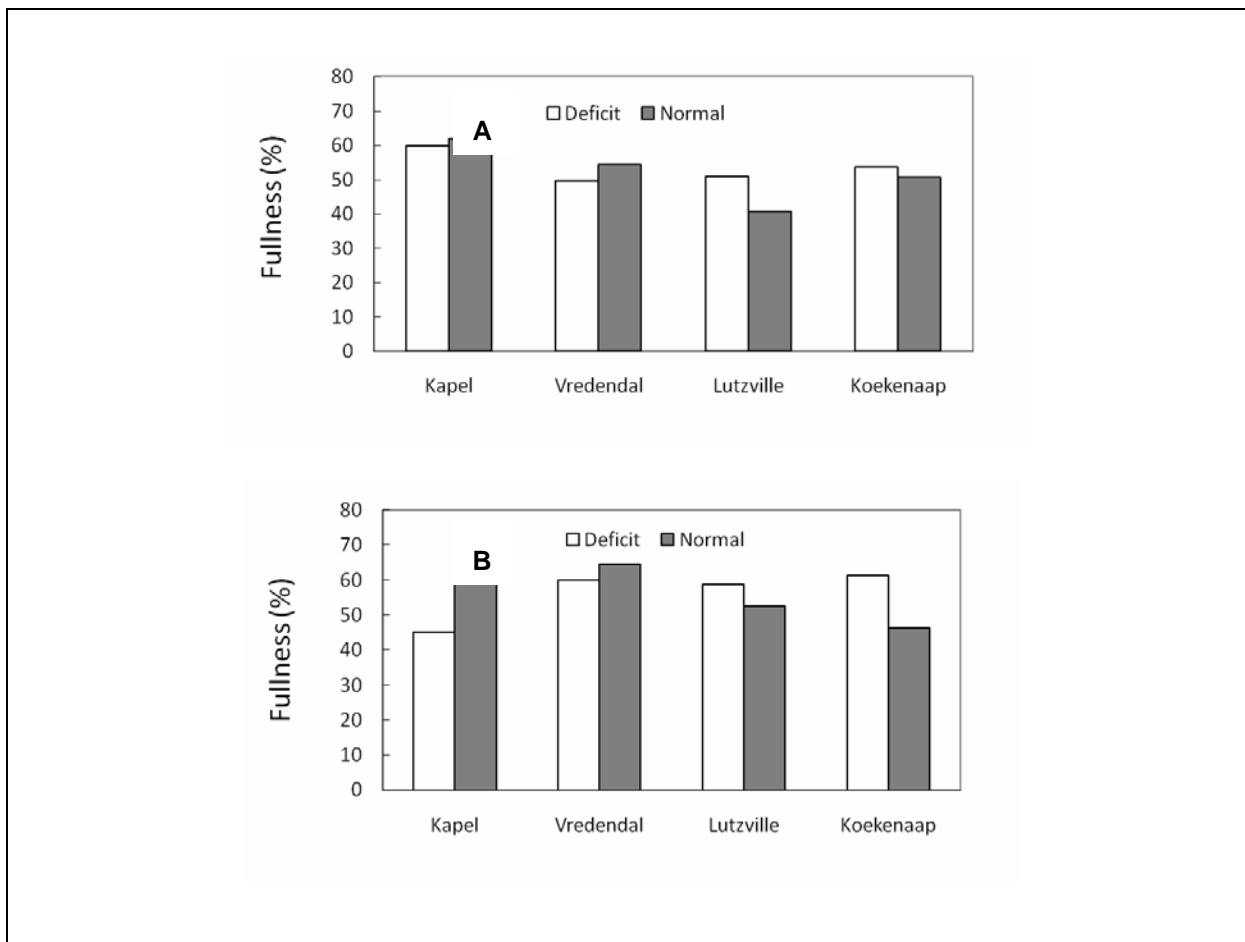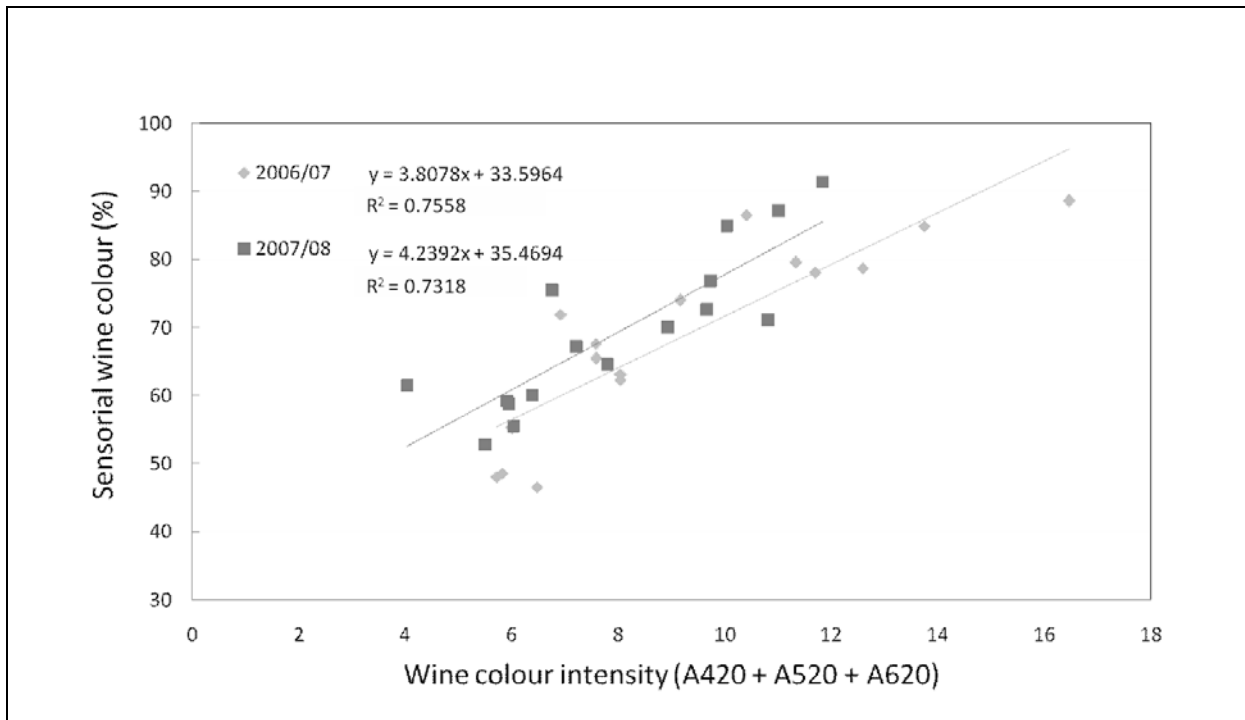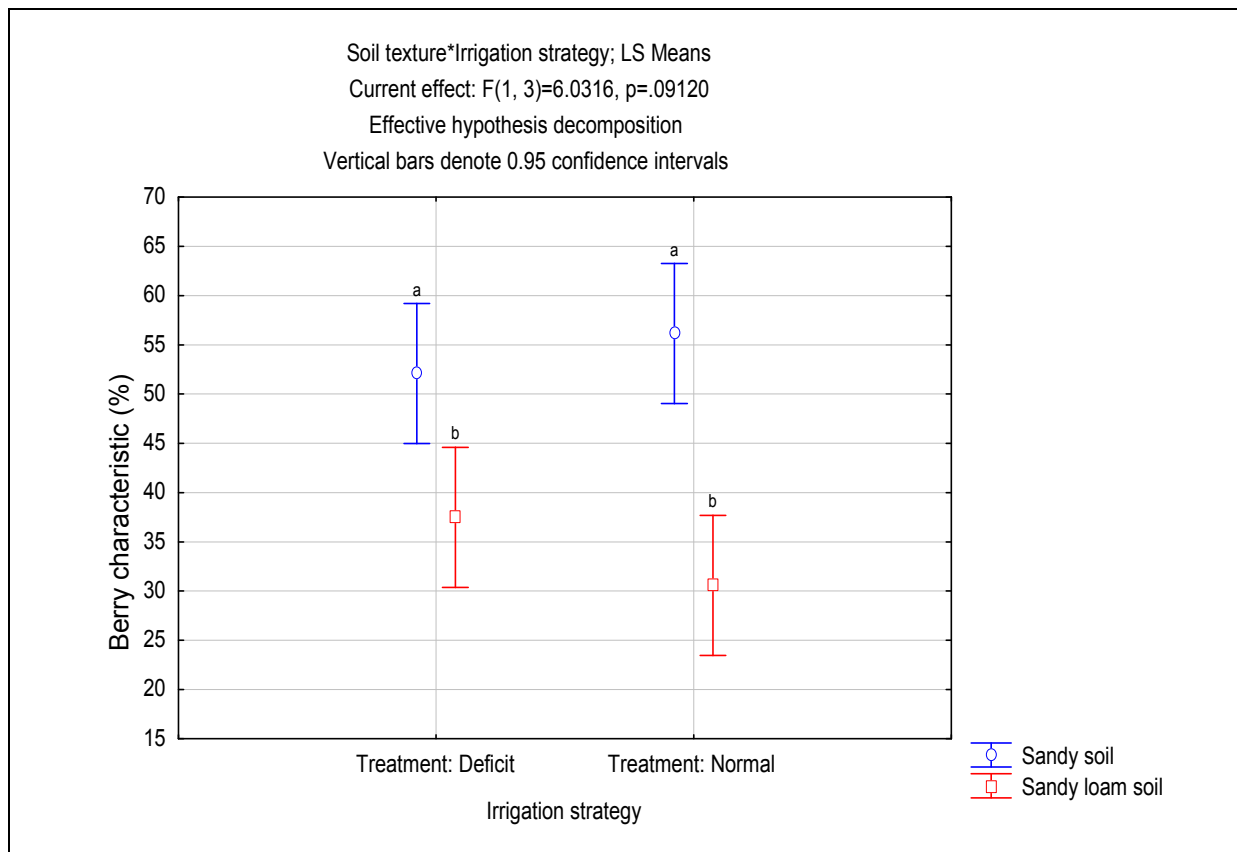

Figure 5.11 Trends in wine fullness of Cabernet Sauvignon in sandy soils at four localities in relation to deficit and normal irrigation strategies in the Lower Olifants River region as measured during (A) the 2006/07 season and (B) the 2007/08 season.
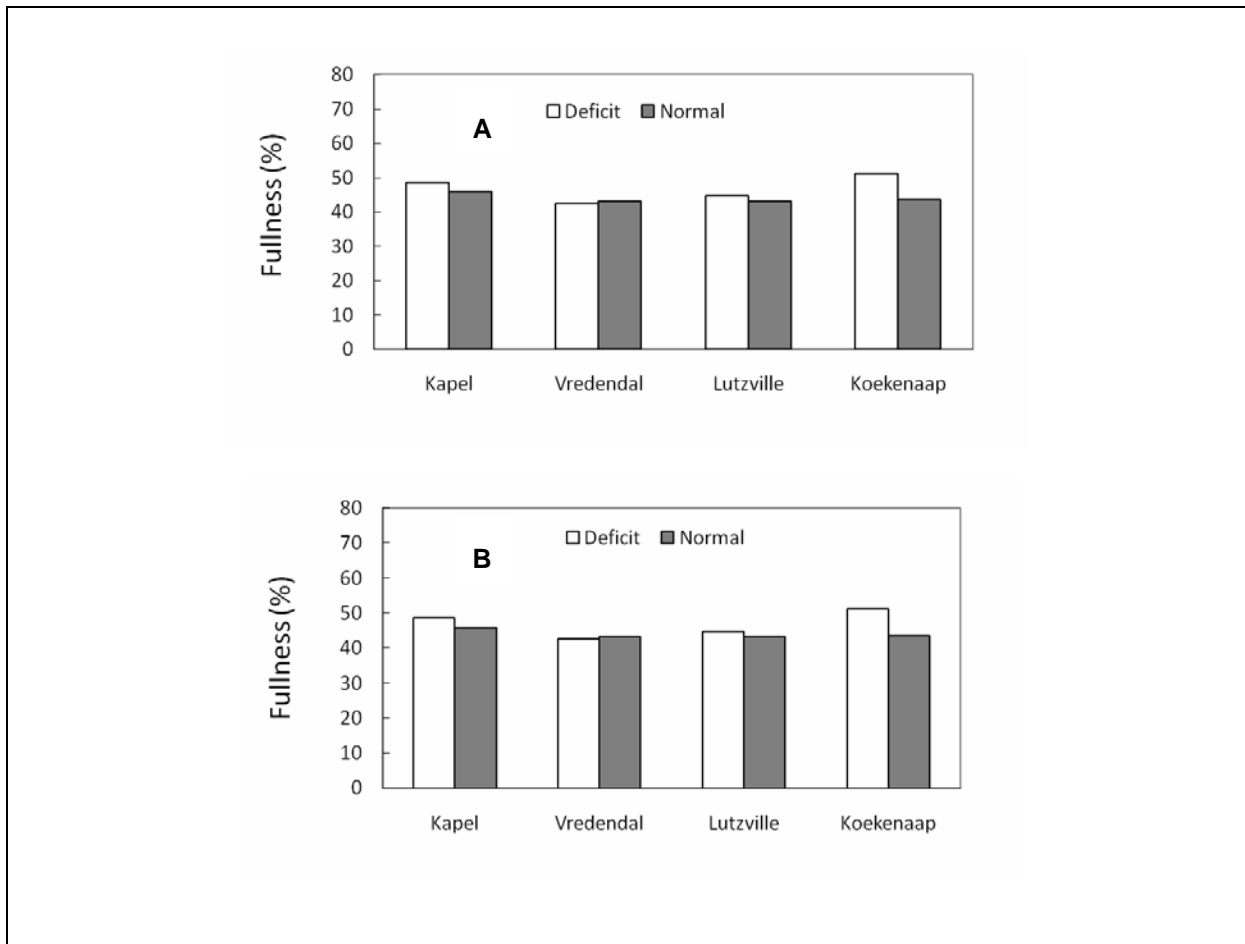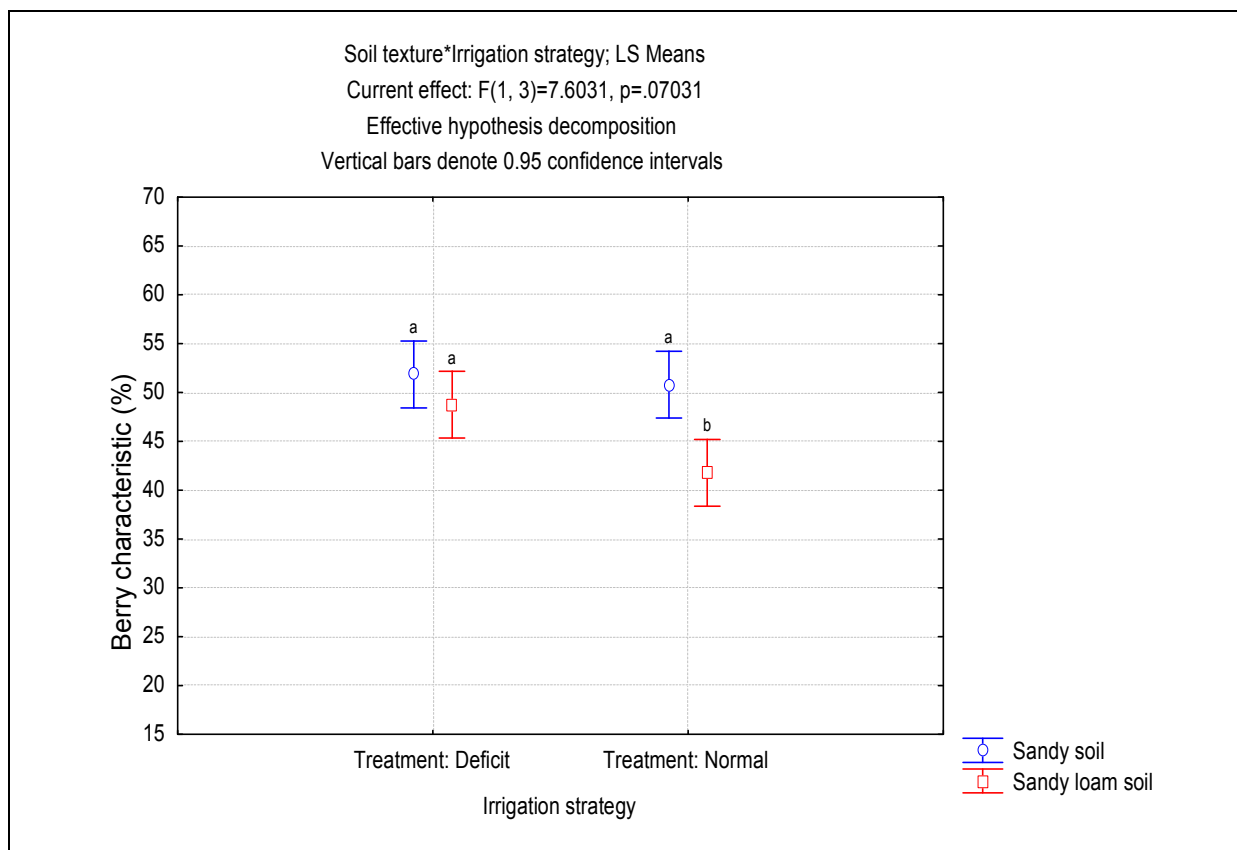
Figure 5.12   Trends in wine fullness of Cabernet Sauvignon in sandy loam soils at four localities in relation to deficit and normal irrigation strategies in the Lower Olifants River region as measured during (A) the 2006/07 season and (B) the 2007/08 season.

Figure 5.13   Relationship between sensorial colour and wine colour intensity of Cabernet Sauvignon wines in the Lower Olifants River region during the 2006/07 and 2007/08 seasons.
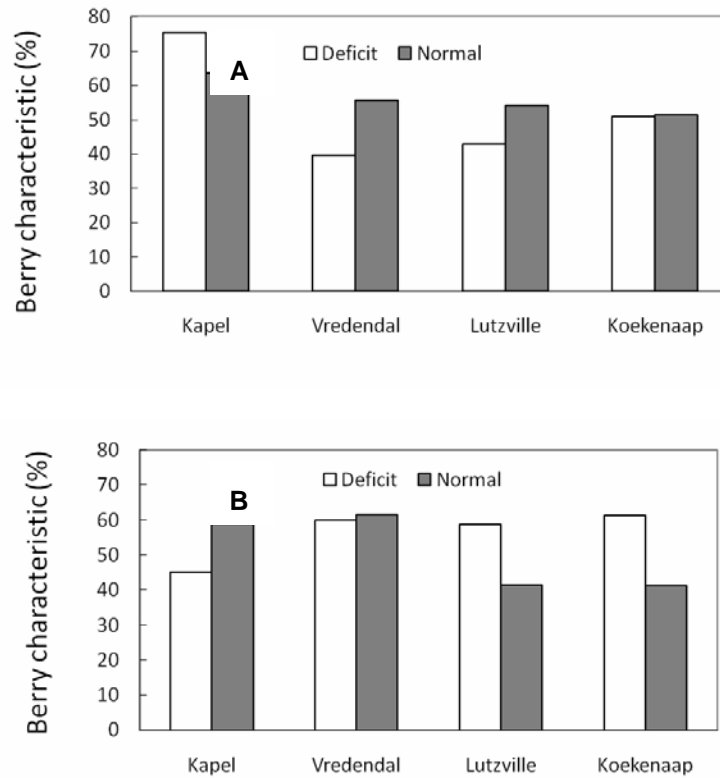
Figure 5.14   The effect of soil texture and irrigation strategy on the berry character in Cabernet Sauvignon wines in the Lower Olifants River region during the 2006/07 season.


Figure 5.15   The effect of soil texture and irrigation strategy on the berry character in Cabernet Sauvignon wines in the Lower Olifants River region during the 2007/08 season.

Figure 5.16 Trends in berry character intensity fullness in Cabernet Sauvignon wine in sandy soils at four localities in relation to deficit and normal irrigation strategies in the Lower Olifants River region as measured during (A) the 2006/07 season and (B) the 2007/08 season.
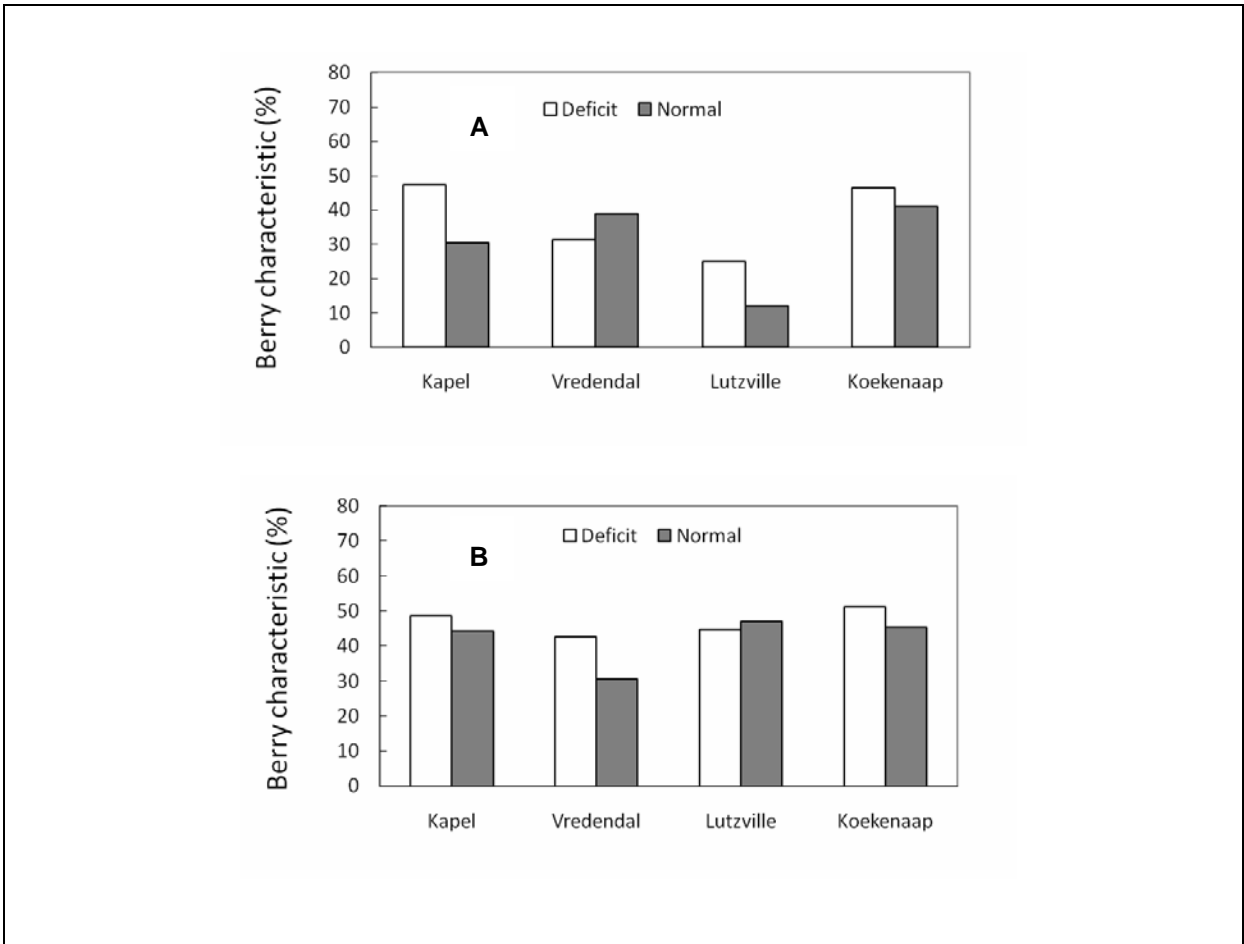
Figure 5.17 Trends in berry character intensity fullness in Cabernet Sauvignon wine in sandy loam soils at four localities in relation to deficit and normal irrigation strategies in the Lower Olifants River region as measured during (A) the 2006/07 season and (B) the 2007/08 season.

Chapter 6

GENERAL DISCUSSION AND CONCLUSIONS

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The proximity of the Atlantic Ocean plays an essential role in describing the potential for viticulture cultivation in the Lower Olifants River region. According to the mean February temperature, the Winkler index and the Huglin heliotermal index, three macro climatic regions were evident, i.e. (i) Klawer which is furthest inland, (ii) Vredendal and Lutzville and (iii) Ebenhaeser which is nearest to the Atlantic Ocean. However, according to the cool night index, only two distinct regions were evident, i.e. (i) Klawer with temperate, warm nights and (ii) Vredendal, Lutzville and Ebenhaeser with temperate nights. Furthermore, Klawer is prone to minimum daily temperatures during May of higher than 10ºC that could delay bud break in the following spring. The forgoing information is essential when deciding on a directive cultivar establishment policy in the Lower Olifants River region. The effect of the sea breeze on temperatures during the ripening period needs further investigation. Given the different macro climatic regions in the Lower Olifants River region, canopy management practices and even long term practices should differ between Kapel and Ebenhaeser on a cultivar basis as well as to obtain a certain wine style.

In general, minimum daily temperatures during February occurred between 05:00 and 07:00. Consequently, when mechanical harvesting is carried out in the night, time must be allowed for grapes to cool down before harvesting commences in order to deliver the coolest possible grapes to the wineries. This could be an important strategy for saving energy cost of cooling units in a winery. Low maximum daily temperatures were related to high relative humidity and low total daily solar radiation. The combination of these effects could lower evapotranspiration in vineyards closer to the ocean.

In the Lower Olifants River region, the top soils of soils further away from the river consist of wind blown sand. Fine sand particles were carried further and higher inland by the prevailing westerly winds from the Atlantic Ocean. Hence, the fine sand content in the top soil near the ocean was lower compared to those further inland. In contrast, the lower lying alluvial soils were formed by the Olifants River over the years. The soil organic carbon content of the sandy soils is very low. The sustainability of these sandy soils would benefit from planting winter cover crops, mulching or composting. These practices should be promoted to the grape growers.

Over the course of the day, irrespective of soil texture or locality, grapevines tended to recover more easily and to a higher level from water deficits early on in the season (November) compared to later (January). This could have been caused by the change in climate as the season progressed. Grapevines at Lutzville, nearest to the ocean tended to experience less water stress compared to the ones at Kapel. Differences in water stress became more pronounced as the season progressed probably due to the difference in prevailing atmospheric conditions between the inland localities and those nearer to the ocean. These results also suggest that measurement of diurnal leaf water potential cycles at various phenological stages is required to understand the effect of the climate and soil on grapevine water status.

During berry ripening, grapevines at Kapel experienced more midday water stress compared to the ones at Koekenaap, nearest to the ocean, irrespective of soil texture. However, seasonal variation in atmospheric conditions could influence the strength of the climatic effect. During a cooler season, e.g. in the 2006/07 season, the effect could be less pronounced compared to a warmer season, e.g. in the 2007/08 season. In a cool season, deficit irrigated grapevines at Kapel and Koekenaap would probably experience the same amount of water stress, irrespective of soil texture. However, during a warm season the effect of deficit irrigation would probably be more pronounced further inland.

Deficit irrigation increased midday water stress in grapevines compared to more frequently irrigated ones. Grapevines in the sandy soils were more easily subjected to water stress compared to the ones in the sandy loam soils. To induce deficit irrigation in grapevines in the sandy loam soils which lies within the flood line of the Olifants River, irrigation should be cut back or stopped at an early stage, i.e. shortly after bud break. This is considerably earlier compared to grapevines in the sandy loam and sandy soils further away from the river. The sandy soils will have a smaller wetted soil volume under drip irrigation compared to the sandy loam soils from which grapevine roots could extract nutrients and water. Irrigation scheduling should be adjusted accordingly.

Stem water potential were a more sensitive indicator of water deficits in grapevines compared to Ψ_L. The variation in Ψ_S could be related to the variation in soil water status, expressed in terms of Ψ_M. At a given Ψ_M, grapevines in the sandy soils experienced more water stress compared to the ones in sandy loam soils. The reason for this could be that the hydraulic conductivity in sandy soils decreases more rapidly as Ψ_M decreases compared to the heavier sandy loam soils.

The different climatic regions did not seem to have any effect on vegetative growth and yield of Cabernet Sauvignon grapevines. Approximately 79% of the variation in vegetative growth, quantified in terms of pruning mass, could be explained by the soil chemical and physical conditions, i.e. the soil organic carbon content, the soil texture, i.e. the amount of course sand and the water supply to the grapevine, i.e. the mean Ψ_M in the wettest soil layer from September to December. Vegetative growth of normal irrigated grapevines in sandy soils was ca. 60% lower compared to the normal irrigated grapevines in the sandy loam soils. Grapevines in the sandy soils were more sensitive to water deficits compared to the ones in the sandy loam soils. Deficit irrigation reduced vegetative growth of grapevines in the sandy soils by ca. 30% compared to little or no growth reduction on sandy loam soils. Deficit irrigation could improve the canopy quality of grapevines in sandy loam soils, i.e. the canopy score and CELAP value. However, CELAP was limited in terms of canopy height. Consequently, trellis systems that will allow higher canopies should be a priority in the Lower Olifants River region to achieve balanced grapevines. On the other hand, severe water deficits in sandy soils could be detrimental to grapevine canopy quality.

Deficit irrigation tended to reduced berry size, irrespective of soil texture. Early water stress in grapevines in sandy soils, i.e. at flowering, could reduce the number of

berries per bunch which will reduce grapevine yield. Variation in bunch mass reflected to a large extent in the yield. Deficit irrigation reduced yield of grapevines in the sandy soils by ca. 30%, whereas yield of grapevines in the heavier soils was only ca. 15% lower. The foregoing indicated that reproductive growth of grapevines in the sandy soils was more sensitive to water deficits compared to the ones in the heavier soils. During the 2006/07 season the yield reduction of grapevines in the sandy soils was induced by applying approximately 50% less water from flowering to véraison and 66% less from véraison to harvest. During the 2007/08 season approximately 40% and 72% less water was applied during the two periods, respectively. During the 2006/07 season the yield reduction of grapevines in the heavier sandy loam soils was induced by applying approximately 83% less water from flowering to véraison and 96% less from véraison to harvest. During the 2007/08 season approximately 83% and 88% less water was applied during the two periods, respectively. These results suggested that deficit irrigation could be applied in the heavier sandy loam soils to decrease berry size without reducing yield too severely. This implies that ca. 80% water could be saved from flowering to harvest as well as creating the possibility that smaller berries could improve wine quality potential. On the other hand, saving approximately 50% water in the sandy soils from flowering to harvest reduced yield by approximately 30%. Yield losses of this magitude would certainly not be economically viable.

The main driver for differences in vegetative growth and yield seems to be the differences in soil texture which determined the water supply to the grapevine. Water deficits had a strong effect on reproductive and vegetative growth of grapevines in sandy soils and can as such be used as a tool to manipulated the grapevine. On the other hand, intensive canopy management practices would play an important role to improve wine quality in Cabernet Sauvignon grapevines in the heavier sandy loam soils. The first step would be to reduce irrigation followed by additional canopy management practices, e.g. leaf removal or removal of laterals to further improve canopy quality. However, a costing needs to be done to estimate if the additional practices will be economically viable in terms of possible yield losses and the eventual wine quality.

Macro climate in the Lower Olifants River region had an influence on the phenological stages of the grapevine, i.e. the physiology of the grapevine was to a large extent driven by temperature. Consequently, the rate of sugar accumulation and the possible harvest date of Cabernet Sauvignon vineyards will be influenced by the proximity to the Atlantic Ocean.

Cabernet Sauvignon grapevines nearer to the ocean did not seem to produce grapes with higher potential for wine quality, i.e. higher TA and lower pH values. However, soil texture had an influence on wine quality and wine style even under climatic variation and intensive irrigation. Grapevines in the sandy soils tended to produce wines of higher overall sensorial quality potential compared to the ones in the sandy loam soils. Deficit irrigation tended to increase wine colour intensity (A420nm + A520nm + A620nm), irrespective of soil texture. Deficit irrigation tended to increase the fullness of wines produced from grapevines in the sandy loam soils. This could have

been an indirect effect due to reduced vegetative growth which could have improved bunch microclimate and stimulated the formation of anthocyanins. However, increased fullness could also have been caused by the decrease in berry size which concentrated metabolites, or stimulated the biosynthesis of phenolics directly. Too severe water stress in grapevines in the sandier soils could produce wines of inferior quality potential. Grapevines in the sandy soils produced wines with more intense berry character compared to those in the sandy loam soils. Deficit irrigation tended to increase the berry character in wines from grapevines in the sandy loam soils. This effect was probably achieved through the regulation of water supply which controlled grapevine vegetative growth. Less vigorous vegetative growth of vineyards in the sandy soils played an important role in producing wines with higher quality potential compared to vineyards in the heavier sandy loam soils. This was probably an indirect effect due to improved bunch microclimate which increased anthocyanin biosynthesis. However, water deficits could also directly affect the stimulation or breakdown of anthocyanins and flavour compounds. Furthermore, berry character in of wines from normal irrigated grapevines in the sandy soils tended to increase as distance from the Atlantic Ocean increased. This was probably caused by the difference in climate between the localities which affected the biosynthesis or breakdown of flavour compounds.

Irrigation strategies for grapevines in the sandy soils should be adapted according to soil depth. (i) In the shallow sandy soils Ψ_M should be ca. -0.005 to -0.010 MPa (no water deficits) from bud break to flowering, ca. -0.010 MPa; from flowering to véraison and ca. -0.015 to -0.020 MPa (mild water deficits) from véraison to harvest. Mean Ψ_M lower than -0.030 MPa from flowering to harvest in the shallow sandy soils could be too low and probably would have detrimental effects on reproductive and vegetative growth of grapevines. (ii) In the deep, red sandy soils Ψ_M should be ca. -0.005 to -0.010 MPa (no water deficits) from bud break to flowering, ca. -0.040 MPa from flowering to véraison and ca. -0.040 MPa (moderate water deficits) from véraison to harvest. Lower mean Ψ_M values during the flowering to harvest stage could be allowed in the deep sands compared to the shallow red sands. These two strategies would probably control the vegetative growth, possibly stimulate anthocyanin synthesis, the concentration of metabolites and increase the skin to flesh ratio.

It seemed that irrigation strategies for grapevines in the heavier sandy loam soils should be adapted according to the distance from the main course of the river. (i) In the sandy loam soil further away from the river Ψ_M should be ca. -0.010 MPa from bud break to flowering (no water deficits), ca. -0.050 MPa from flowering to véraison and ca. -0.070 MPa from véraison to harvest. (ii) In the sandy loam soils on the banks of the river where water tables could have formed when the vineyards were submerged during the winter Ψ_M should be ca. -0.030 MPa from bud break to flowering, ca. -0.050 MPa from flowering to véraison and ca. -0.070 MPa from véraison to harvest. The objective of the latter strategy is to impose higher water deficits early in the season in an attempt to control vegetative growth since the deeper roots, i.e. deeper than 1.5 m, could supply grapevines with water from the water table.

Predawn leaf water potential values of ca. -0.4 MPa in grapevines in sandy soils were probably the ideal in terms of balancing the vegetative and reproductive growth pea size and ripening to achieve high wine quality potential. Predawn leaf water potential values of ca. -0.6 MPa seemed to be a threshold between moderate constraints and severe water stress in the sandy soils. In the heavier sandy loam soils Ψ_{PD} values of ca. -0.5 MPa were probably the ideal in terms of balancing the vegetative and reproductive growth from pea size to ripening.

Further research is necessary to differentiate on a cultivar basis what the effect of soil texture in the Lower Olifants River region would be on wine style and quality potential.