The effect of atmospheric and soil conditions on the grapevine water status

by

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DECLARATION

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

Name of candidate

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SUMMARY

Due to the extraordinary drought resistance of the grapevine, viticulture without irrigation in the winter rainfall coastal areas of South Africa is a feasible and commonly used practice. Wine quality is largely determined by the quality of the grapes from which it is made. Grapevine physiology is affected both directly and indirectly by water stress, which may vary according to soil type and prevailing atmospheric conditions. The water status of the grapevine can affect grape composition profoundly, either directly or indirectly, in either a positive or negative way, depending on the degree as well as the duration of water stress. There are three important factors involved in the development of water stress, namely the transpiration rate, the rate of water movement from the soil to the roots, and the relationship of soil water potential to leaf water potential. All three these factors are affected by atmospheric and/or soil conditions.

In warm winelands such as South Africa (Western Cape), with a mediterranean climate which is characterised by a hot, dry summer period, the most important characteristic of soil is its ability to supply sufficient water to the grapevine during the entire growing season. Leaf water potential (Ψ_l) has gained wide acceptance as a fundamental measure of grapevine water status, and has been widely applied in viticultural research. Shortly before dawn, Ψ_l approaches equilibrium with soil water potential and reaches a maximum daily value.

The study formed an integral part of a comprehensive, multi-disciplinary research project (ARC Infruitec-Nietvoorbij Project No. WW13/01) on the effect of soil and climate on wine quality, which commenced in 1993 and will be completed in 2004. This study was conducted during the 2002/03 growing season in two Sauvignon blanc vineyards situated at Helshoogte and Papegaaiberg, both in the Stellenbosch district, approximately nine kilometres apart. Two experiment plots, representing contrasting soil types in terms of soil water regime, were selected in each vineyard. At Helshoogte the two soils represented the Tukulu and Hutton forms, and the soils at Papegaaiberg were of the Avalon and Tukulu forms.

The aim of this study was to determine the effect of atmospheric conditions and soil water status on the level of water stress in the grapevines for each soil at each locality, as well as the effect of grapevine water stress on yield and wine quality. This was done by determining and comparing the soil water status, soil water holding capacity of the soils and the evapotranspiration of the grapevines on the two different soils, at each of the two localities differing in mesoclimate and topography. The atmospheric conditions at the two localities during the 2002/03 season were also determined and compared to the long-term average atmospheric conditions, and the level of water stress of grapevines on each soil at each locality was measured.

During the 2002/03 growing season, atmospheric conditions were relatively warm and dry in comparison to the long-term averages of previous seasons. These conditions accentuated the effects of certain soil properties that may not come forward during wetter, normal seasons.

The usually wet Tukulu soil at Helshoogte was drier than expected during the 2002/03 season compared to the Hutton soil. Due to more vigorous growth on the Tukulu soil, grapevines extracted more soil water early in the season, leading to a low soil water matric potential and more water stress in the grapevines. Due to the higher vigour, resulting in more canopy shading, and more water stress, the dominant aroma in wines from the Tukulu soil was fresh vegetative. The Hutton soil maintained consistency with regards to both yield and wine quality compared to previous seasons. On the other hand the Tukulu soil supported a higher yield, but with lower than normal wine quality.

The Avalon soil at Papegaaiberg maintained the highest soil water potential towards the end of the season, probably due to capillary supplementation from the sub-soil. Grapevines on the Tukulu soil at Papegaaiberg experienced much higher water stress than ones on the other three soils, especially during the later part of the season. This could be ascribed to a combination of factors, the most important being the severe soil compaction at a shallow depth, seriously limiting rooting depth and root distribution, which is detrimental to grapevine performance.

Both the soil water status and atmospheric conditions played important roles in determining the amount of water stress that the grapevines experienced at different stages. The air temperature and vapour pressure deficit throughout the season were consistently lower at Helshoogte, the cooler terroir, compared to Papegaaiberg, the warmer terroir. At flowering, Ψ_l was lower for grapevines at Helshoogte than at Papegaaiberg, showing that diurnal grapevine water status was primarily controlled by soil water content. The difference in grapevine water status between the two terroirs gradually diminished until it was reversed during the post harvest period when Ψ_l in grapevines at Papegaaiberg tended to be lower compared to those at Helshoogte. The relatively low pre-dawn Ψ_l at Helshoogte indicated that the grapevines were subjected to excessive water stress resulting from the low soil water content. However, grapevines at Helshoogte did not suffer material water stress (*i.e.* $\Psi_l < -1.20$ MPa) during the warmest part of the day, suggesting that partial stomatal closure prevented the development of excessive water stress in the grapevines.

This suggests that low pre-dawn Ψ_l values do not necessarily imply that grapevines will experience more water stress over the warmer part of the day, or *visa versa*. This does not rule out the possibility that side-effects of partial stomatal closure, such as reduced photosynthesis, can have negative effects on grapevine functioning in general. These results also suggest that measurement of diurnal Ψ_l cycles at various phenological stages is required to understand and quantify terroir effects on grapevine water status.

OPSOMMING

Danksy die droogteweerstand van die wingerdstok is die verbouing van wingerde sonder besproeiing ‘n praktiese en algemene verskynsel in die winterreënval-areas van Suid-Afrika. Wynkwaliteit word grootliks bepaal deur die kwaliteit van die druiwe waarvan dit gemaak word. Wingerdfisiologie word direk en indirek beïnvloed deur waterstres, wat kan varieer volgens die grondtipe en die heersende atmosferiese toestande. Die waterstatus van die wingerdstok beïnvloed druifsamestelling, direk of indirek, en positief of negatief, afhangend van die graad en tydsduur van die waterstres. Daar is drie belangrike faktore betrokke by die ontwikkeling van waterstres, naamlik die transpirasietempo, die tempo van waterbeweging vanaf die grond na die wortels, en die verhouding tussen die grondwatermatrikspotensiaal tot blaarwaterpotensiaal. Al drie die faktore word beïnvloed deur die atmosferiese en/of grondtoestande.

In warm wynboulande soos Suid-Afrika (Weskaap), met ‘n meditereense klimaat wat gekarakteriseer word deur ‘n warm, droë somerperiode, is die belangrikste eienskap van grond die vermoë om voldoende water aan die wingerdstok te verskaf gedurende die hele seisoen. Blaarwaterpotensiaal (Ψ_l) het wye aanvaarding bekom as die fundamentele meting van wingerstokwaterstatus, en word wyd toegepas in wingerdkundige navorsing. Kort voor sonsopkoms, nader Ψ_l ‘n ewewig met die grondwatermatrikspotensiaal en bereik ‘n maksimum daaglikse waarde.

Die studie vorm ‘n integrale deel van ‘n omvattende, multi-dissiplinêre navorsingsprojek (ARC Infruitec-Nietvoorbij Projek No. WW13/01) op die effek van grond en klimaat op wynkwaliteit, wat in 1993 in aanvang geneem het en in 2004 afgehandel sal word. Hierdie studie is uitgevoer gedurende die 2002/03 seisoen in twee Sauvignon blanc wingerde geleë by Helshoogte en Papegaaiberg, beide in die Stellenbosch distrik, ongeveer nege kilometer van mekaar. Twee eksperimentele persele, elkeen verteenwoordigend van kontrasterende grondtipes in terme van grondwaterregime, is geselekteer in elke wingerd. By Helshoogte word die twee gronde verteenwoordig deur die Tukulu en Hutton grondvorms, en die gronde by Papegaaiberg is van die Avalon en Tukulu vorms.

Die doel van die studie was om die effek van atmosferiese toestande en grondwaterstatus op die wingerdstok se waterstatus vir elke grond by die twee lokaliteite te bepaal, sowel as die effek van die wingerdstok se waterstatus op die opbrengs en wynkwaliteit. Dit is gedoen deur die grondwaterstatus, die grondwaterhouvermoë, sowel as die evapotranspirasie van die wingerdstokke op die twee verskillende gronde by elk van die twee lokaliteite, wat verskil in mesoklimaat en topografie, te bepaal en vergelyk. Die atmosferiese toestande by die twee lokaliteite gedurende die 2002/03 seisoen is ook bepaal en vergelyk met die

langtermyn gemiddelde atmosferiese toestande. Die vlakke van waterstres in wingerdstokke op elke grond by elke lokaliteit is ook gemeet.

Gedurende die 2002/03 groeiseisoen, was die atmosferiese toestande relatief warm en droog in vergelyking met die langtermyn gemiddeldes van vorige seisoene. Hierdie kondisies aksentueer die effek van sekere grondeienskappe wat nie noodwendig na vore kom gedurende normale, natter seisoene nie.

Die gewoonlike nat Tukulu grond by Helshoogte was droër as verwag gedurende 2002/03 in vergelyking met die Hutton grond. As gevolg van sterker groekrag op die Tukulu grond, het wingerdstokke meer grondwater onttrek vroeg in die seisoen, wat gelei het tot ‘n lae grondwatermatrikspotensiaal en meer waterstres in die wingerdstokke. Die sterker groeikrag het meer beskaduwing van die lower asook meer waterstres veroorsaak, wat gelei het daartoe dat die dominante aroma in wyne vanaf druiwe op die Tukulu grond vars vegetatief was. Die Hutton grond het bestendig gebly in terme van opbrengs en wynkwaliteit in vergelyking met vorige seisoene. Daarteenoor het die Tukulu grond ‘n hoër opbrengs gelewer, maar met laer as gewoonlike wynkwaliteit.

Die Avalon grond by Papegaaiberg het die hoogste grondwatermatrikspotensiaal behou tot die einde van die seisoen, heelwaarskynlik a.g.v. kapillêre aanvulling vanuit die ondergrond. Wingerdstokke op die Tukulu grond by Papegaaiberg het heelwat meer waterstres ondervind as op die ander drie gronde, veral later in die seisoen. Dit kan toegeskryf word aan ‘n kombinasie van faktore, die belangrikse daarvan die erge grondkompaksie vlak in die grond, wat worteldiepte en -verspreiding ernstig beperk het, wat op sy beurt nadelig is vir wingerdprestasie.

Beide die grondwaterstatus en atmosferiese toestande het ‘n belangrike rol gespeel in die bepaling van die hoeveelheid waterstres wat die wingerdstok op verskillende stadiums ondervind het. Die lugtemperatuur en waterdampdruktekort was regdeur die seisoen laer by Helshoogte, die koeler terroir, as by Papegaaiberg, die warmer terroir. Gedurende blom was die Ψ_l laer vir wingerdstokke by Helshoogte as by Papegaaiberg, wat daarop wys dat daaglikse wingerdstok waterstatus hoofsaaklik deur die grondwaterinhoud bepaal was. Die verskil in wingerdstok waterstatus tussen die twee terroirs het geleidelik verminder totdat dit omgekeer was gedurende die na-oes periode toe Ψ_l in wingerdstokke by Papegaaiberg geneig het om laer te wees in vergelyking met die by Helshoogte. Die relatiewe lae voorsonop Ψ_l by Helshoogte het daarop gedui dat die wingerdstokke aan oormatige waterstres onderwerp was. Die wingerdstokke by Helshoogte het egter nie materiële waterstres (*i.e.* $\Psi_l < -1.20$ MPa) gedurende die warmste gedeelte van die dag ondervind nie, wat aandui dat gedeeltelike huidmondjiesluiting plaasgevind het om die ontwikkeling van oormatige waterstres te verhoed.

Dit dui aan dat lae voorsonop Ψ_l waardes nie noodwendig impliseer dat wingerdstokke meer waterstres gedurende die warmste gedeelte van die dag sal ondervind nie, of *visa versa*. Dit sluit nie die moontlikheid uit dat negatiewe newe-effekte van gedeeltelike huidmondjiesluiting, soos ‘n vermindering in fotosintese, ‘n negatiewe effek kan hê op die wingerdstok se funksionering in die algemeen nie. Hierdie resultate stel voor dat die meting van daaglikse Ψ_l siklusse gedurende verskeie fenologiese stadia benodig word om die effek van terroir op die wingerdstok se waterstatus te verstaan en te kwantifiseer.

This thesis is dedicated to my father, Giel Laker, for his belief in me, and all his inspiration.

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PREFACE

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

Chapter 1	**General Introduction and Project Aims**
Chapter 2	**Literature review** Evapotranspiration and grapevine water status in the coastal regions of the Western Cape.
Chapter 3	**Research Results** The effect of soil type and mesoclimate on the evapotranspiration of unirrigated Sauvignon blanc/99Richter.
Chapter 4	**Research Results** The effect of soil type and mesoclimate on the water relations in unirrigated Sauvignon blanc/99Richter.
Chapter 5	**Conclusions**

CONTENTS

CHAPTER 1

INTRODUCTION AND PROJECT AIMS

GENERAL INTRODUCTION AND PROJECT AIMS

1.1 INTRODUCTION

The South African Wine Industry is compelled to increase wine quality because of increasing competitive national and international markets (Hunter & Myburgh, 2001). Wine quality is still largely determined, or limited by the quality of the grapes from which it is produced. The quality of grapes for wine depends on both the variety and the environment in which the grapes are grown (Rankine *et al*., 1971). Soil and climate automatically come to mind when factors that may affect wine quality are considered (Saayman, 1977).

In view of the impact of water stress on growth, grape and wine quality and thus on cultivar aroma, water management of vineyards is a crucial aspect within the total integrated production (Hunter & Myburgh, 2001). Smart & Coombe (1983) suggested that radiation, relative humidity, temperature, atmospheric pollutants, wind, soil environment and plant factors can all affect the grapevine water status on a diurnal and seasonal basis. Grapevine water status can affect berry aroma composition and wine style. This effect may be indirect due to effects of water stress on vegetative growth, and thus canopy structure, but one cannot ignore the possible direct implications of water stress for the metabolic profile of the berry. As such the measurement of grapevine water status is an important measure to better understand the cultivar x terroir interaction (Carey *et al*., 2004).

The most reliable indicators of grapevine water status are measurements made on the plant itself. Estimating the leaf water potential by means of the pressure chamber technique of Scholander *et al.* (1965) is an easy way for the producer to estimate the grapevine water status. The measuring of leaf water potential by means of the pressure chamber is widely recognised and applied in viticultural research (Smart & Coombe, 1983). Due to the dependence of leaf water potential on atmospheric conditions, the leaf water potential fluctuates diurnally. Hence measurements should be standardised. Pre-dawn or covered leaf water potential is usually preferred for the detection of onset of water stress in grapevines because of the large day-to-day variation in temperature, transpiration, relative humidity and wind speed in exposed leaf water potential measurements (Meyer & Green, 1981). Pre-dawn leaf water potential can detect the onset of water stress at an early stage (Van Zyl, 1987).

In-depth study of all the factors involved in the climate-soil-grapevine ecosystem is difficult; each has its own action but acts in synergy with, or opposition to, the others (Seguin, 1986). The single or combined effects of soil and atmospheric conditions on grapevines are still not quite clear (Saayman, 1977). The marked effects of soil type on grapevine performance, phenological characteristics and production is a common phenomenon in the Western Cape. Existing results as well as local and overseas experience indicate that soil type causes differences in wine character. The pronounced effect of atmospheric conditions on wine character and quality is universally recognised. Seen as a whole, atmospheric conditions and soil cannot be separated due to the inter-relationship existing between them (Saayman, 1977).

1.2 SPECIFIC PROJECT AIMS

The aim of this study was to monitor the effect of atmospheric conditions and the soil, especially the soil water status, on the grapevine water status. The soil water status, grapevine water status and atmospheric conditions were monitored throughout the 2002/03 season.

The following were determined at each of the two localities differing in mesoclimate and topography:

- soil water holding capacity of the two soils at each locality
- soil water status of the different soils
- evapotranspiration of the grapevines
- atmospheric conditions during the 2002/03 season
- level of grapevine water stress on each soil at each locality

1.3 LITERATURE CITED

Carey, V.A., Conradie, W.J., Myburgh, P.A., Laker, M.S. & Bruwer, R.J. (2004). The significance of plant water status as a criterion in South African terroir studies. OIV Group d'Éxperts : Physiologie de la vigne - March 2004.

Hunter, J.J. & Myburgh, P.A. (2001). Ecophysiological basis for water management of vineyards in South Africa, with particular reference to environmental limitations. In: Proc. GESCO Journeé professionelle “Gestion de l'eau dans le vignoble”., July 2001, Montpellier, France. pp 23-43.

Meyer, W.S. & Green, G.C. (1981). Plant indicators of wheat and soybean crop water stress. *Irrig. Sci*. **2**, 169-176.

Rankine, B.C., Fornachon, J.C.M., Boehm, E.N. & Cellier, K.M. (1971). The influence of grape variety, climate and soil on grape composition and quality of table wines. *Vitis* **10**, 33-50.

Saayman, D. (1977). The effect of soil and climate on wine quality. . In: Proc. Int. Sym. Quality of the Vintage, February 1977, Cape Town, South Africa. pp 197-208.

Scholander, P.F., Hammel, H.T., Bradstreet, E.D. & Hemmingsen, E.A. (1965). Sap flow in vascular plants. *Science* **148**, 339-346.

Seguin, G. (1986). “Terroirs” and pedology of wine growing. *Experientia* **42**, 861-873.

Smart, R.E. & Coombe, B.G. (1983). Water relations of grapevines. In: Kozlowski T.T. (ed.). Water deficits and plant growth VII. Academic press, New York. pp 137-196.

Van Zyl, J.L. (1987). Diurnal variation in grapevine water stress as a function of changing soil water status and meteorological conditions. *S. Afr. J. Enol. Vitic*. **8**, 45-52.

CHAPTER 2

LITERATURE REVIEW

EVAPOTRANSPIRATION AND GRAPEVINE WATER STATUS IN THE COASTAL REGIONS OF THE WESTERN CAPE

CHAPTER 2

2.1 INTRODUCTION

Dryland viticulture in the winter rainfall coastal areas of South Africa is a feasible and commonly used practice, thanks to the extraordinary drought resistance of the grapevine (Van Zyl & Weber, 1977). In warm winelands with a mediterranean climate which is characterised by hot, dry summers, such as the Western Cape region in South Africa, the most important characteristic of soil is its capacity to supply sufficient water to the grapevine during the entire growing season.

Grapevine physiology, and therefore grape and wine quality, is affected both directly and indirectly by water stress, which may vary according to soil type and prevailing climate. The wine producing regions of South Africa are characterised by many diverse climates, from mediterranean to semi-arid, and, within each climate-type, by many diverse soil forms with different water-holding capacities (Carey *et al*., 2004). Studies performed in the 1970's regarding the effect of climate and soil on wine quality in South Africa showed that soil type had a marked influence on wine quality under dryland conditions. This was ascribed to the water regime of the soil in relation to the prevailing and seasonal climate (Saayman, 1977).

Wine quality is largely determined by the quality of the grapes from which it is made. The quality of grapes for wine depends on both the variety and the environment in which the grapevines are grown (Rankine *et al*., 1971). Soil and climate automatically come to mind when factors that may affect wine quality are considered (Saayman, 1977). In many viticultural regions of South Africa, grape growers are faced with the problem of achieving high yield as well as grape quality with limited water supplies (Van Zyl & Van Huyssteen, 1988). The water status of the grapevine can affect grape composition profoundly, both directly and indirectly. The timing, degree and duration of water stress can have either positive or negative effects on grape composition and quality (Van Zyl, 1984). Grapevine water status can affect berry aroma composition as well as wine style and this effect may be indirect due to effects of water stress on vegetative growth and thus canopy structure, but one cannot ignore the possible direct implications of water stress for the metabolic profile of the berry (Carey *et al*., 2004).

2.2 EVAPOTRANSPIRATION

Grapevines depend on adequate water for normal functioning and economically viable production. Water requirement is defined as the total amount of water, regardless of its source, required by crops for their normal growth under field conditions (Myburgh, 1998). Evapotranspiration (ET) is defined as the combined loss of water from a given area and during a specific period of time, by evaporation from the soil surface and by transpiration from plants (Van der Watt & Van Rooyen, 1990). The dynamics of these processes are controlled by environmental and soil surface conditions as well as viticultural aspects (Myburgh, 1998). Due to variation in viticultural practices, and atmospheric conditions, ET can vary considerably between vineyards. Factors that affect the soil water status, soil surface conditions and transpiration of grapevines such as leaf area, irrigation system, method of cultivation, atmospheric conditions and soil characteristics will, therefore, all affect the ET of a vineyard (Van Zyl, 1975; Smart & Coombe, 1983; Van Zyl & Van Huyssteen, 1988; Myburgh *et al*., 1996; Myburgh, 1998).

2.2.1 FACTORS AFFECTING VINEYARD EVAPOTRANSPIRATION

2.2.1.1 Evaporation

Evaporation from the soil surface (E_S) is one of the major processes responsible for water losses in cropped lands (Hillel, 1980). Transpiration and evaporation were generally regarded as a combined variable in research on grapevine water requirements and irrigation. Hence, knowledge on actual E_s losses, and its contribution to ET, is limited. Variations in tillage and irrigation practices, as well as heterogeneity of soils will cause E_s to vary between different vineyards (Myburgh, 1998).

Evaporation from the soil surface after wetting by rain or irrigation takes place in three stages (Hillel, 1980). During stage one, which is an initial, constant rate stage, the soil is wet and conductive enough to supply water to the site of evaporation at a rate equal to the evaporative demand (ET_0). This means that the rate of E_s is controlled by external atmospheric conditions rather than by properties of the soil profile during this stage. However, the effects of atmospheric conditions acting on the soil can be affected by modifying soil surface conditions by means of tillage or mulching. The duration of stage one is generally short and may last only a few hours in a dry climate. Stage two, which is an intermediate falling-rate stage, occurs when evaporation rate falls progressively below the rate of ET_0 (Hillel, 1980). The rate at which the drying soil profile can supply water to the site of evaporation determines the evaporation rate during this stage. Soil physical properties such as hydraulic conductivity play an important role. Stage two may last for a much longer period than stage one. Lastly, a third residual, slow-rate stage is established. Stage three may persist at a nearly steady rate for many days, weeks, or even months. Water transmission through the desiccated surface layer occurs primarily by the process of vapour diffusion at this stage. This stage is thus affected by the vapour diffusivity of the drier surface zone, and the adsorptive forces acting over molecular distances at the particle surface (Hillel, 1980).

According to Van Zyl (1975), E_s was high during spring when the soil surface was still moist as a result of rain, and high crop coefficients were found. As the soil surface dried out, crop coefficients decreased during early summer. These findings suggested that maintaining a high moisture regime in the soil will lead to higher crop coefficients (Van Zyl, 1975; Myburgh, 1998). This is supported by Van Zyl & Weber (1981) who found that the highest crop coefficient for a season was obtained during the period in which a wet soil surface and, therefore, high evaporative losses prevailed.

Myburgh & Moolman (1991b) concluded that increased exposed soil surfaces due to ridging of vineyard soils caused higher E_s rates which resulted in excessive soil water losses during the final stages of the growing season. They, therefore, concluded that irrigation is essential where vineyard soils are ridged. According to a study by Van Zyl & Van Huyssteen (1988), E_s was limited when irrigation was applied by means of 1 m wide furrows on the grapevine rows because the wet surface area was smaller and mostly shaded in contrast to border irrigation treatments, *i.e.* total soil surface wetting. Van Zyl & Van Huyssteen (1988) reported substantial water losses through E_s in an arid climate as the result of water forming small puddles on the soil surface along drip irrigation lines. The relatively slow water infiltration was due to the fact that the surface layer of the specific soil tended to compact under irrigation and clean cultivation. With respect to grapevine performance, this unfavourable situation became more acute towards the end of the season when poor infiltration caused excessive drying of the subsoil.

According to Hillel (1980), mulching can reduce E_s. This is supported by Van Zyl & Van Huyssteen (1984), who found that E_s can be effectively diminished by minimum cultivation practices. Mulching is applied in vineyards, either directly by adding cover material such as wheat straw (Myburgh, 1998), or indirectly by cultivating a cover crop which eventually acts as a mulch after it has been killed by a herbicide (Fourie *et al*., 2001). However, usually only the initial evaporation rate, *i.e.* during stage one, is reduced (Hillel, 1980). This means that significant water conservation will be obtained if rains are frequent, or irrigation cycles are short (Myburgh, 1998). Van Huyssteen *et al.* (1984) also observed that water is conserved by limiting E_s through mulching. It was reported that cumulative evaporation decreased substantially with an increase in mulch thickness, but due to decay and weathering, this effect became less significant during later stages of the growing season (Van Zyl & Myburgh, 1997).

Shading of the soil surface by grapevine canopies reduced E_s significantly, but the shading effect diminished as the soil dried out (Myburgh, 1998). As a result of this, E_s became practically constant across the work row. Shading also had no significant effect on E_s at any stage after irrigation in the case of mulching. In the study done by Myburgh (1998), canopy orientation had no significant effect on E_s patterns across the North-South work rows. Myburgh (1998) reported that more water will evaporate on a warm, windy day than on a cool, windless day. According to Myburgh (1998) it can be assumed that wind has a more prominent effect on E_s than shading. Van Zyl & Van Huyssteen (1980) reported that more air movement, *i.e*. wind, among bush grapevines, as well as less shading of the soil surface, led to increased E_s compared to slanting trellis systems.

2.2.1.2 Transpiration

Some of the first studies to investigate the individual contribution of evaporation and transpiration to ET showed that transpiration was only 33% of the ET of a Chardonnay vineyard in Texas (Lascano *et al*., 1992). These results were quite contradictory to the general assumption that ET consists primarily of soil water extraction by the grapevine via transpiration (Myburgh, 1998). Development of techniques such as the heat pulse velocity and stem heat balance methods, made it possible to measure sap flow in grapevine trunks in order to quantify total daily sap flow or transpiration of whole grapevines. The heat pulse velocity technique has been shown to be suitable for measuring diurnal sap flow in grapevine trunks. In order to avoid heat damage to the plant tissue surrounding the heaters, measurements should take place in no more than a week after probe installation (Myburgh, 1998).

Atmospheric conditions

Knowledge on the effects of variations in viticultural practices and atmospheric conditions on sap flow, or whole plant transpiration in general, is limited (Myburgh, 1998). Sap flow was largely affected by variations in atmospheric conditions (Schmid, 1997). Earlier research has shown that transpiration, as quantified by means of stomatal conductance (g_s), was strongly affected by atmospheric parameters such as ambient air temperature, radiation and water saturation deficit of the atmosphere (Düring, 1976; Düring & Loveys, 1982).

According to Düring & Loveys (1982), the g_s of Riesling and Sylvaner grapevines were higher under humid, temperate atmospheric conditions, in comparison to semi-arid conditions. This suggests that sap flow rates may vary according to climatic regions. Myburgh (1998) noted that the positive effects of higher stomatal conductance could, to a greater or lesser extent, be counteracted by lower evaporative demand under humid, temperate conditions. In a comprehensive study to determine how transpiration was affected by viticultural and atmospheric conditions, it was found that sap flow tended to be erratic during the day, probably as a natural response to changes in canopy microclimate (Myburgh, 1998).

Hourly sap flow rates measured under semi-arid conditions in South Africa (Myburgh, 1998) were notably lower compared to values for Weisser Riesling under humid, temperate atmospheric conditions in Germany (Schmid, 1997). This suggests that the transpiration component of ET may be higher under humid, temperate conditions than under semi-arid conditions (Myburgh, 1998). In comparison to non-irrigated Pinot noir grapevines, irrigation only resulted in slightly higher hourly sap flow rates on the day after the irrigation was applied (Myburgh, 1998).

Sap flow occurring in grapevines at night was attributed to the replenishment water deficits during the day, which were caused by water uptake being slower than transpiration losses during the day (Myburgh, 1998). However, sap flow rates during the night were substantially lower in comparison to rates measured in full sunshine, and tended to increase with increasing leaf area.

Since stomatal opening of grapevines is controlled by light, transpiration rates generally follow diurnal radiation patterns (Düring, 1976). Consequently, a decrease in sap flow occurs during cloudy or overcast weather (Myburgh, 1998). It was reported that hourly sap flow measured in Barlinka grapevines was strongly related to hourly radiation. However, sap flow did not respond linearly to radiation. This suggested that stomatal control, *i.e.* partial stomatal closure at higher radiation levels, only allowed a certain amount of water loss, causing sap flow to vary asymptotically around a maximum rate (Myburgh, 1998).

Myburgh (1998) suggested that lower sap flow rates measured in furrow irrigated Sultanina grapevines under more water stress, compared to ones where full surface irrigation was applied, were the result of a possible water saving mechanism causing partial stomatal closure under warm, dry atmospheric conditions. Erratic hourly sap flow was probably also the result of stomatal closure. These results were in agreement with the findings of Düring & Loveys (1982).

Leaf area

Recent studies have shown that daily sap flow in Weisser Riesling was directly related to leaf area per grapevine (Schmid, 1997). Eastham & Gray (1998) found that transpiration per unit leaf increased linearly with an increase in ET_0. Despite the variability in hourly sap flow rates, Myburgh (1998) found that cumulative sap flow increased with increasing leaf area. The strong relationship between sap flow and leaf area proved that transpiration was closely related to total leaf area per grapevine and that ET will increase with an increase in leaf area (Myburgh, 1998).

Total leaf removal caused a sharp decrease in sap flow rate, proving that during the day, sap flow is primarily a function of transpiration (Myburgh, 1998). Removing the total crop load of Pinot noir grapevines during ripening, however, had no significant effect on hourly sap flow rates, which indicated that bunches did not significantly contribute towards sap flow at that stage. Hence, during ripening sap flow can be regarded as primarily a function of total leaf area (Myburgh, 1998).

Scion/rootstock

Schmid (1997) found that different rootstocks, *i.e.* Kober 5 BB, Selection Oppenheim 4, Börner and Sori, did not have a significant effect on daily sap flow of Weisser Riesling. Scion cultivar, however, can affect g_s and, consequently, daily sap flow rates. Düring & Loveys (1982) reported that the g_s of Riesling grapes was higher than those of Sylvaner grapevines under comparable atmospheric conditions. In general, information on the effects of scion and/or rootstock on transpiration seems to be limited.

Canopy orientation

Sap flow rates measured in grapevines on vertical trellising systems tended to be lower compared to horizontally orientated trellising systems (Myburgh, 1998). The reason for this is that in the case of vertical canopy surfaces, only about half of the outer layer of north-south canopies, which is the recommended row direction, was exposed to full radiation on normal sunshine days. This caused lower transpirational water losses, which resulted in lower hourly sap flow rates compared to horizontally orientated canopy surfaces where most of the outer leaves were exposed to radiation throughout the day.

2.2.2 WATER REQUIREMENTS OF VINEYARDS IN THE COASTAL REGION

Due to variation in viticultural practices and atmospheric conditions, ET may vary significantly between vineyards (Myburgh, 1998). Furthermore, it was shown that crop coefficients and ET were not only determined by soil and climate, but to a large extent by the moisture regime maintained (Van Zyl & Weber, 1981).

Evapotranspiration

Growing grapevines without irrigation, *i.e*. dryland viticulture, is a long-established form of land use in the coastal region of the Western Cape. Depending on soil type, stored winter rain water provides largely for the water requirements of grapevines during the almost rainless summer months (Van Zyl & Weber, 1981). However, where soil water is limited, irrigation has to be applied. Evapotranspiration decreases with a decrease in plant available water (Van Zyl & Van Huyssteen, 1984). Practical experience, supported by experimental evidence (Van Zyl & Weber, 1977), indicated that a total seasonal requirement of 500 mm water from bud burst to maturity appeared to be adequate for economically viable viticulture in the coastal region of the Western Cape (Van Zyl & Van Huyssteen, 1984). Since mean rainfall is low during the growing season, *e.g*. 168 mm at Stellenbosch compared to 439 mm at

Bordeaux in France, irrigation is often required when stored winter water is limited or soil water is depleted during later in the season.

Grapevines do not distinguish between different sources of water, which includes precipitation, irrigation and stored soil water (Van Zyl & Van Huyssteen, 1984). Although soil type, cultivar and viticultural practices affect the irrigation requirement, climate is regarded as the dominant factor (Van Zyl & Van Huyssteen, 1984). Van Zyl & Weber (1981) found that for two seasons during their experiments on the effect of supplementary irrigation treatments on plant and soil moisture relationships in the Stellenbosch region, all the plant available water in dryland plots was depleted by the second half of January. However, grapevines showed severe water stress earlier, since the water content of the upper soil horizons containing the largest number of roots had already reached wilting point at that stage. Consequently, a more favourable soil water content was obtained by irrigation in comparison to the dryland plots. From the end of December, the soil water content in the dryland plots was at wilting point down to a depth of 600 mm, while the small quantity of available water in the 600-900 mm zone was retained at a very low potential. According to Van Zyl & Weber (1981), it can be accepted that ET was determined by soil resistance to moisture movement at this stage. This is in contrast to the situation of water being readily available throughout the soil profile, in which case ET is principally determined by climatic conditions. According to Ferguson’s hypothesis (Van Zyl & Weber, 1981), ET is mainly determined by leaf resistance to transpiration in cases where the soil surface has dried, and the water content in the rest of the soil profile is intermediate.

The total ET for the Stellenbosch-Paarl region during the growing season (September to March), as calculated by the evaporation and consumptive crop coefficients, is 641 mm (Van Zyl, 1975). This amounts to an average of approximately 3.0 mm/day over the entire growing season. Myburgh *et al*. (1996) found an increase in ET with increased soil depth due to the effect of increased soil volume on vegetative growth. The average daily ET for irrigated Pinot noir grapevines with 800 mm rooting depth reached a maximum of 4.1 mm/day during February and a minimum of 1.1 mm/day during September. A maximum ET of 2.20 mm/day during November and a minimum ET of 0.65 mm/day during April were found for a dryland Pinot noir vineyard. This was much lower than the ET values obtained for the irrigated grapevines.

Crop coefficients

Van Zyl & Weber (1981) found that higher crop coefficients were obtained after a major rainfall or an irrigation, but two or three days later the crop coefficients were already considerably lower. Although crop coefficients are determined in the presence of both evaporation and transpiration, Van Zyl & Weber (1981) found that the initial high crop coefficients can be ascribed to the high E_s while the surface is still wet. After drying of the soil surface, ET and thus the crop coefficients decreased (Van Zyl & Weber, 1981). A crop coefficient of 0.36 was obtained in the 1974/1975 season during the period in which a wet soil surface and, therefore, high evaporative losses prevailed (Van Zyl & Weber, 1981). During the 1973/1974 season a lower crop coefficient of 0.23 was obtained for the same period, but less rain occurred in the early part of the season. During the 1974/75 season, the lowest crop coefficient of 0.22 was found for the period stretching from middle December until middle January.

Van Zyl & Van Huyssteen (1988) reported a crop coefficient of between 0.4 and 0.6 during the two months of peak water consumption, *i.e*. December and January, in the Oudtshoorn region for grapevines under different irrigation systems. In Robertson, a maximum crop coefficient of 0.51 was reached during February and a minimum crop coefficient of 0.29 was obtained in October. The crop coefficients at Robertson increased sharply from October until November, but were quite stable from then onwards (Van Zyl & Van Huyssteen, 1988). The ET and crop coefficients calculated for grapevines by both Van Zyl & Weber (1981) and Van Zyl & Van Huyssteen (1988) were for irrigated vineyards. Myburgh (1998) reported a maximum crop coefficient of 0.44 during October and a minimum crop coefficient of 0.16 during March for dryland Pinot noir in the Stellenbosch region.

2.3 GRAPEVINE WATER STATUS

2.3.1 FACTORS AFFECTING THE WATER STATUS OF DRYLAND VINEYARDS

The storage of winter rainfall in the soil is generally insufficient to prevent detrimental water stress in grapevines during the summers in the South African viticultural areas with a mediterranean climate (Van Zyl & Van Huyssteen, 1984). Under dryland conditions, soil management should strive to put all rain water at the disposal of the grapevine roots through storage and conservation. In order to optimize soil and water management practices that can balance yield, quality and cost benefit, scientifically based knowledge regarding soil-water-plant-climate relationships is needed (Van Zyl & Van Huyssteen, 1984).

Leaf water potential (Ψ_l) has gained wide acceptance as a fundamental measure of plant water status (Kramer, 1983), and has been widely applied in viticultural research (Smart & Coombe, 1983). Shortly before dawn, Ψ_l approaches equilibrium with soil water potential and reaches a maximum daily value. After dawn, Ψ_l decreases rapidly to attain a minimum value after midday, followed by a gradual recovery during the late afternoon and night (Smart & Coombe, 1983). In using Ψ_l reduction as an indicator of water stress, an absence of osmotic adjustment to the stress is assumed (Van Zyl, 1987).

There are three important factors involved in the development of water stress, namely the transpiration rate, the rate of water movement from the soil to the roots, and the relationship of soil water potential to leaf water potential (Kramer, 1983). All three these factors are affected by atmospheric and/or soil conditions.

2.3.1.1 Atmospheric conditions

The soil-water-plant-atmosphere continuum can be described as a water stream flowing from a source of limited capacity and variable potential to the atmosphere (Hillel, 1971). Stomatal opening is affected by water deficits and can be used as an indicator of plant water stress, although it is recognised that environmental factors such as light intensity, CO_2 concentration, hormones and temperature also affect stomatal behaviour (Kramer, 1983). Photosynthetic rate in grapevines reaches a maximum at low water stress (Smart & Coombe, 1983). Stomatal opening, transpiration and photosynthesis often decrease in grapevines subjected to increasing water stress (Van Zyl, 1987). However, there is evidence that water stress not only results in a decline in CO_2 uptake due to closure of stomata, but can also cause inhibition of CO_2 fixation (Kramer, 1983). The most important atmospheric parameters that affect grapevine water status are radiation, temperature, vapour pressure deficit (VPD) and wind.

Radiation

In a study by Van Zyl (1987) it was found that the leaf water potential in sunlit leaves was significantly lower than that in shaded leaves during the middle part of the day (10:00 until 16:00). This fact was further illustrated in another experiment by comparing sunlit and shaded leaves, which yielded a mean leaf water potential of -1.3 MPa in sunlit leaves and -1.0 MPa in shaded leaves, respectively (Van Zyl, 1987). Leaf water potential correlated significantly with leaf temperature and photosynthetic active radiation (PAR) (Van Zyl, 1987). On a normal sunshine day, stomatal resistance (R_s) in sunlit leaves decreased from 04:00 to assume low values (between 1.5 s/cm and 3.0 s/cm) during the middle part of the day and increased to between 30 s/cm and 35 s/cm during the late afternoon (17:00 until 18:00) in unstressed grapevines (Van Zyl, 1987). Stomata of the unstressed grapevines were already partly closed during the middle part of the day. Stomatal resistance of shaded leaves were always much higher than those of sunlit leaves, probably due to reduced light conditions around the shaded leaves. Rapidly changing light conditions early in the morning were responsible for differences in R_s at that stage. In general, R_s correlated best with PAR (Van Zyl, 1987).

As for other C_3 species, the relationship between leaf net CO_2 assimilation rate and photosynthetic photon flux density (PFD) for grapevine leaves can best be described as a rectangular hyperbole. The light compensation point for grapevines, *i.e.* where the nett CO_2 exchange is zero, is between 10 μmol quanta/m^2/s and

20 μmol quanta/m^2/s (Düring, 1988). Stomatal conductance of well-watered grapevines to water vapour showed a hyperbolic response to PFD. Maximum stomatal opening of an individual leaf has been recorded at PFD's of 130 μmol quanta/m^2/s to 300 μmol quanta/m^2/s (Winkel & Rambal, 1990).

Most of the above-mentioned studies regarding light effects on grapevines concentrated on light conditions within the canopy, *i.e.* on a microclimatic level (Jackson & Lombard, 1993). The macroclimatic effects of light have received less attention. Increased radiation, either by higher intensity or longer exposure, will increase temperature, especially of exposed leaves (Jackson & Lombard, 1993). Canopy conductance of grapevines at full canopy cover, unlike single leaf g_s, is linearly related to PFD (Williams *et al*., 1994). Maximum canopy conductance is associated with maximum PFD and occurs when the greatest proportion of the canopy is exposed to direct solar radiation.

Temperature

Every aspect of plant growth and development that is governed by physical processes, enzyme reactions, membrane permeability and transport processes are dependant on the effect of temperature - some subtle and others more dramatic (Coombe, 1987). Van Zyl (1987) found that for variables such as leaf temperature, PAR, relative humidity and wind speed, Ψ_l correlated the best with leaf temperature ($r = -0.95$) on most measurement days. The optimum leaf temperature for photosynthesis of field-grown grapevines is generally accepted to be between 25°C and 30°C (Williams *et al*., 1994).

Differences between grape cultivars in regard to their stomatal response to temperature have been found for the temperature range from 34°C to 43°C (Sepulveda & Kliewer, 1986). Cardinal, for which the control treatment (25°C to 29°C) had a relatively low g_s compared to Chenin blanc and Chardonnay, showed the least response to heat stress. The response of Chardonnay and Chenin blanc to heat stress was similar, whether measured on a diurnal basis, or over 4 to 12 days.

Vapour pressure deficit

Generally, an increase in VPD above a certain threshold causes a reduction in g_s in most plant species, including *Vitis* species (Düring, 1987). However, this effect of VPD on g_s of grapevines appears to be cultivar dependant (Düring, 1987).

Decreases in g_s due to increases in VPD may be more pronounced for grapevines grown under drought conditions (Düring, 1976; Düring, 1979). Stomatal conductance of Müller-Thurgau and Riesling grapevines grown within an aerial environment maintained at 50% relative humidity (RH) decreased significantly when soil water content was maintained at 60% of field capacity, compared to when the soil water content was at 95% of field capacity (Düring, 1979). Field-grown grapevines responded in a similar way (Williams *et al*., 1994). Stomatal conductance decreased as VPD increased throughout the day for grapevines receiving less than full vineyard ET. An increase in VPD from 1 kPa to 3 kPa reduced g_s by 50% and 75%, respectively, for grapevines irrigated at 60% and 20% of grapevine water use as determined by means of a weighing lysimeter (Williams *et al*., 1994). In semi-arid environments, VPD and ambient temperature are highly correlated. The relationship between g_s and ambient temperature is, therefore, similar to the relationship between VPD and g_s (Williams *et al*., 1994).

Wind

Wind has been reported to have little effect on the water status of various plant species, including *V. vinifera* (Kobringer *et al*., 1984). However, in a study by Freeman *et al*. (1982), examining the difference in water relations between sheltered and non-sheltered, field-grown grapevines in windy locations, leaf water potential of sheltered grapevines was always more negative compared to non-sheltered control. Freeman *et al.* (1982) reported that g_s and transpiration is decreased when wind speeds exceeds 3 m/s. According to Williams *et al*. (1994) wind velocities higher than 3 m/s were required to reduce g_s and transpiration significantly.

Researchers who have studied the effects of wind on grapevines suggest that the reduction in g_s due to increased wind speeds, will also reduce leaf net CO_2 assimilation rate. The degree to which leaf net CO_2 assimilation rate is reduced by increased wind speed is largely dependant upon the extent by which g_s is reduced. However, preliminary assessment of wind-breaks on grapevine physiology and growth indicates that there may not always be a large reduction in leaf net CO_2 assimilation rate when g_s is reduced due to chronic wind exposure (Williams *et al*., 1994). Because wind can cause stomatal closure, it can consequently also limit CO_2 uptake and photosynthesis in many plants, even though adequate soil water is available (Freeman *et al*., 1982).

2.3.1.2 Soil water status

Various claims are made about the effect of soil on wine quality. Although the emphasis often falls on geology, as an indication of parent material, it seldom directly has a dominant role in regard to wine quality. It does, however, play an important indirect role by being a major factor determining the physical properties of the soil (Conradie, 2001). According to Saayman (1992b), the effect of soil type is without question the least understood natural factor with regard to wine quality. While the effects of cultivars and climate are relatively easy to determine, the effect of the soil is often confusing, especially in warmer climates, where climate tends to dominate over all other factors (Fregoni, 1977).

Water availability is the result of both the quantity of water present as well as the force with which this water is retained by the soil (Hillel, 1980). The soil water-holding capacity and plant-available water are affected by soil depth, texture and structure (Van Zyl, 1981). Soil water potential determines the ability of the soil to supply water to plants.

According to Van Zyl (1981), “field water capacity“ is at the upper limit of total plant available water (PAW), which is accepted as -0.01 MPa. Research in Stellenbosch has shown, however, that “field water capacity” is usually reached at lower soil water matric potentials in the field. Ratliff *et al.* (1983) showed that the previously accepted norm of -0.033 MPa underestimates the “field water capacity” of sand, sandy loam and sandy clay-loam, while it overestimates the “field water capacity” of silt-loam, silty clay-loam and silty clays (*i.e.* fine textured soils). It has been found that the soil water potential at field water capacity determined in the field can vary from as high as -0.005 MPa in sandy soils to as low as -0.050 MPa in clay soils (Myburgh, 1996; Bennie & Hensley, 2003). By using the traditional -0.033 MPa, the plant available water-holding capacity of especially fine sandy soils are vastly underestimated on the one hand. Consequently too small quantities of water are applied per irrigation during a large number of light irrigations, leading to a waste of water. On the other hand, when clay soils are irrigated to keep them near the -0.033 MPa mark, these soils will be permanently waterlogged. The lower limit of PAW (-1.5 MPa) is known as the “permanent wilting point”, where plant roots are not able to extract any more water from the soil, because the soil water is held at very high soil matric potentials (Van Zyl, 1981).

Various plant physiological parameters, *i.e*. transpiration rate, stomatal resistance or conductance, rate of photosynthesis and leaf water potential are used as indicators of plant water status (Van Zyl & Bredell, 1995). Van Zyl (1987) found that pre-dawn leaf water potential is the most sensitive indicator of water stress in grapevines, and thus also of the availability of soil water to the plant. Pre-dawn leaf water potential provided highly significant correlations with soil water potential ($r = 0.95$) and soil water content ($r = 0.89$). Leaf water potential is, however, not only affected by the soil water status, but also by the vapour pressure deficit of the atmosphere (Myburgh, 2003a).

If the soil water potential decreases below a certain level, the soil is no longer able to supply water at the desired rate and water stress develops in the plant. By using the pre-dawn leaf water potential as criterion, Van Zyl (1987) found that water stress sets in at a soil water potential of -0.064 MPa (42% of the total plant available water) for grapevines. For potted Cabernet Sauvignon grapevines, Pellegrino *et al*. (1987) found that mesophyl-conductance was 42% and 70% lower at soil water potentials of -0.050 MPa and -0.060 MPa, respectively, than at a potential of -0.020 MPa. The decrease at -0.060 MPa is quite drastic and Pellegrino *et al.* (1987) regard this as an indication that this cultivar is not drought resistant. Fourie (1989), working with Barlinka table grapes on a coarse sandy soil, found that plant physiological parameters showed that the onset of water stress occurred at soil water potentials between -0.030 MPa and -0.035 MPa, *i.e.* when 41% of the total plant available water was depleted.

Research in Bordeaux, France, disclosed that the classified vineyards owed their superiority to the ability of the soil to regulate water supply to the grapevines (Saayman, 1992b). Not only can these soils accommodate excessive rain in such a way that it has a minimal negative effect on the desired physiology and growth pattern of grapevines, but they are also able to furnish grapevines with adequate water so that they experience some, but not excessive, stress towards ripening (Saayman, 1992b). If a soil does not have a sufficient water-holding capacity, irrigation must be considered, especially in the Western Cape with its prevailing dry summers. Alternatively, this restriction can partially be overcome by aiming for optimal root densities by using narrower plant densities, so that soil water can be used more efficiently (Archer *et al*., 1988).

Deep, well-drained soils will enable a prolific, deep distribution of roots which, with the assumption that the soil has a reasonably high plant available water-holding capacity per unit soil depth, will buffer grapevines against substantial variations in the plant available water supply (Gladstones, 1992). This will minimize the effect of periodic water deficits in the soil and protect the grapevine against the development of water stress in the plant. In winter rainfall regions it can also help sustain the grapevine throughout the season without detrimental levels of water stress developing. Vineyard performance and wine quality will then be more consistent from year to year (Gladstones, 1992). The best vineyards are characterised by their ability to produce consistently good quality wine even in seasons not so favourable for good wine quality, while at inferior vineyards there is much more variation and the effect of an unfavourable season will be accentuated (Gladstones, 1992). Mild water stress promotes root growth relative to wetter or drier conditions in clay loam soil (Van Zyl, 1988). Thus, an extensive root system can assist the plant more through unforeseen droughts. Myburgh (1996) found that considerably less fine roots developed at a high soil water availability than where less soil water was available. It is not clear whether this was because of poor soil aeration in the wetter soil, or because more roots were required to absorb adequate water in the dry, sandy soil.

In shallow soils, with a limited potential rooting depth, heavy rains can easily increase the water content in the root zone in excess of the soils’ field water capacity, which can lead to waterlogged conditions. Because of their limited water-holding capacity, such soils may tend to dry out rapidly to the point where water stress develops in the plant. According to Gladstones (1992) such soils will vary between being waterlogged and being dry with just a slight deviation from the normal rainfall. Fortunately such soils are mostly present on the top or against steep high-lying slopes, and because of surface run-off and lateral drainage, waterlogging of such soils is seldom a serious problem. Where these soils do occur, irrigation must be considered. According to Bridges *et al.* (1998) shallow soils (Leptosols) are used successfully for viticulture in Mediterranean regions, particularly when terracing is used to improve soil depth and limit erosion.

The effective depth of a soil determines, to a great extent, its ability to provide the grapevine with sufficient nutrients and water (Saayman, 1981). Soil depth determines the buffer capacity of the soil to overcome unfavourable conditions such as drought or malnutrition (Van Zyl & Van Huyssteen, 1979). Deep soil preparation to increase the effective soil depth can, in some cases, increase the soil water storage capacity in the root zone (Myburgh *et al*., 1996). Conradie & Myburgh (1995) found that the optimum depth of soil preparation for vineyards is between 600 mm and 1000 mm. Soil preparation to a depth of 1000 mm resulted in excessive vegetative growth due to the increased nitrogen absorption by the larger root system, and a reduction in wine quality. The Ψ_l for rain-fed grapevines at harvest on a gravelly soil with different root depths were -1.45 MPa for 400 mm root depth, -1.34 MPa for 800 mm root depth and -1.30 MPa for 1000 mm root depth (Myburgh *et al*., 1996). This showed clearly that grapevine water status tended to increase with increasing soil depth.

Some of the factors that restrict the effective soil depth are fluctuating water tables, solid or weathered bedrock, excess salts, high pH, which normally indicate high sodium adsorption ratios and resulting unfavourable soil physical conditions, as well as a low pH, with resulting aluminium toxicity (Van Zyl & Van Huyssteen, 1979). A compacted subsoil also restricts the effective depth of a soil. Sub-surface soil compaction has various negative effects on grapevines. Root growth is seriously restricted (Van Zyl & Van Huyssteen, 1984). Due to the fact that roots are restricted to a very shallow soil layer, only a small volume of water is available to the plant and the plant becomes extremely sensitive to drought – even in profiles where large quantities of water are still potentially available underneath the compacted layer, but can not be reached by the roots. Under these circumstances shoot growth of the grapevines are restricted (Van Zyl & Van Huyssteen, 1984). Van Huyssteen (1988) also showed that deep tillage can limit the negative effects of soil compaction on grapevines.

Waterlogging during spring is a common soil physical restriction to root development and functioning. Approximately 15% of the soils in the Western Cape are classified as waterlogged (Myburgh, 1994). Permanent waterlogged subsoils also restrict the effective depth of vineyard soils (Van Zyl & Van Huyssteen, 1979). Grapevine roots are adversely affected by poor aeration caused by waterlogged conditions, and their vigour and lifespan are further reduced by root-rotting pathogens (Myburgh, 1994). Therefore adequate drainage of soils are important (Fregoni, 1977). Myburgh & Moolman (1991a, 1991b, 1993) showed that ridging could be used to improve internal drainage of waterlogged soils in the root zone, and so increase the soil depth above the water table. Improved internal drainage, aeration and soil temperature in ridges resulted in stronger vegetative growth during early summer (Myburgh, 1994). At the same time, the soil surface from where evaporation occurs is increased to accelerate the loss of excessive water. Ridging also resulted in more run-off and less infiltration, which also leads to a drier soil water status and better soil aeration (Myburgh & Moolman, 1991a).

2.3.2 GROWTH, YIELD AND GRAPEVINE QUALITY RESPONSES TO GRAPEVINE WATER STATUS

The literature provides positive as well as negative results concerning the effect of available water on almost every aspect of viticulture. Hence, results from scientific vineyard irrigation experiments also differ widely.

Vegetative growth

Most researchers found an increase in vegetative growth with the maintenance of high soil water content levels, obtained by increased frequency of water application (Smart *et al*., 1974; Van Zyl & Weber, 1977, 1981; Myburgh, 1996; Myburgh, 2003a). Others, such as Nieuwoudt (1962), however, found no differences at all in the responses of grapevines to different soil moisture regimes. These seemingly contradictory results may be attributed to differences in soils, and particularly in climate, between experimental localities (Van Zyl & Weber, 1981). According to Van Zyl (1981), a decrease in shoot growth can be an indication of water stress in the grapevine.

Only one irrigation (after flowering) resulted in a significant increase in cane mass compared to no irrigation (Van Zyl & Weber, 1977). This can apparently be attributed to the pattern of shoot elongation as well as to soil water conditions. According to Saayman (1992a), luxurious water supply during the ripening stage stimulates vegetative growth and furthermore actively growing shoots tend to monopolise the carbohydrates synthesised by green leaves and are consequently in direct competition with berries for these substances (Saayman, 1992a). Myburgh (2003a) found that irrigation at 90% plant available water (PAW) depletion reduced vegetative growth significantly in comparison to irrigation at 30% depletion. Van Zyl & Weber (1977) found that as a result of severe water stress, grapevines can lose basal leaves. Mild water stress will reduce vigour, possibly improving canopy light penetration (Williams *et al*., 1994 and references therein).

Yield

Most researchers have reported an increase in grape yield with frequent water applications (Van Zyl & Weber, 1977; Van Zyl & Weber, 1981), while others found a decrease in production with irrigation (Van Zyl & Weber, 1981). Differences in the atmospheric conditions and soil types could be the reason for these contradictory results (Van Zyl & Weber, 1981).

In general, growth and productivity are affected by the plant water status, which serves as an excellent indicator of the availability of soil water to the plant (Van Zyl & Weber, 1981). Water supply generally increase crop yields (Hepner *et al*., 1985). The grapevine is sensitive to soil water conditions during a number of critical periods in the seasonal growth cycle (Van Zyl & Weber, 1981 and references therein). It seems therefore that apart from climatic and soil water conditions, the response of grapevines to irrigation is mainly determined by the growth stage (Hardie & Considine, 1976). The availability of sufficient water during specific growth stages has important implications (Van Zyl, 1984). According to Van Zyl & Weber (1981), Branas found that production and growth showed almost the same degree of improvement with irrigation during the active growing period only, as with continual irrigation throughout the season. Myburgh (2003b) found that periods of water deficit early in the season tended to affect yield of Sultanina more negatively than deficits induced between pea size and harvest. Hardie & Considine (1976) reported similar results. Since severe water stress can induce cluster abscission, the period after flowering is a particularly sensitive period for moisture stress (Hardie & Considine, 1976).

Van Zyl (1984) found that water stress during flowering and fruit set (phase I) reduced berry mass significantly, and despite increased water applications in the lag phase (phase II) of berry development, berries remained small until harvest. According to literature moisture stress during phase I limits cell division, a limitation that cannot be rectified by favourable moisture conditions at a later stage (Van Zyl, 1984). In the coastal regions of the Western Cape, sufficient winter rain limits the use of water stress to reduce berry mass during budbreak to flowering, as well as during phase I of berry growth, because water stress can not be obtained when the soil water content is high. In the study by Van Zyl (1984), fruit set was negatively affected by a dry soil moisture regime. He also found that moisture stress during the ripening stage had a deleterious effect on berry mass. Berry mass was, however, not nearly as sensitive to moisture stress during the ripening period as during the cell division phase. Berry size was also significantly reduced by water deficits induced after flowering. According to Van Zyl & Weber (1977) higher yields were obtained in treatments receiving irrigation compared to dryland treatments. The largest increase in yield per irrigation was obtained by one irrigation and subsequent irrigations resulted in much smaller yield responses. Van Zyl & Weber (1977) ascribed the yield increase to improved fruit set and larger berries, resulting in bigger clusters.

Juice composition

It is well-known that the availability of soil water affects sugar concentration, total titratable acidity, the malic/tartaric acid ratio, colour in musts of red cultivars, berry size, harvesting date and eventually wine quality. Van Zyl & Weber (1977) found that, as a result of severe water stress, incomplete ripening can occur.

The importance of the period from veraison to ripening for grape quality is well-known. Luxurious water supply during the ripening stage stimulates vegetative growth. Actively growing shoots tend to monopolise the carbohydrates synthesised by green leaves and are consequently in direct competition with berries. The end result is less sugar in berries (Saayman, 1992a). Also, if there is no water stress, the osmotic pressure in cells needs not be that high in order to acquire water. Osmotic pressure in cells is mainly determined by soluble substances like sugar, so there is less incentive for the grapevine to produce more sugar when there is no water stress (Saayman, 1992a). It appears that either an over-abundance of water in grapevines on the one hand, as well as severe moisture stress on the other hand, is equally detrimental to the quality of the harvest. Various research reports lead to the conclusion that an increase in grapevine water stress towards maturity is beneficial to grape quality, and subsequently wine quality, providing the stress is not too severe (Van Zyl & Weber, 1977). Sugar-accumulation can be delayed by grapevine water stress, but mild water stress reduces the vegetative growth and can increase sugar-accumulation (Smart & Coombe, 1983). Water deficit had no significant effect on juice sugar content in Sultanina grapes according to Myburgh (2003b). Van Zyl & Weber (1977) found no difference in sugar concentrations between irrigated and dryland treatments, and concluded that, should sugar content be used as criterion for time of harvest, no difference will exist among treatments as regards ripening date. Van Zyl (1984) and Van Zyl & Van Huyssteen (1988), however, found that water stress usually increased the sugar content of grapes, but that the effect varies immensely because of the influence of different factors, *i.e.* a decrease of the crop load, the microclimate around the bunches and the rate of photosynthesis. Stressed grapevines produced small berries, and also yielded a low shoot growth which improved sunlight penetration to the bunches. Higher temperatures, resulting from this, were beneficial to sugar accumulation (Van Zyl, 1984).

Conversely, Van Zyl & Weber (1977), Van Zyl (1984) and Van Zyl & Van Huyssteen (1988) found that increased irrigation frequencies and levels before the ripening period increased the total titratable acid (TTA). The TTA concentration was higher in berries from grapevines grown on soils with high soil moisture regimes compared to ones on drier soils (Van Zyl, 1984). Total titratable acid also decreased significantly in berries from grapevines subjected to water stress during phase I of berry growth. The rate of decrease was most rapid in berries from grapevines on the driest soil after veraison. From veraison onwards malate concentrations of berries from the driest treatment were significantly lower than those of the other irrigation treatments. These differences may be due to the microclimate inside the grapevine canopy as affected by shoot growth. According to Van Zyl (1984), the slow decrease in TTA towards the end of the season can largely be attributed to malic acid decomposition which continued until harvest. The tartrate/malic ratio was highest in the dry treatment and lowest in grapes grown at higher soil moisture regimes. Myburgh (2003b) reported that water deficits had no significant effect on TTA. According to Jackson & Lombard (1993) high crop loads of more than 10 kg grapes per kg pruning mass, resulted in low total soluble solids (TSS).

Van Zyl & Bredell (1995) mention results which showed that grape colour, and in particular, the colour of red wine benefit from water stress. In contrast, Winkler *et al*. (1974) state that severe water stress will result in dull fruit colour. Van Zyl & Bredell (1995) emphasize that differences between cultivars and localities (*i.e.* terroir) can affect the experimental results, and thus also recommendations based on them. Myburgh (1996) reported that both dry and wet treatments caused poor fruit colour in Barlinka.

Matthews & Anderson (1988) showed that, although water stress increased phenols in juice and skins, increased anthocyanins in skins, reduced malate and increased proline, it had no effect on onset of veraison or duration of ripening. In a review, Smart & Coombe (1983) noted that excessive irrigation slows ripening, increases yield partially by berry enlargement, elevates juice pH and acid content, and reduces anthocyanins because of shading due to continuous and excessive shoot growth. In contrast, water stress enhances early ripening but reduces yield, berry weight, and malic acid due to excessive exposure.

Wine Quality

There appears to be strong evidence that water availability can affect wine quality. In a review of factors important for wine quality, Seguin (1983) stresses the significance of water, but concludes that insufficiency can be as bad as excess. However, information on wine quality as a direct function of soil water under dryland conditions in South Africa is limited.

Müller-Thurgau grapevines grown in pots under soil water deficits from veraison to harvest, produced wine which was rated as “fruity, fragrant and elegant”, while wines from grapevines that were under moist soil water conditions during this period were “full-bodied and less elegant” (Jackson & Lombard, 1993 and references therein). Preferred wines were obtained from grapevines on soils that remained moist until veraison, wherafter soil water deficits occurred until harvest, and the least preferred wines were from grapevines on soil that were dry until veraison, whereafter they were irrigated. Increased water availability often increases the potassium (K) and pH level in the must and wine (Freeman *et al*., 1983), and may reduce colour (Rankine *et al*., 1971) as well as content of anthocyanins (Matthews & Anderson, 1988). According to Mpelasoka *et al.* (2003), irrigation strategies that reduce the water supply to grapevines may be used to reduce berry K accumulation. However, Iland (1988) reported that water stress can result in stomatal closure and thus a decrease in photosynthesis, lowering available sugar and preferentially moving leaf K to the berry. Similar results were found in the ARC Infruitec-Nietvoorbij Project No. WW 13/01 (W.J. Conradie, personal communication). According to Van Zyl (1981), studies in France during the 1960's reported that irrigation decreased the quality of red wines, mainly due to a decrease in colour.

Hepner *et al*. (1985) found that the quality of wine from grapevines grown on a soil with a high soil moisture regime, was consistently inferior compared to wines from grapevines grown on soils with lower soil moisture regimes. Negative relationships were found between wine quality and several parameters such as high pruning mass, berry mass, leaf K, must K and wine K content, total acid and malic acid content, as well as high wine pH.

2.4 SUMMARY

Evapotranspiration and crop coefficients of grapevines are not only affected by atmospheric conditions and the soil, but also by the moisture regime maintained, *e.g.* irrigated vs. dryland grapevines, which may cause significant ET variation between vineyards. A decrease in plant-available water as the season progresses also causes a decrease in ET. An understanding of the vineyard and soil factors affecting evaporation and transpiration is essential to develop improved management practices to optimize grape yield and wine quality.

Scientifically based knowledge regarding the soil-plant-atmosphere-continuum is essential to optimize soil and water management practices in order to balance vegetative growth, yield and quality. The measurement of leaf water potential to quantify the plant water status in viticultural research is widely accepted and used as a means to gain this knowledge.

The water status of the grapevines is mainly affected by various atmospheric conditions as well as the soil water status. Factors affected by the grapevine water status are vegetative growth, yield, juice composition and wine quality. Not only is the amount of water stress important, but the period and duration of the water stress can also have significant effects on the grapevine performance.

A reduction in vegetative growth and yield is usually found under conditions of water stress. Flowering is particularly a sensitive period for the grapevine to experience water stress. Mild water stress not only increases sugar accumulation, but the colour of grapes as well as red wine will also benefit from it. Total titratable acid, however, decreases with water stress. Moist soil conditions until veraison, followed by mild soil water deficits, usually produces high quality wines. An overabundance of water as well as severe water stress is equally detrimental to the quality of grapes and wines.

2.5 LITERATURE CITED

Archer, E., Swanepoel, J.J. & Strauss, H.C. (1988). Effect of plant spacing and trellising systems on grapevine root distribution. In: Van Zyl, J.L. (Compiler). The grapevine root and its environment. Techn. Comm. 215, 74-87. Dept. Agric. & Water Supply, Pretoria.

Bennie, A.T.P. & Hensley, M. (2003). Advances in soil physics and soil water management in South Africa, 1979-2003. Paper presented at Soil Science Society of South Africa, Golden Jubilee Congress, Stellenbosch, 20-23 January 2003.

Bridges, E.M., Batjes, N.H. & Nachtergaele, F.O. (1998). World reference base for soil resources. Atlas. Acco Press, Leuven.

Carey, V.A. (2001). Spatial characterization of natural terroir units for viticulture in the Bottelaryberg-Simonsberg-Helderberg winegrowing area. M.Sc. Thesis, University of Stellenbosch, Private Bag X1, Matieland 7602 (Stellenbosch), South Africa.

Carey, V.A., Conradie, W.J., Myburgh, P.A., Laker, M.S. & Bruwer, R.J. (2004). The significance of plant water status as a criterion in South African terroir studies. *OIV Group d'Éxperts : Physiologie de la vigne* - March 2004.

Conradie, W.J. (2001). Die effek van grond en klimaat op wyngehalte in die Overberg. In: Grondkundige aspekte vir optimum wynkwaliteit in die Overberg. LNR Infruitec-Nietvoorbij, Stellenbosch. 10pp.

Conradie, W.J. & Myburgh, P.A. (1995). The effect of soil depth on the performance of grapevines. In: Goussard, P.G., Archer, E., Saayman, D., Tromp, A. & Van Wyk, C.J. (eds). In: Proc. SASEV International Congress, November 1995, Cape Town, South Africa. pp 115-117.

Coombe, B.G. (1987). Influence of temperature on composition and quality of grapes. *Acta Hort*. **206**, 23-33.

Düring, H. (1976). Studies on the environmentally controlled stomatal transpiration in grapevines. I. Effects of light intensity and air humidity. *Vitis* **15**, 82-87.

Düring, H. (1979). Effects of air and soil humidity on vegetative growth and water relationships of grapevines. *Vitis* **18**, 211-220.

Düring, H. (1987). Stomatal responses to alterations of soil and air humidity in grapevines. *Vitis* **26**, 9-18.

Düring, H. (1988). CO_2 assimilation and photorespiration of grapevine leaves: Responses to light and drought. *Vitis* **27**, 199-208.

Düring, H. & Loveys, B.R. (1982). Diurnal changes in water relations and absisssic acid in field grown *Vitis vinifera* cvs. I. Leaf water potential components and leaf conductance under humid temperate and semiarid conditions. *Vitis* **21**, 223-232.

Eastham, J. & Gray, S.A. (1998). A preliminary evaluation of the suitability of sap flow sensors for use in scheduling vineyard irrigation. *Am. J. Enol. Vitic*. **49**, 171-176.

Fourie, A. (1989). Effect of water stress on table grapes. M.Sc. Thesis, University of Stellenbosch, Private Bag X1, Matieland 7602 (Stellenbosch), South Africa.

Fourie, J.C., Louw, P.J.E. & Agenbag, G.A. (2001). Effect of seeding date on the performance of grasses and broadleaf species evaluated for cover crop management in two wine grape regions of South Africa. *S. Afr. J. Plant Soil* **18**, 118-127.

Freeman, B.M., Kliewer, W.M. & Stern, P. (1982). Research note – Influence of windbreaks and climatic region on diurnal fluctuation of leaf water potential, stomatal conductance, and leaf temperature of grapevines. *Am. J. Enol. Vitic*. **33**, 233-236.

Freeman, B.M. & Kliewer, W.M. (1983). Effect of irrigation, crop level and potassium fertilization on Carignane grapevines. II. Grapes and wine quality. *Am. J. Enol. Vitic*. **34**, 197-207.

Fregoni, M. (1977). Effects of soil and water on the quality of the harvest. In: Proc. Int. Sym. Quality of the Vintage, February 1977, Cape Town, South Africa. pp 151-168.

Gladstones, J. (1992). Viticulture and Environment. Winetitles, Adelaide. 310pp.

Hardie, W.J & Considine, J.A. (1976). Repsonse of grapes to water deficit stress in particular stages of development. *Am. J. Enol. Vitic*. **27**, 55-61.

Hepner, Y., Bravdo, B., Loinger, C., Cohen, S. & Tabacman, H. (1985). Effect of drip irrigation schedules on growth, yield, must composition and wine quality of Cabernet Sauvignon. *Am. J. Enol. Vitic*. **36**, 77-85.

Hillel, D. (1971). Soil and Water – Physical Principles and Processes. Academic Press, New York & London, 288 pp.

Hillel, D. (1980). Fundamentals of soil physics. Academic Press, New York, 385pp.

Iland, P.G. (1988). Grape berry ripening: the potassium story. *Aust. Grapegrower and Winemaker* **289**, 22-24.

Jackson, D.I.& Lombard, P.B. (1993). Environmental and management practices affecting grape composition and wine quality – a review. *Am. J. Enol. Vitic*. **44**, 409-430.

Kobringer, J.M., Kliewer, W.M. & Lagier, S.T. (1984). Effects of wind on stomatal behaviour of several grapevine cultivars. *Am. J. Enol. Vitic*. **35**, 164-169.

Kramer, P.J. (1983). Water relations of plants. Academic press, New York, 489 pp.

Lascano, R.J. Baumhart, R.L. & Lipe, W.N. (1992). Measurement of water flow in young grapevines using the stem heat balance method. *Am. J. Enol. Vitic*. **43**, 159-165.

Matthews, M.A. & Anderson, M.W. (1988). Fruit ripening in *Vitis vinifera* L.: responses to seasonal water deficits. *Am. J. Enol. Vitic*., **39**, 313-320.

Mpelasoka, B.S., Schachtman, D.P., Treeby, M.T. & Thomas, M.R. (2003). A review of potassium nutrition in grapevines with special emphasis on berry accumulation. *Aust. J. Grape Wine Res.* **9**, 154-168.

Myburgh, P.A. (1994). Effect of ridging on the performance of young grapevines on a waterlogged soil. *S. Afr. J. Enol. Vitic*. **15**, 3-8.

Myburgh, P.A. (1996). Response of *Vitis vinifera* L. cv. Barlinka/Ramsey to soil water depletion levels with particular reference to trunk growth parameters. *S. Afr. J. Enol. Vitic*. **17**, 3-14.

Myburgh, P.A. (1998). Water consumption of South African vineyards: A modelling approach based on the quantified combined effects of selected viticultural soil and meteorological parameters. Ph.D. Dissertation, University of Stellenbosch, Private bag X1, Matieland 7602 (Stellenbosch), South Africa.

Myburgh, P.A. (2003a). Responses of *Vitis vinifera* L. cv. Sultanina to level of soil water depletion under semi-arid conditions. *S. Afr. J. Enol. Vitic.* **24**, 16-24.

Myburgh, P.A. (2003b). Responses of *Vitis vinifera* L. cv. Sultanina to water deficits during various pre- and post-harvest phases under semi-arid conditions. *S. Afr. J. Enol. Vitic.* **24**, 25-33.

Myburgh, P.A. & Moolman, J.H. (1991a). The effect of ridging on the soil water status of a waterlogged vineyard soil. *S. Afr. J. Plant. Soil* **8**, 184-188.

Myburgh, P.A. & Moolman, J.H. (1991b). Ridging – A soil preparation practice to improve aeration of vineyard soils. *S. Afr. J. Plant. Soil* **8**, 189-193.

Myburgh, P.A. & Moolman, J.H. (1993). The effect of ridging on the temperature regime of a waterlogged vineyard soil. *S. Afr. J. Plant. Soil* **10**, 17-21.

Myburgh, P.A., Van Zyl, J.L. & Conradie, W.J. (1996). Effect of soil depth on growth and water consumption of young *Vitis Vinifera* L. cv. Pinot noir. *S. Afr. J. Enol. Vitic.* **17**, 53-62.

Nieuwoudt, A.D. (1962). Agro-hydrological studies on the Elephants River Irrigation Scheme. Ph.D. Dissertation, University of Stellenbosch, Private bag X1, Matieland 7602 (Stellenbosch), South Africa.

Pellegrino, A., Moon, J. (Jr.) & Matthias, A. (1987). Effect of soil moisture stress on the gas exchange characteristics and mesophyll conductance of Cabernet Sauvignon grapes. In: Proc. Int. Conf. on Measurement of Soil and Plant Water Status, July 1987, Vol. 2, Utah State University, Logan. pp 121-122.

Rankine, B.C., Fornachon, J.C.M., Boehm, E.N & Cellier, K.M. (1971). The influence of grape variety, climate and soil on grape composition and quality of table wines. *Vitis* **10**, 33-50.

Ratliff, L.F., Ritchie, J.T. & Cassel, D.K. (1983). Field measured limits of soil water availability as related to laboratory measured properties. *Soil Sci. Soc. Am. J*. **47**, 770-775.

Saayman, D. (1977). The effect of soil and climate on wine quality. . In: Proc. Int. Sym. Quality of the Vintage, February 1977, Cape Town, South Africa. pp 197-208.

Saayman, D. (1981). Klimaat, grond en wingerdbougebiede. In: Burger, J. & Deist, J. (eds). Wingerdbou in Suid-Afrika. Maskew Miller, Cape Town. pp 48-66.

Saayman, D. (1992a). Natural influences and wine quality Part 1. Climate. *Wynboer* Jul. 1992, 46-48.

Saayman, D. (1992b). Natural influences and wine quality Part 2. The role of soil. *Wynboer* Aug. 1992, 49-51.

Schmid, J. (1997). Xylemflussmessungen an Reben. Geisenheimer Berichte, Band 33, Gesellschaft zur Förderung der Forschungsanstalt, Gesienheim, 164pp.

Seguin, G. (1983). Influence des terroirs viticoles sur la constitution et la qualité des vendages. Bull. OIV **56**, 3-18.

Sepulveda, G. & Kliewer, W.M. (1986). Stomatal response of three grapevine cultivars (*Vitis vinifera* L.) to high temperatures. *Am. J. Enol. Vitic*. **37**, 44-52.

Smart, R.E., Turkington, C.R. & Evans, J.C. (1974). Grapevine response to furrow and trickle irrigation. *Am. J. Enol. Vitic*. **25**, 62-66.

Smart, R.E. & Coombe, B.G. (1983). Water relations of grapevines. In: Kozlowski T.T. (Ed.). Water deficits and plant growth VII. Academic press, New York. pp 137-196.

Van der Watt, H.v.H. & Van Rooyen, T.H. (1990). A glossary of science. Soil Science Society of South Africa, P.O. Box 30030, Sunnyside, 0132, Pretoria, 464pp.

Van Huyssteen, L. (1988). Soil preparation and grapevine root distribution – A qualitative and quantitative assessment. In: The grapevine root and its environment. Techn. Comm. No. 215, Dept. Agric. & Water Supply, Pretoria, 1-15.

Van Huyssteen, L., Van Zyl, J.L. & Koen, A.P. (1984). The effect of cover crop management on soil conditions and weed control in a Colombar vineyard in Oudshoorn, *S. Afr. J. Enol. Vitic*. **5**, 7-17.

Van Zyl, E. & Myburgh, P.A. (1997). Effect of straw mulching and tillage on topsoil water loss and grapevine performance. Poster presented at 21st SASEV Congress, 27-28 November 1997, Cape Town.

Van Zyl, J.L. (1975). Wingerdbesproeiing in die Stellenbosch-gebied binne die raamwerk van die plaaslke grond-water-plant-atmosfeer-kontinuum. M.Sc. Thesis, University of Stellenbosch, Private bag X1, Matieland 7602 (Stellenbosch), South Africa.

Van Zyl, J.L. (1981). Waterbehoefte en besproeiing. In: Burger, J. & Deist, J. (eds). Wingerdbou in Suid-Afrika. Maskew Miller, Cape Town. pp 234-283.

Van Zyl, J.L. (1984). Response of Colombar grapevines to irrigation as regards quality aspects and growth. *S. Afr. J. Enol. Vitic*. **5**, 19-28.

Van Zyl, J.L. (1987). Diurnal variation in grapevine water stress as a function of changing soil water status and meteorological conditions. *S. Afr. J. Enol. Vitic*. **8**, 45-52.

Van Zyl, J.L. (1988). Response of grapevine roots to soil water regimes and irrigation systems. In: Van Zyl, J.L. (Compiler). The grapevine root and its environment. Techn. Comm. 215, 30-43. Dept. Agric. & Water Supply, Pretoria.

Van Zyl, J.L. & Bredell, G.S. (1995). Irrigation research and development for horticultural crops. Proc. S. Afr. Irrigation Symposium, Durban, 4-6 June 1991, WRC Report No. TT 71/95, 98-109.

Van Zyl, J.L & Van Huyssteen, L. (1979). Die indeling van gronde volgens potensiaal vir wyndruiwe met spesiale verwysing na die Bo-Bergriviervallei. *Wynboer* **573**, 46-47, 57-58, 60.

Van Zyl, J.L & Van Huyssteen, L. (1980). Comparative studies on wine grapes on different trellising systems: I. Consumptive water use. *S. Afr. J. Enol. Vitic*. **1**, 7-14.

Van Zyl, J.L. & Van Huyssteen, L. (1984). Soil and water management for optimum grape yield and quality under conditions of limited or no irrigation. In : Proc. 5th Australian Wine Industry Technical Conf., November - December 1983, University of Western Australia, Perth, Australia. pp 25-66.

Van Zyl, J.L. & Van Huyssteen, L. (1988). Irrigation systems – Their role in water requirements and the performance of grapevines. *S. Afr. J. Enol. Vitic*. **9**, 3-8.

Van Zyl, J.L. & Weber, H.W. (1977). Irrigation of Chenin blanc in the Stellenbosch area within the framework of the climate-soil-water-plant continuum. In: Proc. Int. Sym. Quality of the Vintage, February 1977, Cape Town, South Africa. pp 331-349.

Van Zyl, J.L. & Weber, H.W. (1981). The effect of various supplementary irrigation treatments on plant and soil moisture relationships in a vineyard. *S. Afr. J. Enol. Vitic*. **2**, 83-99.

Williams, L.E., Dokoozlian, N.K. & Wample, R. (1994). Grape. In: Shaffer, B. & Anderson, P.C. (eds). Handbook of environmental physiology of fruit crops, Vol I, Temperate crops. CRC Press, Boca Raton. pp 85-133.

Winkel, T. & Rambal, S. (1990). Stomatal conductance of some grapevines growing in the field under a Mediterranean environment. *Agric. For. Meteorol*. **51**, 107.

Winkler, A.J., Cook, J.A., Kliewer, W.M. & Lider, L.A. (1974). General Viticulture. University of California Press, Berkeley, 710pp.

CHAPTER 3

RESEARCH RESULTS

THE EFFECT OF SOIL TYPE AND MESOCLIMATE ON THE EVAPOTRANSPIRATION OF SAUVIGNON BLANC/99RICHTER

CHAPTER 3

3.1 INTRODUCTION

Carey (2001) defines terroir as a complex of natural environmental factors (topography, climate, soil and parent material), which cannot be easily modified by the producer. The effect of this complex, as modified by vineyard practices, is expressed in the final product, resulting in distinctive wines with identifiable origins. Thus terroir cannot be viewed in isolation from human interference, although the latter does not form part of the intrinsic definition. Good terroirs are those permitting complete but quite slow grape maturation (Seguin, 1986). The most important aspect that distinguishes between a good terroir and an inferior one is the fact that the former provides a high quality wine with distinctive properties every season, while the inferior terroir will provide a quality wine only in some seasons (Conradie, 2001).

Various claims are made about the effect of soil on wine quality. Although the emphasis often falls on geology, as an indication of parent material, it seldom directly has a dominant role in regard to wine quality (Van Schoor, 2001). It does, however, play an important indirect role by contributing to the physical properties of the soil (Conradie, 2001). According to Saayman (1992), the effect of soil type is without question the least understood natural factor with regard to wine quality. While the effect of cultivars and climate is relatively easy to determine, the effect of the soil is often confusing, particularly in warmer climates, where climate dominates over all other factors (Fregoni, 1977).

In warm winelands such as South Africa (Western Cape), with a mediterranean climate which is characterised by a hot, dry summer period, the most important characteristic of soil is its ability to supply sufficient water to the grapevine during the entire growing season. The soil water holding capacity, and thus plant available water, are affected by soil depth, texture and structure (Van Zyl, 1981). Soil water potential determines the ability of the soil to supply water to plants. If the soil water potential decreases below a certain level, the soil is no longer able to supply water at the desired rate and water stress develops in the plant.

Grapevines depend on adequate water for normal functioning and economically viable production. Water requirement is defined as the total quantity of water, regardless of its source, required by crops for their normal growth under field conditions (Myburgh, 1998). Evapotranspiration (ET) is defined as the combined loss of water from a given area and during a specific period of time, by evaporation from the soil surface and by transpiration from plants (Van der Watt & Van Rooyen, 1990). Due to variation in viticultural practices and atmospheric conditions, ET can vary considerably between vineyards (Myburgh, 1998). The dynamics of this process are controlled by environmental and soil surface conditions as well as the conditions of the grapevine (Myburgh, 1998). Factors that affect the soil water status and transpiration of the grapevines, such as leaf area, irrigation, method of cultivation, atmospheric conditions and soil characteristics, will therefore all affect the water consumption of a vineyard.

The aim of this study was to determine and compare: (i) the soil water status, (ii) the soil water holding capacity of the soil, and (iii) the ET of the grapevines on two different soils at each of the two localities differing in mesoclimate and topography.

3.2 MATERIALS AND METHODS

The experiment was conducted during the 2002/03 growing season in two Sauvignon blanc vineyards in the Stellenbosch district.

3.2.1 TERROIR DESCRIPTION

3.2.1.1 Topography

The two Sauvignon blanc vineyards were situated at Helshoogte and Papegaaiberg, both in the Stellenbosch district, approximately nine kilometres apart (Fig. 3.1). Their co-ordinates, altitudes as well as slope aspects and gradients are summarized in Table 3.1. Two experiment plots, representing different soils, were selected in each vineyard.

The Helshoogte vineyard was situated 413 m above sea level on the south-easterly foot slopes of the Simonsberg mountain with a 5% gradient. The two plots were approximately 55 m apart with an altitude difference of approximately 3.0 m (Fig. 3.2). At Papegaaiberg, the vineyard was situated at 148 m altitude on the north-western foot hills of the Papegaaiberg mountain with a 6% gradient. The two plots were approximately 60 m apart with an altitude difference of approximately 3.5 m (Fig. 3.2).

3.2.1.2 Soils

Two contrasting soil types in terms of soil water regime were identified in each vineyard (Table 3.1). Soils were classified at form and family level by Conradie *et al.* (2002), using the South African Soil Classification System (Soil Classification Working Group, 1991). Particle size distribution and bulk density data for the soils are presented in Table 3.2.

At Helshoogte the two soils represented the Tukulu (Entunja family) and Hutton (Hayfield family) forms respectively, both with uniform clay loam texture throughout the profile. The Tukulu soil, which occupied a lower landscape position than the Hutton (Fig. 3.2), consisted of a 400 mm yellow-brown orthic A horizon overlying a 400 mm non-luvic yellow-brown neocutanic B horizon. The C horizon consisted of semi-weathered granite rock showing advanced physical and strong chemical weathering and having signs of wetness (Van Schoor, 2001). The Hutton soil had a 300 mm reddish brown orthic A horizon on a 400 mm mesotrophic non-luvic red apedal, B horizon, overlying a semi-weathered granitic C horizon with no signs of wetness (Van Schoor, 2001). The homogeneous red subsoil and absence of signs of wetness indicated that this was a well-drained soil.

The soils at Papegaaiberg were of the Avalon (Vryheid family) and Tukulu (Mostertshoek family) forms respectively, both with uniform clay loam texture throughout the profile. The Avalon soil had a 250 mm orthic A horizon overlying a 350 mm mesotrophic luvic yellow-brown, apedal B horizon which overlay a mottled and concretionary (Fe- and Mn-oxides) soft plintic B horizon and C horizon. The Tukulu soil had a 250 mm bleached orthic A horizon, overlying a 250 mm yellow-brown, non-luvic, neocutanic B horizon, overlying a gleyed clay C horizon (Van Schoor, 2001). The soft plinthic horizon in the Avalon soil indicated a zone with a fluctuating water table low in the profile. The gleyed clay layer in the Tukulu indicated a zone with prolonged (almost permanent) excessive wetness in the bottom of the profile. The Tukulu soil occupied a lower landscape position than the Avalon (Fig. 3.2).

3.2.1.3 Atmospheric conditions

Automatic weather stations (MC Systems, Cape Town) were erected halfway between the two plots at each locality and recorded temperature, rainfall, net radiation, hours of sunshine, evapotranspiration as well as wind speed and direction every minute. These values were averaged or summed for periods of an hour and the hourly data set was used to calculate daily minimum, maximum and mean temperatures, number of hours with temperatures above 30°C or below 12°C, and growing degree-days and Huglin index (Conradie *et al*., 2002). The weekly rainfall at each locality was also calculated. The weather stations recorded data for the period from September 2002 until March 2003, except for Helshoogte, which only recorded until February 2003, since the weather station was removed in middle March 2003.

3.2.2 EXPERIMENT VINEYARDS

The experiment was conducted in two 20-year old Sauvignon blanc vineyards grafted onto 99Richter. According to the general practice for this district, all soils had been delve ploughed to a depth of approximately 800 mm before grapevines were planted (Conradie *et al.*, 2002). No irrigation was applied. The plant spacing for both vineyards was 2.75 m x 1.0 m. The vineyards were trained on vertical trellis systems (Booysen *et al*., 1992). At Papegaaiberg there were two wires for the foliage, whereas at Helshoogte there were four foliage wires. Two experiment plots, each consisting of two adjacent rows, with ten adjacent grapevines per row, on the different soil types, were selected in each vineyard. Grapevines were spur-pruned annually to 16 buds per meter cordon. Suckering, *i.e.* removal of shoots not located on spurs, was done before bloom. Apart from this, growers applied normal viticultural practices at the experiment localities.

3.2.3 SOIL WATER MEASUREMENTS

The soil water content and soil water matric potential of both soils at each locality were monitored during the growing season, *i.e.* September 2002 until middle March 2003.

3.2.3.1 Soil water matric potential

The soil water matric potential (Ψ_m) of the two soil forms at each of the localities was measured twice a week by means of Bourdon gauge type tensiometers (Continental Fan Works, Cape Town) at 300 mm, 600 mm and 900 mm depths.

Tensiometers were placed on the grapevine row between grapevines. Two sets of tensiometers were used per plot, with one set close to the neutron probe access tube also used for measuring soil water content for another study (Conradie *et al.*, 2002). The tensiometers were installed in winter to allow soil settling around the ceramic cups.

3.2.3.2 Soil water content

3.2.3.2.1 Neutron scattering method

Neutron probe access tubes were already installed at each plot and were used to determine the soil water content during the season for both soils at the two localities (Conradie *et al*., 2002). The soil water content was monitored in relation to Ψ_m after saturation and a graph was plotted for the three depths (300 mm, 600 mm and 900 mm) of each soil. A power equation fitted these curves best, and was used to convert soil water content to Ψ_m once the latter decreased to potentials below *ca* -0.08 MPa, *i.e.* below the range of the tensiometers.

3.2.3.2.2 Gravimetric method

The mass percentage soil water content (θ_m) of the two soil forms at each locality was monitored once or twice a week. This was done to determine the *in situ* soil water characteristic curves in order to calculate the soil water retaining capacity of each soil, as well as the volumetric soil water content during the 2002/03 season. Soil water content was determined gravimetrically at 250-350 mm, 550-650 mm and 850-950 mm depth increments. Soil samples were collected in sealed tins, immediately weighed using an electronic balance and subsequently dried in an oven at 105°C for a minimum of 18 hours to constant weight, after which it was again weighed. The θ_m was then calculated using the following equation:

$$\theta_m = \left(\frac{A-B}{B-C}\right) \times 100 \qquad (3.1)$$

where: θ_m = Mass percentage soil water content (%)
A = Mass of wet sample (g)
B = Mass of oven dry sample (g)
C = Mass of sample tin (g)

The volumetric soil water content (θ_v) for each layer (0-300 mm, 300-600 mm and 600-900 mm) was then calculated using the following equation:

$$\theta_v = \theta_m \times \rho_b \qquad (3.2)$$

where:
θ_v = volumetric soil water content (%)
θ_m = soil water content (%)
ρ_b = bulk density (kg/m^3)

Soil water content in millimetres (SWC) were calculated as follows:

$$SWC = \theta_v \times d \qquad (3.3)$$

where:
θ_v = volumetric soil water content (%)
d = thickness of layer (dm)

Water content of the 900 mm profile depth was obtained for a specific date by summation of the SWC for three different layers, *i.e.* 0-400 mm, 400-700 mm and 700-900 mm, as represented by the tensiometers.

3.2.3.3 Soil water characteristic curves

Soil water characteristic curves were determined *in situ* for the two soil forms at both localities at 300 mm, 600 mm and 900 mm, in order to calculate the soil water retaining capacity of each soil. This was done by monitoring mass percentage soil water content in relation to Ψ_m after saturation and then plotting a graph. A power equation fitted the soil water characteristic curves best at the three different depths, and was used to convert Ψ_m to gravimetric soil water content. The readily available water, *i.e.* water retained between -0.01 MPa and -0.10 MPa, was calculated as follows:

$$RAW = (\theta_{m0.01} - \theta_{m0.1}) \times \rho_b \times d \qquad (3.4)$$

where:
RAW = readily available water (mm/m)
$\theta_{m0.01}$ = mass percentage soil water content at -0.01 MPa (%)
$\theta_{m0.1}$ = mass percentage soil water content at -0.10 MPa (%)
ρ_b = bulk density (kg/m^3)
d = thickness of layer (dm)

The power equations of the characteristic curves were also used to calculate the total plant available water, *i.e.* water retained between -0.01 MPa and -1.50 MPa, as follows:

$$PAW = (\theta_{m0.01} – \theta_{m1.5}) \times \rho_b \times d \qquad (3.5)$$

where: PAW = plant available water (mm/m)
$\theta_{m0.01}$ = mass percentage soil water content at -0.01 MPa (%)
$\theta_{m1.5}$ = mass percentage soil water content at -1.50 MPa (%)
ρ_b = bulk density (kg/m^3)
d = thickness of layer (dm)

Assuming that the soil water content was at field capacity at the beginning of the season (budbreak), the percentage soil water depletion of PAW of each soil for the growing season (budbreak to post harvest) were calculated as follows:

$$SWD = (SWC_b – SWC_e)/ PAW \times 100 \qquad (3.6)$$

where: SWD = soil water depletion (%)
SWC_b = soil water content at the beginning of the season (mm)
SWC_e = soil water content at the end of the season (mm)
PAW = plant available water (mm/m)

3.2.4 EVAPOTRANSPIRATION

3.2.4.1 Vineyard evapotranspiration

Mean daily evapotranspiration was calculated over weekly intervals during the growing season (September 2002 until March 2003) for each of the four localities using the following universal soil water balance equation:

$$ET = (SWC_b – SWC_e + P + I – D – R) / t \qquad (3.7)$$

where: ET = vineyard evapotranspiration (mm/day)
SWC_b = soil water content at the beginning of the week (mm)
SWC_e = soil water content at the end of the week (mm)
P = rainfall (mm)
I = irrigation (mm)

D = drainage (mm)
R = run-off (mm)
t = time (days)

Mean monthly crop evapotranspiration was calculated from the mean daily ET. Since both vineyards received no irrigation, D and R were assumed to be negligibly small. Thus, to calculate ET equation 3.7 was reduced as follows:

$$ET = (SWC_b - SWC_e + P) / t \qquad (3.8)$$

3.2.4.2 Reference evapotranspiration and crop coefficients

Hourly reference evapotranspiration (ET_0) was calculated from the radiation, air temperature and wind speed measured by the automatic weather stations. The following modified Penman-Monteith equation was used (Allen *et al.*, 1998):

$$ET_0 = 0.408\ \Delta\ (R_n - G) + \gamma\ \frac{900}{T + 273}\ u_2\ (e_s - e_a) / \Delta + \gamma\ (1 + 0.34u_2) \qquad (3.9)$$

where: ET_0 = reference crop evapotranspiration (mm/day)
R_n = net radiation at the crop surface (MJ/m^2/day)
G = soil heat flux density (MJ/m^2/day)
= mean daily air temperature at 2 m height (°C)
u_2 = wind speed at 2 m height (m/s)
e_s = saturation vapour pressure (kPa)
e_a = actual vapour pressure (kPa)
$e_s - e_a$ = saturation vapour pressure deficit (kPa)
Δ = slope vapour pressure curve (kPa/°C)
γ = psychrometric constant (kPa/°C)

Hourly values were summed to obtain daily ET_0 values. These values were used to calculate mean daily ET_0 for each month from September 2002 until March 2003.

Mean monthly crop coefficients were calculated at each locality for the two different soils from the mean ET_0 and crop evapotranspiration as follows (Myburgh, 1998):

$$k_C = ET/ET_0 \qquad (3.10)$$

where: k_C = crop coefficient
ET = crop evapotranspiration (mm/day)
ET_0 = reference evapotranspiration (mm/day)

3.3 RESULTS AND DISCUSSION

3.3.1 SOIL WATER

3.3.1.1 Soil water characteristics

The soil water characteristic curves for all four soils are presented in Fig. 3.3. The non-linear regression equations and correlation coefficients for the fitted lines in Fig. 3.3 are given in Table 3.3. The soil water characteristic curves of both soils at Helshoogte (Fig. 3.3A and 3.3B) tended to level off between 15% to 20% soil water content. This is expected for medium-textured soils (Van Zyl, 1981). The RAW tended to be slightly higher for the Hutton soil than the Tukulu soil (Table 3.4). The soil water characteristic curves revealed that Ψ_m would be at *ca* -0.04 MPa and -0.035 MPa for the Tukulu and Hutton soils respectively, when most of the RAW had been depleted. The total PAW between field capacity and -1.50 MPa was also slightly higher for the Hutton soil than the Tukulu soil.

The soil water characteristic curves of the Avalon and Tukulu soils at Papegaaiberg, tended to level off between 5% and 10% SWC (Fig. 3.3C and 3.3D). This is normally associated with sandy soils (Van Zyl, 1981). The RAW of the Tukulu soil was considerably lower than for the Avalon soil (Table 3.4). This was probably due to the high gravel content of the Tukulu soil (Table 3.2). The soil characteristic curves revealed that Ψ_m would be at *ca* -0.03 MPa and -0.035 MPa for the Tukulu soil and Avalon soils respectively, when most of the RAW water had been depleted. For the Tukulu soil this means that plant water stress could be expected at relatively high Ψ_m. The Tukulu soil with *ca* 103 mm/m PAW (Table 3.4) had almost 30% less PAW than the Avalon soil (*ca* 141 mm/m PAW). This can cause excessive water stress in grapevines that grow on the Tukulu soil in comparison to ones on the Avalon soil.

The *in situ* determined RAW were considerably lower than laboratory determined values reported by Van Schoor (2001). However, the magnitude of the *in situ* values was more realistic than the laboratory values.

3.3.1.2 Soil water content

The relationship between the soil water content in terms of neutron counts, as measured with a neutron probe, and the Ψ_m for both soils at each locality are presented in Fig. 3.4. These calibration curves were used to convert neutron counts to Ψ_m, once the latter decreased to potentials below *ca* -0.08 MPa as explained earlier. The non-linear regression equations for the fitted lines in Fig. 3.4 are presented in Table 3.5. The Hutton soil at Helshoogte had a notably higher neutron count at a given Ψ_m at 900 mm depth compared to the 300 mm and 600 mm depth. This was probably due to the slightly higher clay content of the soil at 900 mm (Conradie *et al*., 2002). This effect seemed to be more pronounced for the soils at Papegaaiberg, particularly the Tukulu soil (Fig. 3.4D). At Papegaaiberg the neutron counts at a given Ψ_m were considerably lower than at Helshoogte, probably due to differences in clay mineralogy or organic matter content (Klute, 1986). This emphasizes the need for calibration of the neutron scattering method and that the use of “universal” calibrations used by industry can be misleading. The seasonal SWC at 0-300 mm, 300-600 mm and 600-900 mm depth increments, as well as for 0-900 mm, for the two soils at Helshoogte and for the two soils at Papegaaiberg are presented in Fig. 3.5 and Fig. 3.6, respectively.

The SWC of the Tukulu soil at Helshoogte (0-900 mm) was approximately 250 mm at budbreak (beginning of the season),and decreased to approximately 130 mm, in other words a 93% depletion of total PAW over the 900 mm root depth occurred. During the first part of the season, *i.e*. until the stage of rapid shoot growth (middle December), there was a gradual depletion of 54% of PAW. Rains during middle September, early October and early November, indicated by the small peaks in the graph, helped to maintain soil water content at a relatively high level. However, over a short period from late December to veraison (early January), the soil water content decreased rather rapidly to a depletion of 70% of PAW. Thereafter, the SWC decrease again became more gradual until the end of the season, possibly because E_s decreased (Van Zyl, 1975) and more than 100% of RAW had been extracted. The 0-300 mm layer and the 600-900 mm layer had less soil water than the 300-600 mm layer throughout the season. Grapevines on the Tukulu soil had more vigorous growth than those on the

Hutton soil (refer to Chapter 4). These grapevines might suffer more water stress later in an exceptionally dry season like the 2002/03 season.

The SWC of the Hutton soil at Helshoogte (Fig. 3.5D) followed a similar pattern to that of the Tukulu soil. The SWC decreased from 250 mm to 130 mm over the growing season, *i.e.* an 87% depletion of PAW over 900 mm depth. This depletion was, as for the Tukulu soil, gradual until middle December (51% depletion of PAW), after which the SWC decreased extremely rapidly to 72% depletion of PAW until veraison (beginning of January). According to Myburgh (1998), the water accumulated from budbreak until harvest in vegetative growth, including bunches, only varies between 2 mm and 7 mm. Hence, the rapid decrease in SWC was not due to water stored in the bunches during berry growth. The decrease in SWC slowed down dramatically at this stage, because E_s was low, and again more than 100% of RAW had been extracted. Most of the soil water was depleted from the 0-300 mm layer (45 mm) over the season. In comparison, the SWC of the 300-600 mm layer and the 600-900 mm layer were both 50 mm at the end of the season.

The two soils at Papegaaiberg tended to follow similar patterns of soil water depletion (Fig. 3.6), but these patterns differed significantly from those for the soils at Helshoogte. Whereas the soils at Helshoogte had a rapid decline in soil water content over a very short period during the second half of December, the soils at Papegaaiberg had a relative fast decline in soil water content (relative to the rest of the season) over a period of nearly two months from around the beginning of November to around the end of December. However, the total decline in SWC for the season was less for the two soils at Papegaaiberg, *i.e.* 85 mm and 90 mm respectively, compared to 120 mm for the two Helshoogte soils.

The SWC of the Avalon soil at Papegaaiberg (Fig. 3.6C) decreased from 200 mm to 115 mm (67% depletion of PAW) during the growing season. By the beginning of January, the SWC had already decreased to 66% depletion of PAW amounting to more than 100% depletion of the RAW of this soil. Thereafter, the SWC stayed almost constant. In comparison to the surface layers, the SWC decreased more in the 600-900 mm layer. This suggested that capillary supplementation of soil water from the sub-soil to the top soil occurred and explains why the 0-300 mm layer of the Avalon did not dry out to the same extent as for the other soils.

In the case of the Tukulu soil at Papegaaiberg, 98% depletion of PAW occurred during the growing season, *i.e.* from 210 mm in September to 120 mm in March (Fig. 3.6D). After a rapid decrease from early November to early January, the SWC decreased more gradually until March. Most of the available soil water was depleted from the 0-300 mm layer (65 mm in September to 25 mm in March). For this soil, with its low PAW and RAW, 100% extraction of RAW through 900 mm depth was already exceeded early in December. This could be a further contributing factor to the water stress experienced by grapevines on this soil later in the season (refer to Chapter 4).

It is noteworthy that, although the percentage decrease in PAW for the two soils at Papegaaiberg differed markedly, *viz.* 67% and 98% for the Avalon and Tukulu respectively, the actual decreases in SWC were similar, *i.e.* 85 mm and 90 mm, respectively.

3.3.1.3 Soil water matric potential

The soil water matric potential (Ψ_m) variation for the four soils, as measured during the 2002/03 growing season, is presented in Fig. 3.7. At Helshoogte, Ψ_m of the Tukulu and Hutton soils were comparable until early December, after which there were slight differences between the two soils, particularly during the ripening (February) and post-harvest (March) stages. In the case of the Tukulu soil, Ψ_m decreased slowly from the beginning of the season (September) until December (Fig. 3.7A). Thereafter Ψ_m decreased quite rapidly at all three depths until March, particularly at 300 mm depth, where Ψ_m reached a minimum of -1.40 MPa in March. At this depth there was a rapid decrease in Ψ_m during the first half of February. At the 600 mm and 900 mm depths the decrease in Ψ_m was not only slower than at 300 mm depth, but also more gradual over time. The faster decline in Ψ_m and the lower final value reached at 900 mm than at 600 mm depth was unexpected. This corresponds, however, with the SWC in Fig. 3.5A where the 300-600 mm depth had more water than the 0-300 mm and 600-900 mm depths. The latter two layers probably had higher root densities compared to the 300-600 mm layer, since the soil water characteristic curves were almost identical (Fig. 3.3A). This was confirmed by root studies done by Conradie *et al*. (2002).

The Ψ_m of the Hutton soil (Fig. 3.7B) followed basically the same pattern as that of the Tukulu soil until early December. On the Hutton soil, the period of more rapid decrease in Ψ_m started somewhat earlier than on the Tukulu soil.

Similar to the Tukulu soil, the Ψ_m at 300 mm depth in the Hutton soil decreased particularly rapidly, to approximately -1.10 MPa in March. Sharp decreases occurred during early February and the first half of March. However, Ψ_m at the 600 mm and 900 mm depths of the Hutton soil decreased more steadily over the rest of the season and much slower than in the Tukulu soil. From middle January to early February, and again from middle February to middle March, the Ψ_m values at these two depths in the Hutton soil seemed to remain constant. This was also reflected in the SWC of this soil (Fig. 3.5B), where the SWC at the 300 mm depth decreased the most and the Ψ_m at 600 mm and 900 mm depths were almost the same. The SWC also decreased rapidly from middle December onwards. Grapevines on the Tukulu soil had more vigorous growth than those on the Hutton soil (refer to Chapter 4). This suggested that the grapevines could have withdrawn more water from the soil, particularly from the sub-soil. From middle December, Ψ_m decreased more or less constant at all depths. At 300 mm depth the decrease was more rapid compared to the deeper layers, and reached a value of *ca* -1.40 MPa, which was close to permanent wilting point (-1.50 MPa). This indicated that grapevines on these soils depend largely on subsoil layers for water during the second half of the season.

At Papegaaiberg the Ψ_m of both the Avalon and Tukulu soils (Fig. 3.7C and D) showed almost no decrease until the end of November, after which a slight decrease followed. This decrease only continued until middle December on the Avalon soil when Ψ_m at all three depths became almost constant to reach a minimum of approximately -0.10 MPa during March, *i.e.* it never declined below the lower limit of RAW. The Avalon soil tended to be wetter than the other soils during the later part of the season. Cane masses measured in the winter of 2003 indicated that grapevines on the Tukulu soil tended to have more vigorous growth than those on the Avalon soil (refer to Chapter 4). At 600 mm and 900 mm depths Ψ_m of the Tukulu soil followed the same pattern as those of the Avalon soil, but Ψ_m at 300 mm depth decreased slowly over the entire period up to middle March, reaching a final value of -0.20 MPa. This corresponds with the SWC in Fig. 3.6B, where the 0-300 mm layer dried out more than the other two layers of the Tukulu soil.

Grapevines should have a widely distributed root system as a buffer against unfavourable climatic conditions (Conradie, 2001). The bulk density of the Tukulu soil of Papegaaiberg at 500 mm depth is 1870 kg/m^3 (Van Schoor, 2001), which is an extremely high value. Since high bulk densities severely limit the root penetration of grapevines (Van Zyl & Van Huyssteen, 1984), this probably explains why the Ψ_m decreased only at the 300 mm depth at this locality. The Tukulu soil showed inferior root distribution in comparison to the Avalon soil during root studies in 1993 (Conradie *et al*., 2002). Hence, the Tukulu soil thus had a very shallow rooting depth which restricted effective utilization of available soil water, resulting in excessive water stress in the grapevines at this locality late in the season (Refer to Chapter 4). The Tukulu soil at Papegaaiberg also had a relatively high gravel content (Table 3.2), resulting in a lower PAW than at the other localities. On the other hand, capillary rise could have supplemented water content at 300 mm depth of the Avalon soil as discussed earlier.

3.3.2 EVAPOTRANSPIRATION

The ET_0, as well as vineyard ET and crop coefficients are presented in Tables 3.6 and 3.7 for Helshoogte and Papegaaiberg, respectively. Mean daily ET_0 was *ca* 1 mm/day lower at Helshoogte when compared to Papegaaiberg throughout the growing season (Table 3.6 and 3.7). This is to be expected since the Papegaaiberg is much warmer than the Helshoogte locality, and ET_0 is largely affected by temperature and relative humidity. Evapotranspiration for grapevines on the different soils at Helshoogte and Papegaaiberg is shown in Fig. 3.8. The ET at Helshoogte was probably higher than at Papegaaiberg because of the faster trellising covering rate at Helshoogte due to the visually more vigorous growth there. This led to grapevines with larger total leaf areas at Helshoogte compared to grapevines at Papegaaiberg, and thus higher ET. Evapotranspiration reached a maximum during October and December for the soils at Helshoogte and Papegaaiberg, respectively. Vineyard ET decreases with a decrease in the availability of water (Van Zyl & Van Huyssteen, 1980), or with increased soil water depletion and *visa versa* (Van Zyl, 1984).

For both the Tukulu soil and Hutton soil at Helshoogte, there was a large decrease in ET from October to November, but it increased again in December, whereafter another decrease occurred until a minimum ET was reached in February. The SWC and Ψ_m of these soils started to decrease rapidly in December. The ET values of the Avalon soil and Tukulu soil at Papegaaiberg remained high and reached a maximum in December, whereafter it decreased rapidly to reach a minimum in January. At the beginning of the season, when the soil was still wet and there was still some rainfall, E_s could be high, which caused the higher ET. By January and February, when the soil was drier, and E_s had decreased, the ET was mainly dependent on transpiration. Transpiration could also be very low because of stomatal closure during very warm, dry climatic conditions.

The crop coefficients (Tables 3.6 & 3.7) for the soils at both Helshoogte and Papegaaiberg were slightly lower in comparison to values reported by Myburgh (1998), Van Zyl & Weber (1981) and Van Zyl & Van Huyssteen (1988), particularly the minimum crop coefficients at Papegaaiberg. However, the ET and crop coefficients for both Van Zyl & Weber (1981) and Van Zyl & Van Huyssteen (1988) were for irrigated vineyards. Van Zyl & Weber (1981) reported a maximum crop coefficient of 0.36 in the Stellenbosch region that was obtained during a period in which a wet soil surface and, therefore, high evaporative losses prevailed. The lowest crop coefficient they found, were 0.22 during middle December to middle January. Van Zyl & Van Huyssteen (1988) reported a maximum crop coefficient of approximately 0.5 during December and January in the Oudtshoorn region. Myburgh (1998) reported a maximum crop coefficient of 0.44 during October and a minimum crop coefficient of 0.16 during March for dryland Pinot noir in the Stellenbosch region. A maximum ET of 2.20 mm/day during November and minimum ET of 0.65 mm/day during April were found for the Pinot noir vineyard (Myburgh, 1998). These values correspond with the ET and crop coefficients found at Helshoogte and Papegaaiberg. The crop coefficients at Papegaaiberg during January and February were, however, relatively low compared to the values reported by Myburgh (1998). Due to variation in viticultural practices and atmospheric conditions, water consumption may vary significantly between vineyards (Myburgh, 1998). Crop coefficients are not only determined by soil, climate and crop, but to a large extent by the moisture regime maintained (Van Zyl & Weber, 1981).

3.4 CONCLUSIONS

More vigorous growth earlier in the season on the Tukulu soil at Helshoogte probably resulted in more soil water withdrawal and lower Ψ_m, and thus grapevines on this soil could experience more water stress, *i.e.* lower Ψ_l compared to ones on the Hutton soil later in the season. More water stress could also affect yield and wine quality, either positively or negatively, depending on the amount of water stress. Less vigorous growth on the Hutton soil resulted in the Ψ_m and SWC to decrease less than in the Tukulu soil.

Due to capillary supplementation, the Avalon soil at Papegaaiberg had a more favourable soil water regime for growth than the other three soils. This could result in less water stress, *i.e.* higher Ψ_l in grapevines on this soil, which could affect the wine quality and yield, either positively or negatively depending on the amount of water stress. Grapevines on the Tukulu soil at Papegaaiberg might experience more water stress compared to ones on the other three soils due to the high gravel content resulting in a low RAW and PAW. The inferior root distribution in this soil also restricts the effective utilization of the available soil water, and excessive water stress in grapevines might occur later in the season.

High ET values at the beginning of the season indicated that the SWC, which affected the E_s, was still high for the four soils. The sudden decrease in ET after December is an indication of the sudden decrease in SWC, and water availability as the season progressed. Warm atmospheric conditions later in the season could result in stomatal closure and decreasing ET. Dryland vineyards tend to have lower crop coefficients compared to irrigated vineyards, particularly later in the season when soils are drier.

3.5 LITERATURE CITED

Allen, R.G., Pereira, L.S., Raes, D. & Smith, M. (1998). Crop evapotranspiration. Guidelines for computing crop water requirements. FAO irrigation and drainage paper **56**. 299pp.

Booysen, J.H., Steenkamp, J. & Archer, E. (1992). Names of vertical trellising systems (with abbreviations). *Wynboer* Sept. 1992, 15.

Carey, V.A. (2001). Spatial characterization of natural terroir units for viticulture in the Bottelaryberg-Simonsberg-Helderberg winegrowing area. M.Sc. Thesis, University of Stellenbosch, Private Bag X1, Matieland 7602 (Stellenbosch), South Africa.

Conradie, W.J. (2001). Die effek van grond en klimaat op wyngehalte in die Overberg. In: Grondkundige aspekte vir optimum wynkwaliteit in die Overberg. LNR Infruitec-Nietvoorbij, Stellenbosch. 10pp.

Conradie, W.J., Carey, V.A., Bonnardot, V., Saayman, D. & Van Schoor, L.H. (2002). Effect of different environmental factors on the performance of Sauvignon blanc grapevines in the Stellenbosch/Durbanville districts of South Africa. I. Geology, soil, climate, phenology and grape composition. *S. Afr. J. Enol. Vitic*. **23**, 78-91.

Fregoni, M. (1977). Effects of soil and water on the quality of the harvest. In: Proc. Int. Sym. Quality of the Vintage, February 1977, Cape Town, South Africa. pp 151-168.

Klute, A. (1986). Water retention: Laboratory methods. In: Klute, A. (ed.). Methods of soil analysis. Part I: Physical and mineralogical methods. American Society for Agronomy, Madison, Wisconsin, U.S.A. pp 635-662.

Myburgh, P.A. (1998). Water consumption of South African vineyards: A modelling approach based on the quantified combined effects of selected viticultural soil and meteorological parameters. Ph.D. Dissertation, University of Stellenbosch, Private bag X1, Matieland 7602 (Stellenbosch), South Africa.

Saayman, D. (1992). Natural influences and wine quality Part 2. The role of soil. *Wynboer* Aug. 1992, 49-51.

Seguin, G. (1986). “Terroirs” and pedology of wine growing. *Experientia* **42**, 861-873.

Soil Classification Working Group (1991). Soil classification – A taxonomic system for South Africa. Department of Agricultural Development: Memoirs on natural agricultural resources of South Africa No. 15, Department of Agricultural Development, Pretoria, South Africa.

Van der Watt, H.v.H. & Van Rooyen, T.H. (1990). A glossary of soil science. Soil Science Society of South Africa, P.O. Box 30030, Sunnyside, 0132 Pretoria, 464pp.

Van Schoor, L.H. (2001). Geology, particle size distribution and clay fraction mineralogy of selected vineyard soils in South Africa and the possible relationship with grapevine performance. M.Sc. Thesis, University of Stellenbosch, Private bag X1, Matieland 7602 (Stellenbosch), South Africa.

Van Zyl, J.L. (1975). Wingerdbesproeiing in die Stellenbosch-gebied binne die raamwerk van die plaaslke grond-water-plant-atmosfeer-kontinuum. M.Sc. Thesis, University of Stellenbosch, Private bag X1, Matieland 7602 (Stellenbosch), South Africa.

Van Zyl, J.L. (1981). Waterbehoefte en besproeiing. In: Burger, J. & Deist, J. (eds). Wingerdbou in Suid-Afrika. Maskew Miller, Cape Town. pp 234-283.

Van Zyl, J.L. (1984). Interrelationships among soil water regime, irrigation and water stress in the grapevine (*Vitis vinifera* L.) Ph.D. Dissertation, University of Stellenbosch, Private bag X1, Matieland 7602 (Stellenbosch), South Africa.

Van Zyl, J.L. & Van Huyssteen, L. (1980). Comparative studies on wine grapes on different trellising systems. I Consumptive water use. *S. Afr. J. Enol. Vitic*. **1**, 7-14.

Van Zyl, J.L. & Van Huyssteen, L. (1984). Soil and water management for optimum grape yield and quality under conditions of limited or no irrigation. In : Proc. Fifth Australian Wine Industry Technical Conf., November - December 1983, University of Western Australia, Perth, Australia. pp. 25-66.

Van Zyl, J.L. & Van Huyssteen, L. (1988). Irrigation systems – Their role in water requirements and the performance of grapevines. *S. Afr. J. Enol. Vitic*. **9**, 3-8.

Van Zyl, J.L. & Weber, H.W. (1981). The effect of various supplementary irrigation treatments on plant and soil moisture relationships in a vineyard. *S. Afr. J. Enol. Vitic*. **2**, 83-99.

Table 3.1 Characteristics of the experimental localities, all planted to Sauvignon blanc/Richter99 (After Conradie *et al.*, 2002).

Locality	Altitude (m)	Aspect	Slope (%)	Soil Form	Description
Helshoogte	413	SE	5.2	Tukulu	Medium textured, yellow-brown, weakly structured, slight signs of wetness with depth.
				Hutton	Medium textured, reddish-brown, very weakly structured, well-drained.
Papegaaiberg	148	NW	5.7	Avalon	Medium textured, yellow-brown, weakly structured, mottled subsoil.
				Tukulu	Medium textured, yellow-brown, weakly structured, signs of wetness in subsoil.

Table 3.2 Soil particle distribution (%), gravel content and bulk density for soils at the two localities in the Stellenbosch district. Values are depth weighted means to a depth of 1000 mm (After Conradie *et al.*, 2002).

Locality	Soil form	Clay(1) (<0.002 mm)	Fine silt(1) (0.02-0.002 mm)	Coarse silt(1) (0.05-0.02 mm)	Very fine sand(1) (0.10-0.05 mm)	Fine sand(1) (0.25-0.10 mm)	Medium sand(1) (0.50-0.25 mm)	Coarse sand(1) (2.0-0.50 mm)	% Gravel (>2.0 mm)	Bulk density (kg/m^3)
Helshoogte	Tukulu	30.6	14.5	10.1	8.4	11.5	9.2	14.0	9.8	1250
	Hutton	31.8	12.8	8.4	8.7	14.1	10.7	11.7	8.9	1360
Papegaaiberg	Avalon	32.4	8.0	5.3	10.2	16.0	13.6	11.5	5.0	1460
	Tukulu	33.4	7.3	9.8	8.8	16.2	12.8	12.4	36.1	1670

(1) Particle size analyses for soil fraction <2 mm, excluding gravel.

Table 3.3 Equations of soil water characteristic curves for the soils at Helshoogte and Papegaaiberg in the Stellenbosch district. Actual data are presented in Fig. 3.3.

Depth (mm)	Helshoogte		Papegaaiberg	
	Tukulu	Hutton	Avalon	Tukulu
300	$y=11.271x^{-0.1511}$ $R^2=0.9645$	$y=10.931x^{-0.1451}$ $R^2=0.9354$	$y=4.3217x^{-0.2554}$ $R^2=0.9384$	$y=4.8611x^{-0.2061}$ $R^2=0.9577$
600	$y=11.677x^{-0.1456}$ $R^2=0.9434$	$y=10.073x^{-0.1713}$ $R^2=0.9777$	$y=5.9668x^{-0.1756}$ $R^2=0.9363$	$y=6.7252x^{-0.1143}$ $R^2=0.8800$
900	$y=11.874x^{-0.1473}$ $R^2=0.9611$	$y=10.682x^{-0.1520}$ $R^2=0.9546$	$y=5.8298x^{-0.2235}$ $R^2=0.9035$	$y=6.9386x^{-0.1098}$ $R^2=0.8581$

Table 3.4 Readily available water (RAW) and total plant available water (PAW) for the different soils at the two localities measured during the 2002/03 growing season.

Locality	Soil type	Readily available water (mm/m)	Plant available water (mm/m)	Plant available water (mm/900mm)
Helshoogte	Tukulu	79.5	144.0	129.6
	Hutton	85.2	153.1	137.8
Papegaaiberg	Avalon	84.2	140.7	126.6
	Tukulu	57.3	102.6	92.3

Table 3.5 Equations used for estimating soil matric potential from neutron probe measurements. Actual data are presented in Fig. 3.4.

Depth (mm)	Helshoogte		Papegaaiberg	
	Tukulu	Hutton	Avalon	Tukulu
300	$y=3E + 68x^{-16.403}$ $R^2=0.9905$	$y=3E + 60x^{-14.606}$ $R^2=0.9395$	$y=1E + 24x^{-6.4272}$ $R^2=0.9630$	$y=3E + 27x^{-7.2905}$ $R^2=0.99252$
600	$y=6E + 52x^{-12.748}$ $R^2=0.9772$	$y=8E + 49x^{-12.139}$ $R^2=0.8927$	$y=1E + 30x^{-8.050}$ $R^2=0.9630$	$y=1E + 29x^{-7.5968}$ $R^2=0.9574$
900	$y=3E + 65x^{-15.654}$ $R^2=0.9491$	$y=2E + 62x^{-14.900}$ $R^2=0.9574$	$y=1E + 32x^{-8.1906}$ $R^2=0.9498$	$y=3E + 50x^{-12.434}$ $R^2=0.99420$

Table 3.6 Reference evapotranspiration (ET_0), calculated evapotranspiration (ET) and crop coefficients for grapevines on two soil types at Helshoogte during the 2002/03 growing season.

Month	ET_0 (mm/day)	ET (mm/day)		Crop coefficients	
		Tukulu	Hutton	Tukulu	Hutton
Sep	3.51	2.25	2.37	0.64	0.68
Oct	4.39	2.52	2.60	0.57	0.59
Nov	5.69	1.83	1.54	0.32	0.27
Dec	5.83	1.93	2.35	0.33	0.40
Jan	6.59	1.37	1.15	0.21	0.17
Feb	5.64	0.75	0.66	0.13	0.12

Table 3.7 Reference evapotranspiration (ET_0), calculated evapotranspiration (ET) and crop coefficients for grapevines on two soil types at Papegaaiberg during the 2002/03 growing season.

Month	ET_0 (mm/day)	ET (mm/day)		Crop coefficients	
		Avalon	Tukulu	Avalon	Tukulu
Sep	4.16	1.86	2.07	0.48	0.50
Oct	5.40	1.70	1.79	0.31	0.33
Nov	6.58	1.86	1.85	0.28	0.28
Dec	7.04	1.99	2.18	0.28	0.31
Jan	7.25	0.40	0.43	0.06	0.06
Feb	6.78	0.69	0.56	0.10	0.08

Figure 3.1 Map to indicate locations of (A) the Helshoogte and (B) the Papegaaiberg vineyards in the Stellenbosch district.

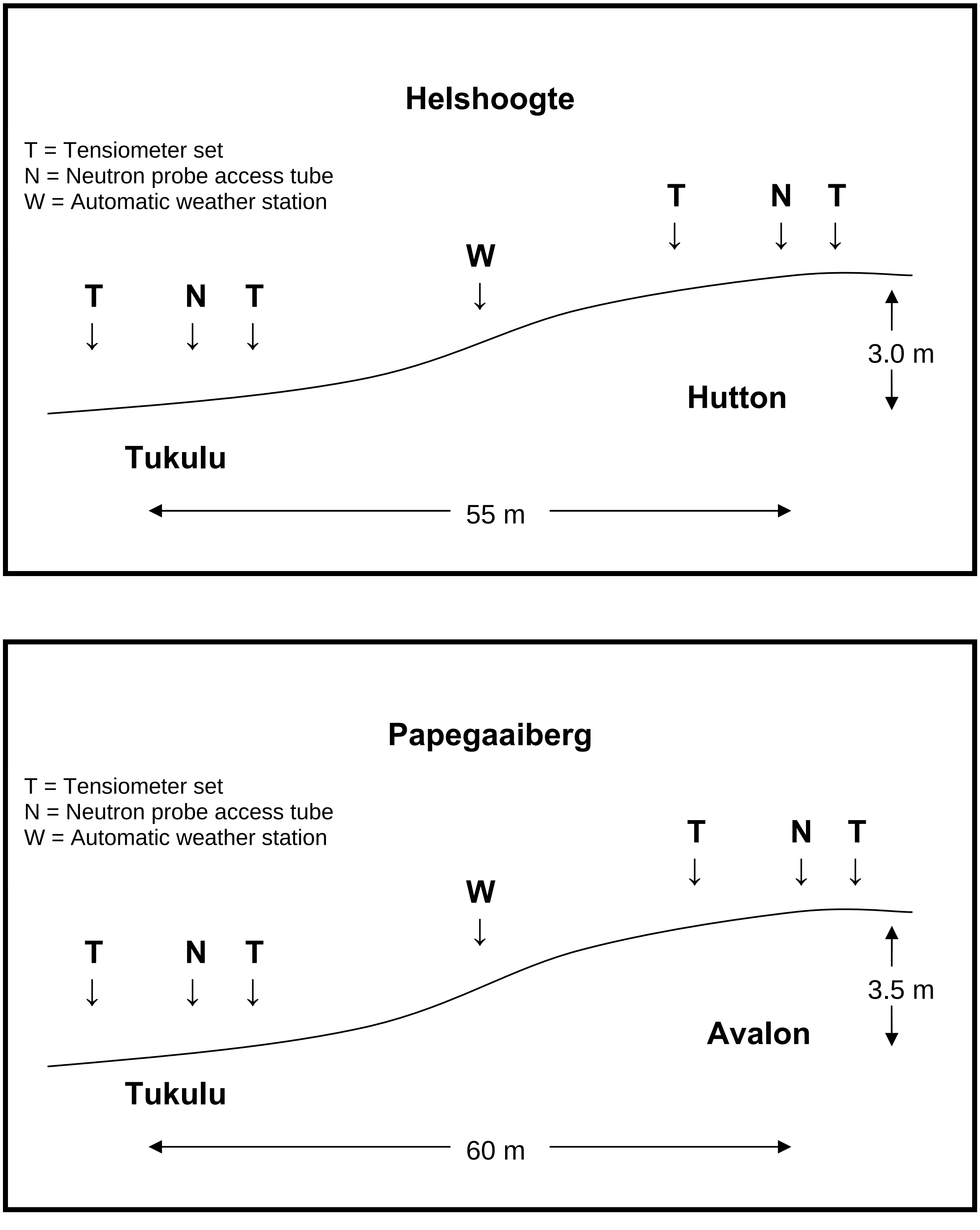

Figure 3.2 A diagram of the topography at two localities, Helshoogte and Papegaaiberg, to illustrate localities and measuring positions on the different soil forms.

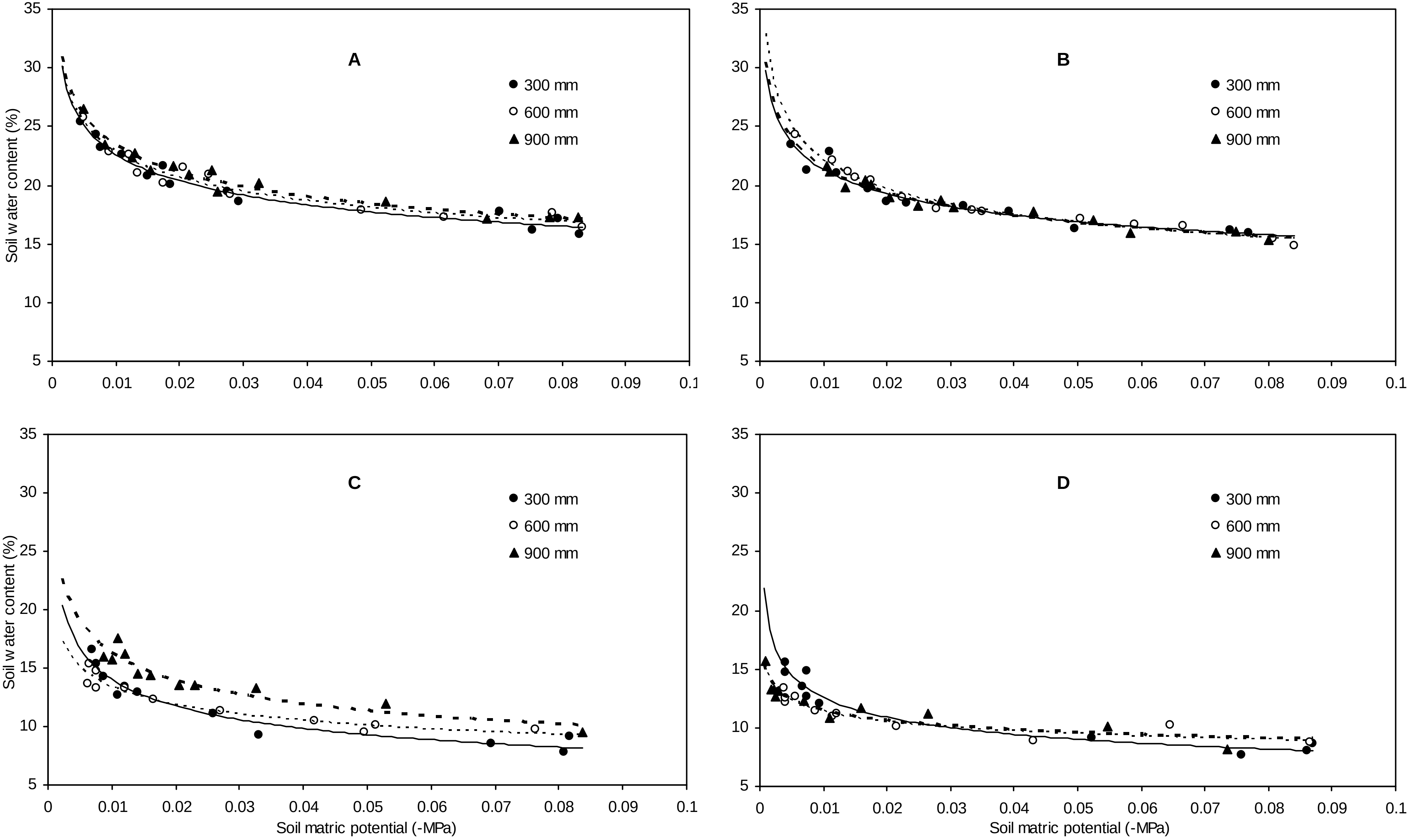

Figure 3.3 The soil water characteristic curves for (A) the Tukulu and (B) the Hutton soils at Helshoogte and for (C) the Avalon and (D) the Tukulu soils at Papegaaiberg. Symbols are actual values. Refer to Table 3.4 for equations of fitted lines.

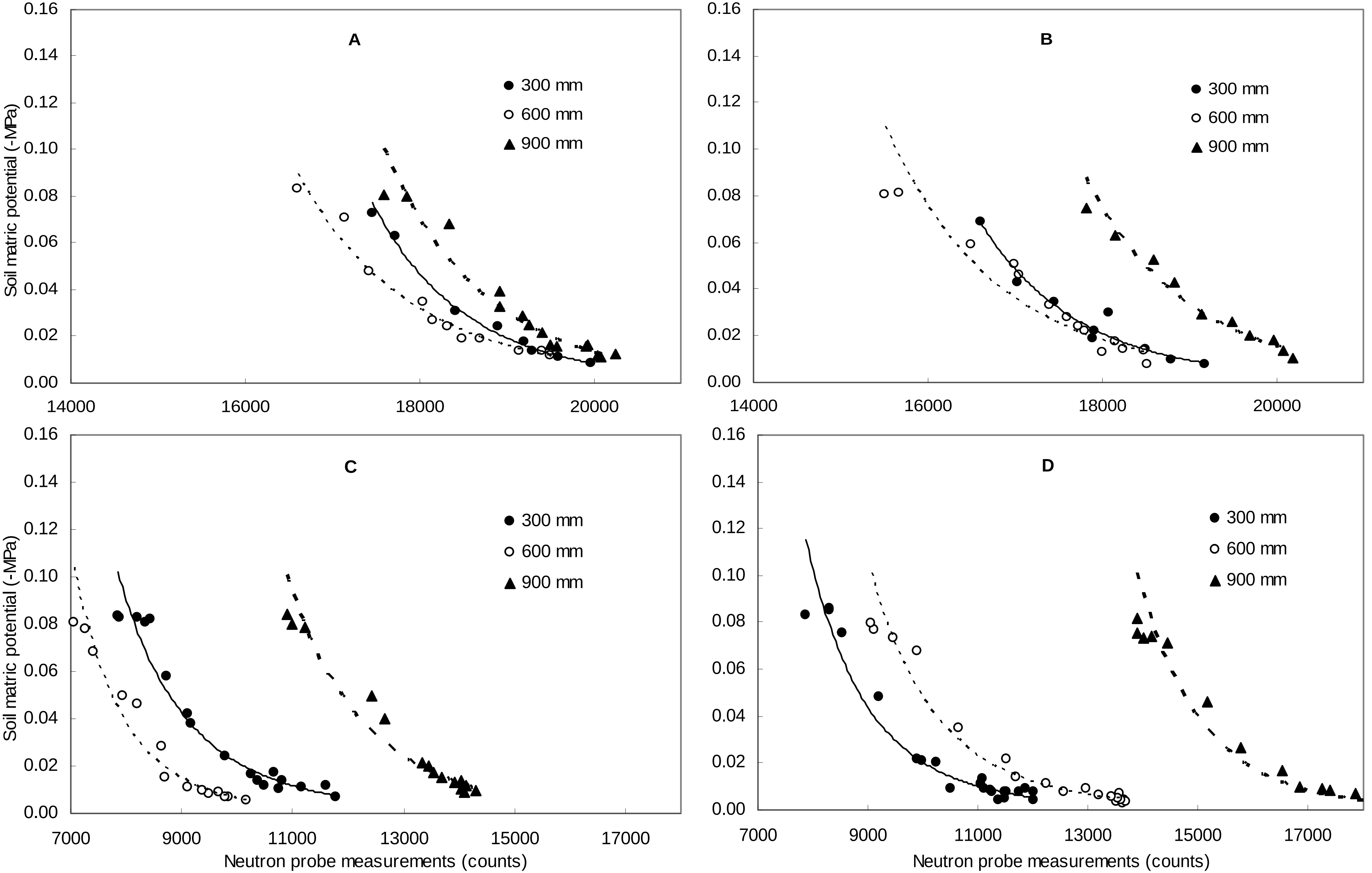

Figure 3.4 Soil matric potential in relation to the neutron probe measurements at Helshoogte for (A) the Tukulu and (B) the Hutton soils, as well as at Papegaaiberg for (C) the Avalon and (D) the Tukulu soils. Symbols are actual values. Refer to Table 3.5 for equations of fitted lines.

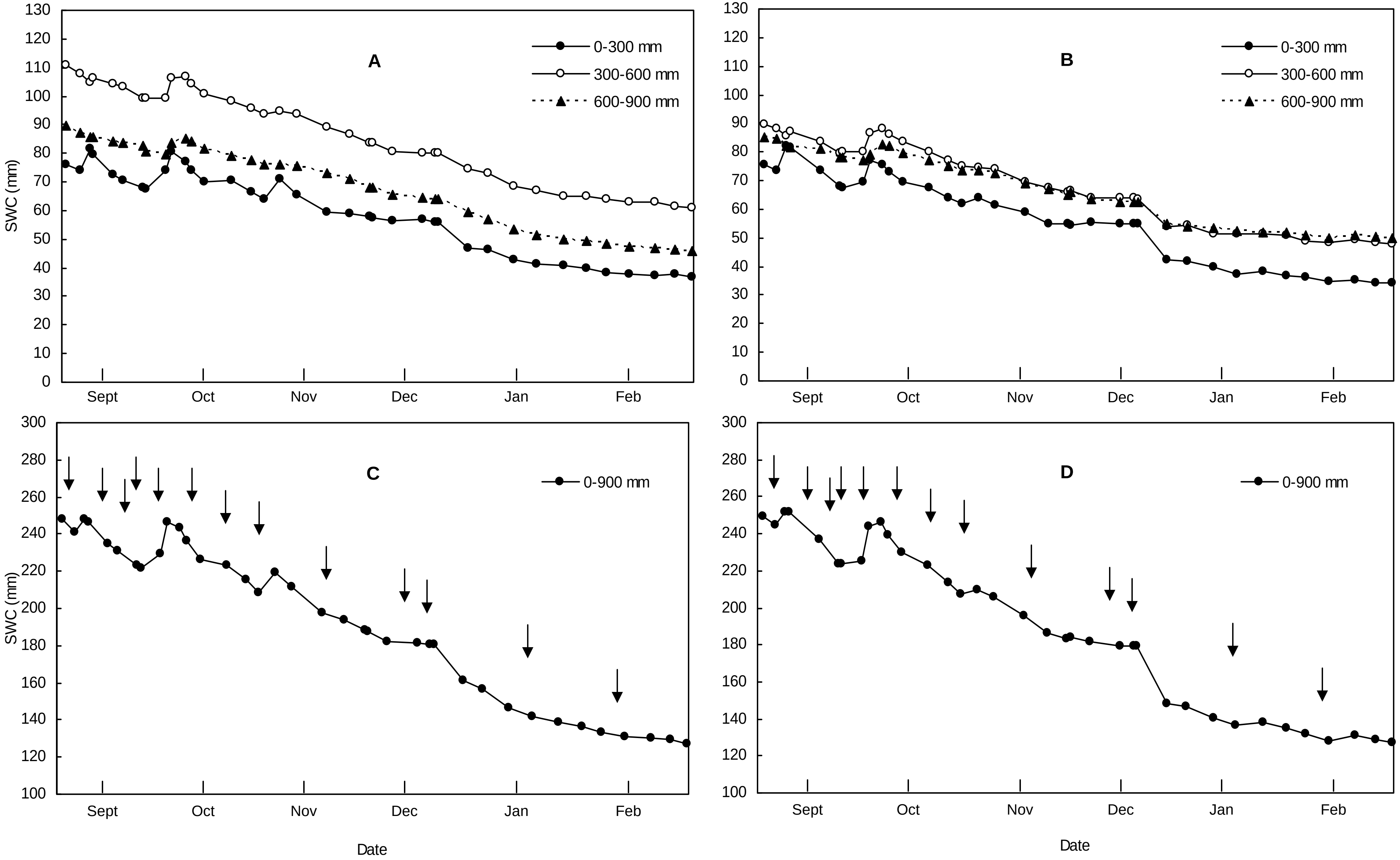

Figure 3.5 Soil water content (SWC) at three depths during the season at Helshoogte for (A) the Tukulu and (B) the Hutton soils as well as the soil water content over 900 mm depth during the season for (C) the Tukulu and (D) the Hutton soils. Vertical arrows indicate rainfall > 5 mm.

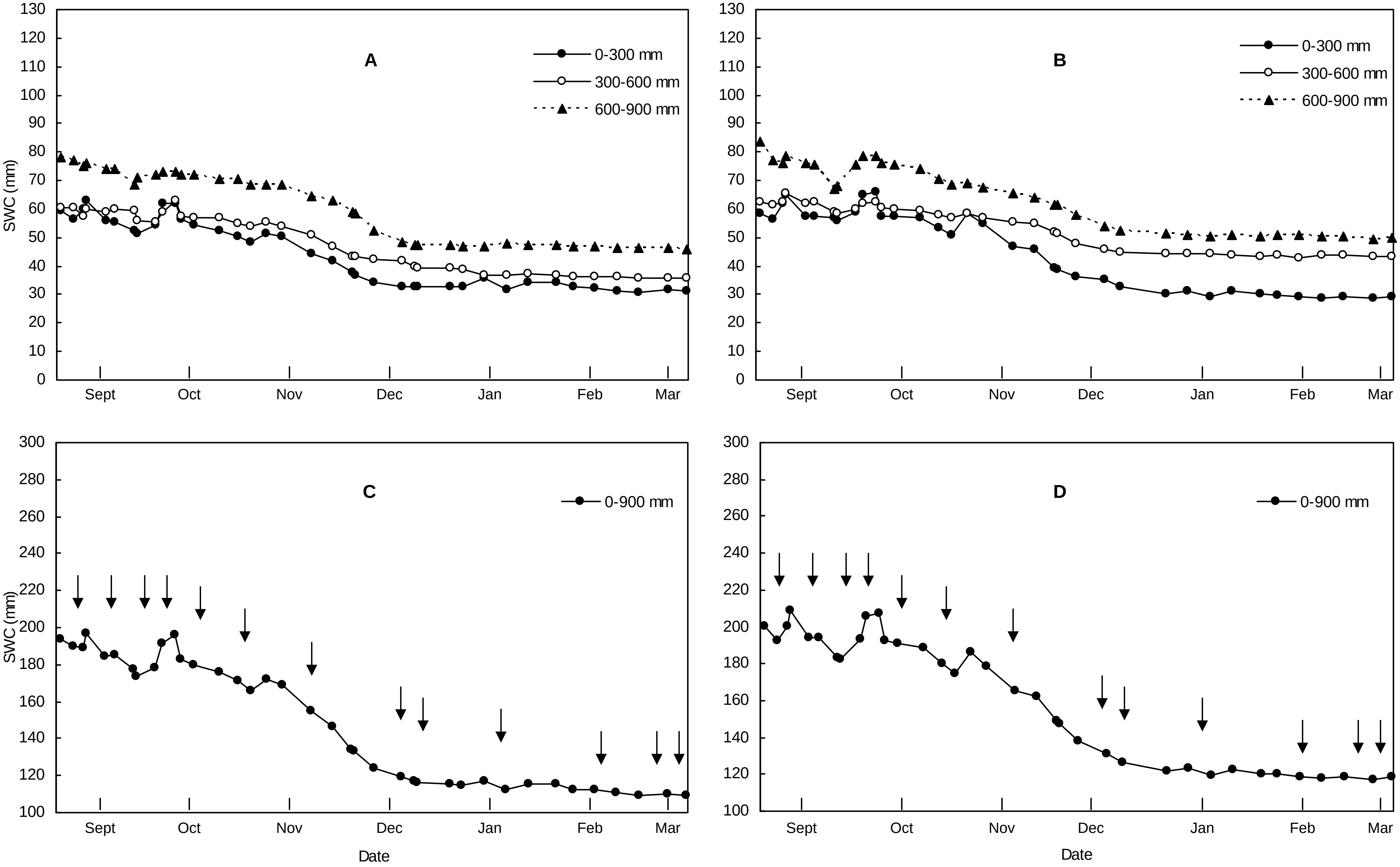

Figure 3.6 Soil water content (SWC) at three depths during the season at Papegaaiberg for (A) the Avalon and (B) the Tukulu soils as well as the soil water content over 900 mm depth during the season for (C) the Avalon and (D) the Tukulu soils. Vertical arrows indicate rainfall > 5 mm.

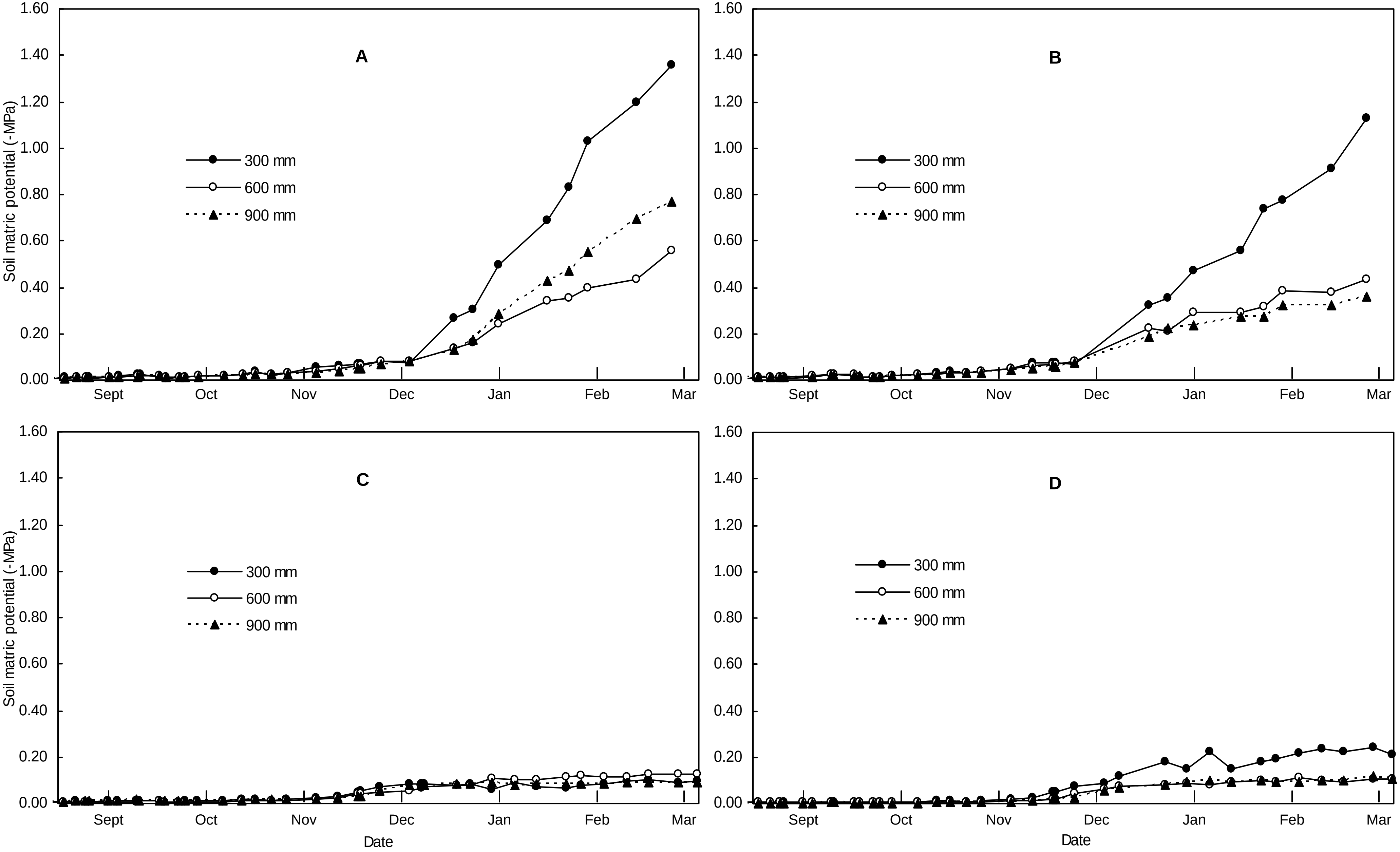

Figure 3.7 Variation in soil matric potential during the 2002/03 season at Helshoogte for (A) the Tukulu and (B) the Hutton soils, as well as at Papegaaiberg for (C) the Avalon and (D) the Tukulu soils.

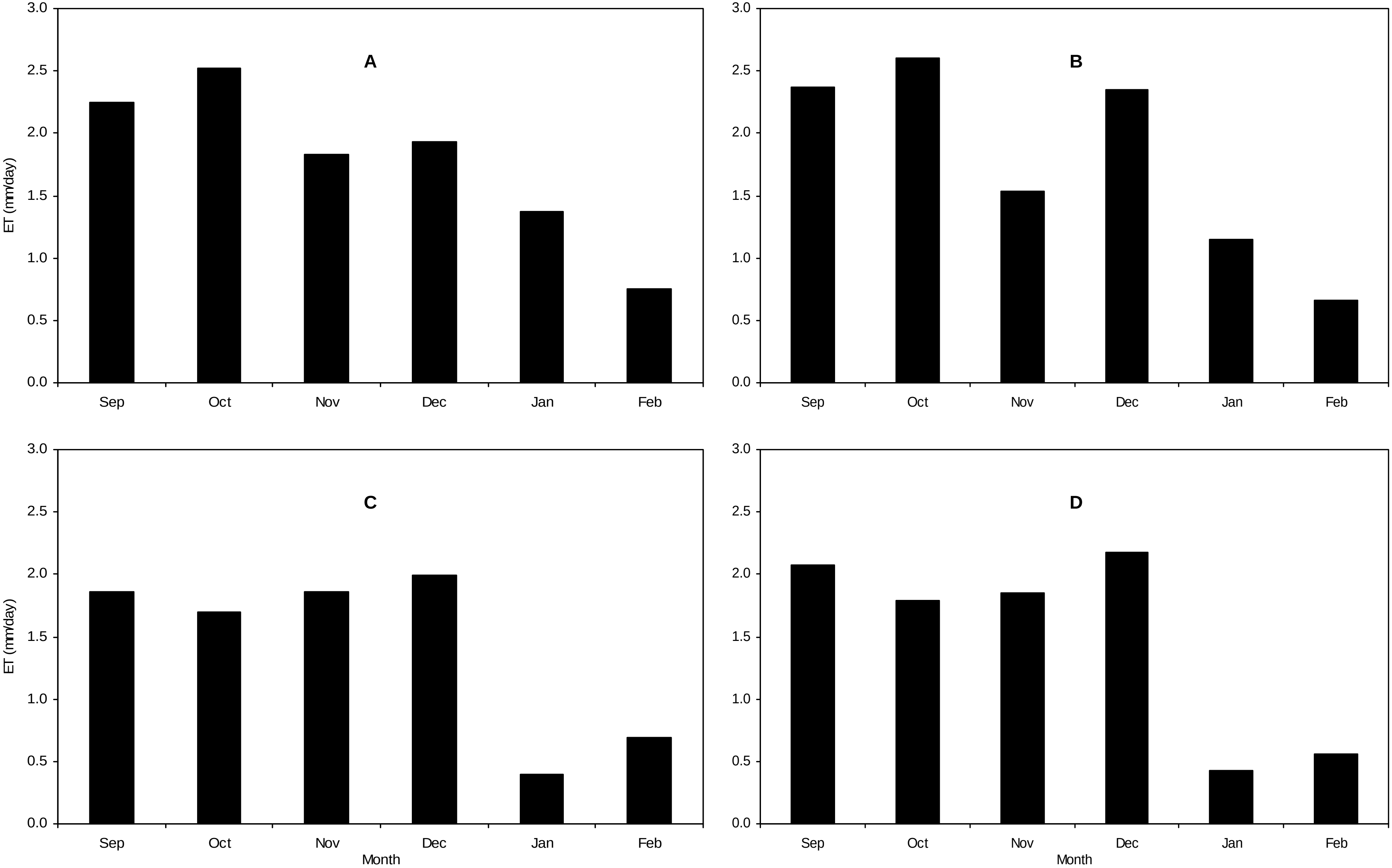

Figure 3.8 Vineyard evapotranspiration (ET) during the 2002/2003 season at Helshoogte for (A) the Tukulu and (B) the Hutton soils, as well as at Papegaaiberg for (C) the Avalon and (D) the Tukulu soils.

CHAPTER 4

RESEARCH RESULTS

THE EFFECT OF SOIL TYPE AND MESOCLIMATE ON THE WATER RELATIONS IN SAUVIGNON BLANC/99RICHTER

CHAPTER 4

4.1 INTRODUCTION

Due to the extraordinary drought resistance of the grapevine, viticulture without irrigation in the winter rainfall coastal areas of South Africa is a feasible and commonly used practice (Van Zyl & Weber, 1977). Bearing grapevines in the coastal districts of the Western Cape require approximately 500 mm of water during the growing season, from September to April (Van Zyl & Van Huyssteen, 1984). Of this, an average of about 300 mm is contributed by rainfall received during the growing season, whereas the remainder must be supplied by either irrigation or water stored in the root zone (Myburgh *et al*., 1996).

Saayman (1992) stated that the effect of soil type is without question the least understood natural factor with regard to wine quality. It is well-known that the most important soil component affecting wine quality is soil water availability (Seguin, 1986). Soil water contents that are either near the upper or lower limit of plant-available water for prolonged periods during the growing season are unfavourable for achieving the desired balances between yield and wine quality (Seguin, 1983). Soil conditions that restrict root development and root activity, *e.g.* unfavourable soil physical conditions, such as soil compaction, impact negatively on the efficiency with which grapevines utilize soil water (Saayman & Van Huyssteen, 1980). This is a major problem in the Western Cape, since in many vineyards root development is limited by unfavourable soil physical and/or chemical conditions (Saayman & Van Huyssteen, 1980).

The water status of the grapevine can affect grape composition profoundly, either directly or indirectly (Smart, 1974), and in either a positive or negative way, depending on the degree as well as the duration of water stress (Fregoni, 1977). Water deficits develop in grapevines when transpiration exceeds the ability of the root system to supply water to the transpiring leaves (Choné *et al*., 2001). According to Van Zyl (1987) temporary plant water deficits develop during the day under conditions of high atmospheric demand, which leads to water losses which exceed water uptake. Generally temporary plant water deficits do not have lasting effects on grapevines (Van Zyl, 1987). However, plant water stress of longer duration as a result of decreasing soil water content is of great importance to viticulture. Such long-term deficits commence as transient plant water deficits, but as soil water potential gradually decreases, a point is reached where plants eventually become unable to recover at night. The soil water potential therefore sets the level of recovery at night (Slayter, 1976). “Permanent” plant water stress is the result of insufficient water supply from the soil and it impacts negatively on the physiology of the grapevine.

Morphological responses to water stress are often associated with more sensitive underlying physiological processes which should, therefore, be ideal indicators of onset of plant water stress (Van Zyl, 1987). Leaf water potential is generally accepted as a reliable indicator of plant water status (Myburgh, 2003). Under normal conditions, leaf water potential approaches equilibrium with soil water potential, and reaches its maximum daily value during the pre-dawn period (Van Zyl, 1987). After sunrise it decreases rapidly to a minimum value during midday, followed by a rapid increase until sunset, whereafter it increases gradually until a new pre-dawn maximum is reached. Leaf water potential values of -0.50 MPa during the pre-dawn period and minimum values of -0.90 MPa to -1.20 MPa during the day can be regarded as the onset of negative effects of water stress on grapevine physiology (Williams *et al*., 1994). Hensley & De Jager (1982) coined the term "First Material Stress" (FMS) for the leaf water potential at which negative effects on the physiological functions of plants set in. Under comparable atmospheric conditions leaf water potential is normally well related to soil water content (Williams *et al*., 1994), as well as soil water matric potential (Van Zyl, 1987).

Stomatal opening is affected by water deficits and can be used as an indicator of grapevine water stress, although it is recognised that several environmental factors such as light, CO_2 concentration and air temperature also affect stomatal behaviour (Kramer, 1983). Stomatal opening, transpiration and photosynthesis often decrease in grapevines subjected to increasing water stress (Van Zyl, 1987).

The aim of this study was to (i) determine the atmospheric conditions at two localities during the 2002/03 season and compare it to the long-term average atmospheric conditions, (ii) determine the level of water stress of grapevines on each soil at each locality and (iii) determine the effect of the atmospheric conditions and the soil water status on the level of water stress in the grapevines.

4.2 MATERIALS AND METHODS

4.2.1 EXPERIMENT GRAPEVINES

The experiment was conducted in two, 20-year old Sauvignon blanc vineyards in the Stellenbosch district. The vineyards were at Helshoogte and Papegaaiberg, both in the Stellenbosch district, approximately nine kilometres apart (Fig. 3.1). Their co-ordinates, altitudes as well as slope aspects and gradients are summarized in Table 3.1. Two experiment plots with contrasting soil forms were selected in each vineyard.

The Helshoogte vineyard was situated 413 m above sea level on the south-easterly foot slopes of the Simonsberg mountain with a 5% gradient. The two plots were approximately 55 m apart with an altitude difference of approximately 3.0 m (Fig. 3.2). At Papegaaiberg, the vineyard was situated at 148 m altitude on the north-western foot hills of the Papegaaiberg mountain with a 6% gradient. The two plots were approximately 60 m apart with an altitude difference of approximately 3.5 m (Fig. 3.2).

Two contrasting soil types in terms of soil water regime were identified in each vineyard (Table 3.1). At Helshoogte the two soils represented the Tukulu (Entunja family) and Hutton (Hayfield family) forms, respectively according to Van Schoor (2001). The soils at Papegaaiberg were of the Avalon (Vryheid family) and Tukulu (Mostertshoek family) forms, respectively.

4.2.2 ATMOSPHERIC CONDITIONS

Air temperature, rainfall, relative humidity, precipitation, net radiation as well as wind speed and direction were recorded every minute by means of automatic weather stations (MC Systems, Cape Town), that were erected midway between the two plots at each locality. For convenience, the term “radiation” will refer to “net radiation” from hereon. These values were averaged or summed per hour and the hourly data set was then used to calculate daily minimum, maximum and mean values. These daily values were then averaged or summed to calculate mean monthly maximum and minimum values. The automatic weather stations measured the atmospheric conditions from September 2002 to March 2003. The automatic weather station at Helshoogte was removed during the middle of March 2003 when the vineyard was pulled out to be replanted, and mean monthly values for March could thus not be determined. Reference evapotranspiration (ET_0) was calculated using a modified Penman-Monteith equation as discussed in Chapter 3.

On days when grapevine water status were determined during four growth stages, *i.e.* flowering (30 to 31 October), pea size (5 to 6 December), prior to harvest (11 to 12 February) and during the post harvest period (11 to 12 March), diurnal variations in air temperature, radiation and wind speed were obtained from the hourly data base. Vapour pressure deficit (VPD) of the atmosphere was calculated using the atmospheric pressure, saturation vapour deficit at the wet-bulb temperature and the saturation vapour pressure at air temperature (dry-bulb temperature) as follows:

Atmospheric pressure at each locality was calculated according to Doorenbos & Pruitt (1977):

$$P = P_0 - 0.01152 \times z + 0.544 \times 10^{-6} \times (z)^2 \tag{4.1}$$

where: P = atmospheric pressure (kPa)
P_0 = atmospheric pressure at sea level (= 101.3 kPa)
z = elevation above sea level (m)

The saturation vapour pressure at wet-bulb temperature and at air temperature was calculated according to Allen *et al.* (1998):

$$ESN = 6.11 \times \exp\left(\frac{17.27Tw}{Tw + 237.3}\right) / 10 \tag{4.2}$$

where: ESN = saturation vapour pressure at wet-bulb temperature (kPa)
Tw = wet-bulb temperature (°C)

$$ES = 6.11 \times \exp\left(\frac{17.27T}{T + 237.3}\right) / 10 \tag{4.3}$$

where: ES = saturation vapour pressure at air temperature (kPa)
T = dry-bulb temperature (°C)

Actual vapour pressure was calculated using the atmospheric pressure and the saturation vapour deficit at wet-bulb temperature, as well as the wet-bulb and dry-bulb temperatures according to Bosen (1958):

$$ED = ESN - 0.000661 \times P \times (T - Tw) \times (1 + 0.00115 \times Tw) \tag{4.4}$$

where: ED = actual vapour pressure (kPa)
ESN = saturation vapour pressure at wet-bulb temperature (kPa)
P = atmospheric pressure (kPa)
T = dry-bulb temperature (°C)

Vapour pressure deficit is the difference between the saturation and actual vapour pressure according to Allen *et al.* (1998):

$$VPD = ES - ED \tag{4.5}$$

where: VPD = vapour pressure deficit (kPa)
ES = saturation vapour pressure at air temperature (kPa)
ED = actual vapour pressure (kPa)

In order to calculate the total accumulated VPD at each site for each of the four 24-hour periods during the four growth stages, the total area of the VPD graph of each locality was calculated as follows using the trapezoidal rule (Granville *et al.*, 1941):

$$\text{AVPD} = (\frac{1}{2}\text{VPD}_0 + \text{VPD}_1 + \text{VPD}_2 + \ldots\ldots+\text{VPD}_{n-1} + \frac{1}{2}\text{VPD}_n)\ \Delta t \qquad (4.6)$$

where: AVPD = accumulated vapour pressure deficit (kPa^2)
VPD_n = vapour pressure deficit at time n (kPa)
Δt = time interval between measurements (h)

Long-term atmospheric data (1994-2001) were obtained from the data base of the Institute for Soil, Water and Climate of the Agricultural Research Council in Pretoria.

4.2.3 LEAF WATER POTENTIAL

In order to quantify grapevine water status, leaf water potential (Ψ_l) was measured by means of the pressure chamber technique (Scholander *et al.*, 1965). Diurnal cycles of Ψ_l were established on an hourly basis (04:00 to 03:00) during the days representing the four different growth stages mentioned in Section 4.2.2, *i.e.* flowering, pea size, ripening period prior to harvest and during the post harvest period. Leaf water potential was measured on grapevines from both soils at each locality on the same day. Three uncovered, mature leaves, fully exposed to the sun (when applicable) were sampled from three different grapevines on each of the four experiment plots representing different soil types. Two separate field teams measured Ψ_l simultaneously at the two localities.

To calculate the total accumulated water stress over the 24-hour period during each of the four growth stages, the total area of the leaf water potential graph for each soil was calculated using the trapezoidal rule (Granville *et al.*, 1941) as follows:

$$\text{AWS} = (\frac{1}{2}\Psi_0 + \Psi_1 + \Psi_2 + \ldots\ldots+\Psi_{n-1} + \frac{1}{2}\Psi_n)\ \Delta t \qquad (4.7)$$

where: AWS = accumulated water stress (MPa^2)
Ψ_n = leaf water potential at time n (-MPa)
Δt = time interval between measurements (h)

4.2.4 SAP FLOW

Sap flow was determined by means of the heat pulse velocity technique according to the protocol described by Myburgh (1998). Four sensors were installed in the trunk xylem of each grapevine used, and sap flow was recorded at 15 minute intervals using a specially designed heat pulse generation and temperature measurement system (Micro Innovations, Pretoria). Mean hourly values were calculated from these data for time intervals which corresponded to those of the Ψ_l measurements, during the four stages. Trunk cross-sectional areas were measured by means of the profile measuring apparatus described by Myburgh & Coetzee (2004) at the points where sap flow sensors were installed. Heat pulse propagation time (seconds) was converted to hourly sap flow (ml/hour/m^2) by means of the following equations developed by Myburgh (1998):

$$F_{TOT} = 22.6e^{(-0.0082t)} \times A \qquad (4.8)$$

where: F_{TOT} = Total sap flow (ml/h)
t = Equilibrium time (seconds)
A = cross-sectional area of the trunk (m^2)

The leaf area (LA) per grapevine at Helshoogte was measured using an electronic area meter (Li-Cor). At Papegaaiberg, the leaf area was calculated using the following equation for vertical grapevine canopies according to Myburgh (1998):

$$LA = 7.81 \times M_p - 0.23 \qquad (4.9)$$

where: LA = Leaf area per grapevine (m^2)
M_p = cane mass (kg/grapevine)

The leaf area per grapevine was calculated at Papegaaiberg because measuring it with an electronic area meter is a destructive method. Since the vineyard was being uprooted at Helshoogte, this method could be used there.

The sap flow per unit leaf area was calculated as follows (Myburgh, 1998):

$$F_{LA} = F_{TOT} / LA \qquad (4.10)$$

where: F_{LA} = Sap flow per unit leaf area (ml/h/m^2)
F_{TOT} = Total sap flow (ml/h)
LA = Leaf area per grapevine (m^2)

4.2.5 GRAPEVINE RESPONSES

This study formed an integral part of a comprehensive, multi-disciplinary research project (ARC Infruitec-Nietvoorbij Project No. WW13/01) on the effect of soil and climate on wine quality, which commenced in 1993 and will be completed in 2004. Since measurement of grapevine responses, *i.e.* vegetative growth, yield and wine quality, were not an objective of this study, these data were obtained from researchers responsible for the main study.

4.2.6 STATISTICAL ANALYSIS

The data were subjected to an analysis of variance. Tukey'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. Statgraphics® was used to determine relationships between parameters by means of linear regression.

4.3 RESULTS AND DISCUSSION

4.3.1 ATMOSPHERIC CONDITIONS

4.3.1.1 Atmospheric conditions during the growing season

Although slight variations occurred, the air temperature regime during the 2002/03 season followed patterns similar to the long-term average at both localities (Fig. 4.1A and B). Helshoogte was consistently cooler than Papegaaiberg. September and December were slightly warmer and October and November slightly cooler compared to the long-term mean. Net radiation was higher than the long-term average over the entire season at both localities (Fig. 4.1C and D). The vineyards at Papegaaiberg, *i.e.* on a north-western slope, received more radiation than those at Helshoogte, *i.e.* at high altitude on a south-easterly slope, thereby causing air temperatures to be higher.

As can be expected from the temperature and radiation data, ET_0 was higher than the long-term mean (Fig. 4.2A and B). These figures also showed that ET_0 at the warmer locality (Papegaaiberg) was higher than at the cooler locality (Helshoogte). During the 2002/03 growing season less rainfall occurred than the long-term mean at both localities (Fig. 4.2C and D). Only at the end of the season, *i.e.* March, more than normal rain occurred. No rainfall data were available for Helshoogte for March, but above normal rainfall was reported for the entire Stellenbosch district during this month. The relatively dry growing season of 2002/03, however, was preceded by a winter with normal rainfall (data not shown).

At Helshoogte, the maximum relative humidity (RH) tended to be higher during the 2002/03 season compared to the long-term average for most of the growing season, while the minimum RH was more comparable to the long-term average (Fig. 4.3A). The higher than average maximum RH values are contrary to what would be expected during such a relatively dry season, especially when the higher net radiation and lower rainfall during the 2002/03 season are considered. Although slight variations occurred, the maximum RH at Papegaaiberg followed a similar pattern during the 2002/03 compared to the long-term average, whilst the minimum RH values tended to be slightly lower during the 2002/03 growing season than the long-term average (Fig. 4.3B).

Except for higher wind speed recorded during January at Helshoogte, wind speeds during the 2002/03 growing season were comparable to the long-term means at both localities (Fig. 4.3C and D). The distribution of wind direction during the 2002/03 season was comparable with the long-term mean at both Helshoogte and Papegaaiberg (Table 4.1). However, at Helshoogte the percentage north-westerly (NW) and westerly (W) winds were higher during 2002/03 than the long-term mean. Since the NW and W winds were probably more humid breezes, this could explain why the RH were higher than expected during such a relatively warm season.

4.3.1.2 Atmospheric conditions when diurnal Ψ_l cycles were determined

Flowering

From 30 to 31 October 2002 the sunlight hours at both localities stretched from 06:00 until 20:00 (Fig. 4.4A). At Helshoogte radiation reached a maximum between 12:00 and 13:00. The maximum radiation at Papegaaiberg was recorded at 13:00, and was higher than the maximum at Helshoogte. The radiation at Helshoogte was higher during the morning (06:00 to 11:00) and lower than at Papegaaiberg during the afternoon (12:00 to 20:00). This corresponded with the south-easterly aspect (exposed to morning sun) of Helshoogte and the north-westerly aspect (exposed to afternoon sun) of Papegaaiberg (Table 3.1). Air temperature was higher at the warmer Papegaaiberg locality compared to Helshoogte, especially during late afternoon (Fig. 4.4B). Air temperatures were not higher than usual for that part of the year, and normal sunshine occurred on the day of measurement (Fig. 4.4A). The VPD was also notably higher at Papegaaiberg than at Helshoogte from 11:00 until 22:00 (Fig. 4.4C), correlating with the higher air temperatures encountered. Wind speeds at both localities never increased above 2.5 m/s on this particular day, and tended to follow the same pattern over the course of the day (Fig. 4.4D).

Pea size

Radiation at pea size (5 to 6 December 2002) followed a similar pattern to that at flowering (Fig. 4.5A). The plots at Papegaaiberg received less radiation during the morning, but more during the afternoon compared to the plots at Helshoogte. Radiation at Papegaaiberg reached its peak later than at Helshoogte but it attained higher values. As explained earlier, this is ascribed to the difference in aspect between the two localities. During the early morning (04:00 to 09:00) and late night hours (00:00 to 03:00), air temperatures at Helshoogte were higher compared to those at Papegaaiberg. However, during the midday Papegaaiberg was again the warmer locality (Fig. 4.5B). This was reflected in the VPD at these localities (Fig. 4.5C). The VPD was higher at Helshoogte during the early morning and again late at night, but lower than Papegaaiberg during the afternoon and pre-midnight. Both air temperature and VPD were relatively high during this day at both localities. The wind speed at Helshoogte stayed relatively constant during the day (Fig. 4.5D), and then increased slightly from midnight (approximately 3 m/s). The wind speed at Papegaaiberg was low during the morning, and then increased from midday to reach a maximum of 4 m/s at 20:00.

Ripening period prior to harvest

In contrast to flowering and pea size, radiation at Helshoogte and Papegaaiberg showed similar variation from 11 to 12 February 2003 (Fig. 4.6A). Both localities reached a maximum of approximately 4 MJ/m^2/h at 13:00, whereafter it decreased. The sky tended to be cloudy at times, which reduced the levels of radiation, particularly during the afternoon. Air temperatures as well as VPD were lower on this day than on 5 to 6 December (Fig. 4.6B and C) at both localities. Once again, the VPD at Papegaaiberg was higher than the VPD at Helshoogte, especially during the day. The wind speed at Helshoogte remained relatively constant during the 24-hour period (between 1 m/s and 2 m/s). At Papegaaiberg, the wind speeds varied between 1 m/s and 4 m/s during the day, and decreased to below 1 m/s at 02:00.

Post harvest

The radiation was lower than on any of the other days at both localities from 11 to 12 March 2003 (Fig. 4.7A). The maximum radiation at both localities occurred at 13:00, with Papegaaiberg slightly higher and later than Helshoogte. Air temperatures were comparable to those during 11 to 12 February (Fig. 4.7B) at both localities. Papegaaiberg was again slightly warmer compared to Helshoogte during the midday and cooler during the early morning and late night. This was also reflected in the VPD, where Helshoogte had a higher VPD during the early morning and late night, and lower VPD compared to Papegaaiberg during the midday (Fig. 4.7C). The VPD was lower than during 11 to 12 February, and much lower than during 5 to 6 December. In fact, it was similar to the VPD's on 30 to 31 October, especially at

Helshoogte. The wind speeds were similar at the two localities (Fig. 4.7D), with an increase in wind speed from 10:00 to 15:00, whereafter it decreased again.

4.3.2 GRAPEVINE RESPONSE

4.3.2.1 Vegetative growth

Based on long-term mean cane mass, *i.e.* 1994-2001, growth vigour of grapevines was comparable between the Tukulu and the Hutton soils at Helshoogte (Table 4.2). Unfortunately no cane mass for the 2002/03 season was available, since the vineyard was pulled out in March 2003. Canopy densities were, however, measured during the 2002/03 season at veraison and harvest (W.J. Conradie, unpublished data). At veraison grapevines on the Tukulu soil had a leaf layer number (LLN) of 4.0 with 50.1% shaded leaves, whereas grapevines on the Hutton soil had a LLN of 3.7 and 48.1% shaded leaves. At harvest, grapevines on the Tukulu soil had a LLN of 3.5 in comparison to a LLN of 3.0 for grapevines on the Hutton soil. This indicated a higher growth vigour for grapevines on the Tukulu compared to those on the Hutton soil.

Long-term cane mass measurements (1994-2001) were comparable for grapevines on the Avalon and those on the Tukulu soils at Papegaaiberg (Conradie *et al*., 2002). However, the long-term mean cane mass was considerably less than at Helshoogte (Table 4.2). During the dry 2002/03 season, the average cane mass for grapevines on the Avalon and Tukulu soils were significantly different from the long-term averages (W.J. Conradie, unpublished data).

4.3.2.2 Grapevine water status

Grapevine water status, as quantified by means of Ψ_l and sap flow measurements will be discussed according to the various growth stages.

Flowering

At flowering (30 to 31 October), Ψ_l in grapevines on both soils at Helshoogte remained above -0.85 MPa during the diurnal cycle (Fig. 4.8A). There were no significant differences in the diurnal Ψ_l in grapevines from the two different soils, and grapevines experienced the same amount of water stress at this stage, as could be seen from the accumulated diurnal water stress (Fig. 4.11). Since the Ψ_m of the two soils were similar at this stage (Fig. 3.7), this was to be expected. Both soils were still relatively wet at this point, and air temperatures as well as VPD were relatively low during this particular day (Fig. 4.4). The pre-dawn Ψ_l values were -0.28 MPa and -0.34 MPa in grapevines on the Tukulu and Hutton soils, respectively. The First Material Stress value for grapevines is between -0.90 MPa and -1.20 MPa (Williams *et al*., 1994). Since the Ψ_l at flowering did not fall below -0.90 MPa at any time of the day on any of the soils at Helshoogte, it can be concluded that the grapevines on neither of the two soils were subjected to water stress that would have negatively affected grapevine functioning at this stage.

A slight increase in Ψ_l in grapevines on the Hutton soil at 08:00 (Fig. 4.8A) coincided with a decrease in sap flow (Fig. 4.13A). There were also indications that stomatal control prevented a decrease in Ψ_l at 12:00 and 13:00. At 15:00 stomatal closure again caused a rise in Ψ_l in grapevines on the Hutton soil. Stomatal control was not as pronounced during the morning in grapevines on the Tukulu soil (Fig. 4.8A). However, according to variations in the Ψ_l and sap flow, stomatal control did occur around 16:00. These results indicated that partial stomatal closure occurred although the soil was relatively wet (Fig. 3.7) and atmospheric conditions relatively mild (Fig. 4.4).

During the diurnal Ψ_l cycle at flowering, the Ψ_l in grapevines on both soils at Papegaaiberg remained above -0.75 MPa (Fig. 4.9A), and there were no significant differences between the Avalon and Tukulu soils. Furthermore, there was no significant difference in the accumulated diurnal water stress between grapevines on the Avalon and Tukulu soils, respectively (Fig. 4.11). The pre-dawn Ψ_l values were -0.03 MPa and -0.04 MPa for the Avalon and Tukulu soils, respectively. Since the SWC and Ψ_m of both soils were still high at this time (Fig 3.6 and Fig. 3.7), and the air temperatures and VPD were low (Fig. 4.4), the grapevines at Papegaaiberg did not experience significant water stress at this stage.

According to fluctuations in sap flow, stomatal control also seemed to have occurred in grapevines on the Tukulu soil at Papegaaiberg. The constant Ψ_l from 10:00 to 11:00 (Fig. 4.9A) was probably the result of the partial stomatal closure observed at 11:00 (Fig. 4.13B). A slight increase in Ψ_l at 13:00 also corresponded with a slight decrease in sap flow. In terms of sap flow, grapevines on the Avalon soil seemed to show less stomatal control, except around 14:00 (Fig. 4.13B). Furthermore, the higher Ψ_l at 11:00 and 12:00 could not be accounted for in terms of sap flow. It should be noted that sap flow were measured in a single plant which might not always have been in phase with Ψ_l measurements that were more representative of the larger population on a specific plot.

When mean Ψ_l values for each locality were compared, the grapevines at Helshoogte experienced significantly more water stress during flowering than those at Papegaaiberg throughout most of the diurnal cycle (Fig. 4.10A), even though the accumulated VPD (Fig. 4.12) and the air temperature (Fig. 4.4) was slightly higher at Papegaaiberg than at Helshoogte. The accumulated diurnal water stress was significantly higher in grapevines on both soils at Helshoogte compared to the ones on the two soils at Papegaaiberg (Fig. 4.11). Higher sap flow per unit leaf area in grapevines at Papegaaiberg compared to those at Helshoogte (Fig. 4.13) also indicated that grapevines at the latter locality were subjected to more water stress. Hence, higher Ψ_m of the two soils at Papegaaiberg (*ca* -0.01 MPa) in comparison to *ca* -0.03 MPa of the two soils at Helshoogte clearly reflected in the water status of the grapevines at the respective localities. As in the case of Helshoogte, grapevines on both soils at Papegaaiberg were not subjected to water stress that would have negatively affected grapevine functioning.

Pea size

At pea size (5 to 6 December), the RAW of both the soils at Helshoogte had not been depleted and the soils were still relatively wet (Fig. 3.5). Similar to the results obtained at flowering, the pre-dawn Ψ_l was approximately -0.30 MPa in grapevines on both soils. The diurnal Ψ_l of grapevines on the Tukulu soil tended to be higher compared to those on the Hutton soil and the difference was only significant at 09:00 and 11:00 (Fig. 4.8B). However, grapevines on the Hutton soil experienced significantly more accumulated diurnal water stress than those on the Tukulu soil (Fig. 4.11). A maximum temperature of 34°C was reached at 15:00 at Helshoogte (Fig. 4.5B) and the VPD was much higher than during the first cycle at flowering (Fig. 4.5C), but lower than the VPD at Papegaaiberg at this stage. During the morning, Ψ_l in grapevines on the Hutton soil decreased rapidly from 06:00 to 07:00, and then tended to remain constant until 08:00. The constant Ψ_l corresponded to a decrease in sap flow at 07:00 (Fig. 4.14A). This indicated that partial stomatal control probably occurred early in the day to prevent excessive water stress under the relatively warm, dry atmospheric conditions. A reduction in sap flow after 10:00 in grapevines on the Hutton soil also coincided with a slight increase in Ψ_l (Fig. 4.14A). After the decrease in sap flow at 11:00, Ψ_l measured at 12:00 also showed an increase. This suggested that several stomatal control cycles occurred to prevent excessively high Ψ_l in the grapevines. Since Ψ_m was high for the Hutton soil, *i.e. ca* 0.07 MPa, the continued stomatal control throughout the day was probably caused by high air temperatures and VPD.

Except for a increase at 11:00, Ψ_l in grapevines on the Tukulu soil at Helshoogte seemed to follow the normal diurnal pattern. Sap flow did not show any signs of stomatal control. Due to the higher root density on the Tukulu soil (Table 4.2), adequate water could be absorbed so that stomatal control was probably not necessary in grapevines on the Tukulu soil as opposed to the Hutton soil where root density was considerably lower. Since Ψ_m was low for both soils, the combination of low root density and atmospheric conditions seemed to have induced the observed stomatal control.

At pea size, there were still no significant differences in Ψ_l in grapevines on the two soils at Papegaaiberg (Fig. 4.9B). From 09:00 until 14:00 the Ψ_l in grapevines on the Tukulu soil tended to be slightly lower than in those on the Avalon soil. However, Ψ_l in grapevines on the Tukulu soil tended to decrease at a slower rate from 10:00 until 14:00 (Fig. 4.9B). This occurred after the decrease in sap flow at 10:00 which indicated towards some stomatal control. On the Avalon soil, a slight increase in Ψ_l at 14:00 coincided with increased sap flow (Fig. 4.14B). The sharp decrease in sap flow that followed again coincided with a decrease in Ψ_l at 15:00. This indicated that stomatal control was required in grapevines on both soil types. Due to lower root density, *i.e.* 261 per square meter (Conradie *et al.*, 2002), stomatal control was probably required earlier in grapevines on the Tukulu soil than in ones on the Avalon soil. The accumulated diurnal water stress in grapevines on the Avalon and Tukulu soils did not differ significantly (Fig. 4.11). The RAW of the Tukulu soil had been depleted by this stage, but not in the case of the Avalon soil (Fig. 3.6). Air temperature (maximum 37°C at 16:00), as well as VPD (maximum 3.76 kPa at 16:00), were exceptionally high on this day (Fig. 4.5). As mentioned earlier, the VPD at Papegaaiberg was higher than at Helshoogte during the midday, but lower during the night. The difference between maximum Ψ_l values during the night (pre-dawn) and minimum Ψ_l values during the day (midday) was more pronounced at Papegaaiberg than at Helshoogte (Fig. 4.8B).

At pea size, grapevines at Helshoogte still seemed to experience significantly more water stress than the ones at Papegaaiberg (Fig. 4.10B), especially during the early morning and at night. Once again, the pre-dawn value at Helshoogte (Ψ_l = -0.31 MPa) was considerably lower than at Papegaaiberg (Ψ_l = -0.02 MPa). The higher VPD and air temperature at Helshoogte compared to Papegaaiberg at that time (Fig. 4.5) could explain why the Ψ_l was lower in grapevines at Helshoogte during the pre-dawn period. By midday, the Ψ_l in grapevines at Papegaaiberg had decreased to such an extent that it was lower than Ψ_l measured at Helshoogte from 13:00 until 18:00. The VPD at Papegaaiberg (Fig. 4.5C), as well as the air temperature (Fig 4.5B), were higher from 12:00 until 23:00 compared to Helshoogte. This could explain the large decrease in Ψ_l in grapevines at Papegaaiberg during the day although the soils tended to be wetter than at Helshoogte. This shows that even when there is still enough soil water available, harsh atmospheric conditions can induce water stress in grapevines. Due to higher VPD during the night, accumulated VPD was slightly higher at Helshoogte than at Papegaaiberg. At both localities, accumulated VPD was considerably higher than during any of the days when the other three Ψ_l cycles were determined (Fig. 4.12).

For the biggest part of the day during the pea size stage, leaf water potential in the grapevines on all soils at both localities decreased to below -0.90 MPa, but did not decrease below -1.20 MPa at any stage. However, on three of the soil types Ψ_l in grapevines approximated -1.20 MPa at some stage during the day. At Papegaaiberg, Ψ_l in grapevines on both soils reached a minimum of -1.18 MPa at 15:00 in the afternoon. On the Hutton soil at Helshoogte, a value of -1.16 MPa was reached at 11:00 in the morning, after which some recovery occurred. It is possible that the grapevines might have suffered at least limited "material" water stress on this particular day. Only grapevines on the Tukulu soil at Helshoogte were not subjected to limited water stress.

Ripening period prior to harvest

During the ripening period, just prior to harvest (11 to 12 February), Ψ_m of both soils at Helshoogte had decreased considerably (Fig. 3.7). However, air temperature, and especially VPD (Fig. 4.6), was substantially lower than on 5 to 6 December. Even though the atmospheric conditions were milder, the diurnal Ψ_l values in grapevines on both soils were considerably lower during ripening than during the previous cycle (Fig. 4.8C). This demonstrated the effect of the soil water status on the amount of stress that grapevines experience, even when the atmospheric conditions are mild. Grapevines on the Tukulu soil seemed to experience more water stress during the day (Ψ_l = -1.56 MPa), especially the midday period, than grapevines on the Hutton soil (Ψ_l = -1.37 MPa). Grapevines on the Tukulu soil experienced significantly more water stress at 14:00 and 19:00. The pre-dawn Ψ_l values, however, tended to be lower for grapevines on the Hutton soil (-0.40 MPa) in comparison to the ones on the Tukulu soil (-0.28 MPa). The accumulated diurnal water stress over the 24-hour period did not differ significantly in grapevines on the two soils (Fig. 4.11A). However, during the day, the accumulated water stress was significantly higher in grapevines on the Tukulu soil (Fig. 4.11B), but during the night it was significantly higher in ones on the Hutton soil (Fig. 4.11C). During previous seasons, *i.e.* 1994 to 2001, grapevines on the Tukulu soil experienced slightly less midday water stress in January and February compared to those on the Hutton soil (Conradie *et al.*, 2002). However, during the 2002/03 season Ψ_m of the Tukulu soil decreased considerably more than that of the Hutton soil and this could explain why grapevines on the Tukulu soil experienced more water stress during 2002/03 than ones on the Hutton soil. The drier Tukulu soil was probably caused by more growth vigour of grapevines on this soil, extracting more water compared to less vigorous grapevines on the Hutton soil.

On the Tukulu soil at Helshoogte at 10:00, a sap flow reduction indicated that the increased Ψ_l at 10:00 was probably caused by stomatal control (Fig. 4.15A). The reduction in sap flow at 13:00 also coincided with a slight increase in Ψ_l at that time. In grapevines on the Hutton soil, the increased sap flow at 11:00 coincided with a slight decrease in Ψ_l at that time (Fig. 4.15A). From 12:00 to 14:00 lower sap flow in grapevines on the Hutton soil indicated towards stomatal control which could have caused the Ψ_l to be higher in comparison to those on the Tukulu soil. The Ψ_m of the Tukulu soil were lower than that of the Hutton soil at this stage (Fig. 3.7).

During the diurnal Ψ_l cycle measured prior to harvest it seemed as if the grapevines on the Tukulu soil at Papegaaiberg were subjected to slightly more water stress than those on the Avalon soil (Fig. 4.9C). Although there were no significant difference in the pre-dawn Ψ_l in grapevines on the two soils (approximately -0.28 MPa), grapevines on the Tukulu soil reached a minimum of -1.18 MPa compared to the minimum of -1.09 MPa in those on the Avalon soil at 12:00. Grapevines on the Tukulu soil experienced significantly more water stress than grapevines on the Avalon soil at 05:00, 14:00, 17:00 and 02:00. Grapevines on the Avalon soil also seemed to have recovered at 20:00, while the grapevines on the Tukulu soil only recovered after 24:00. During the previous two cycles there was no difference between the amount of accumulated water stress that the grapevines on the two soils experienced, especially during the night. Due to the lower Ψ_m of the Tukulu soil at this stage, especially at the 300 mm depth where most of the roots were located, grapevines probably experienced more water stress on this soil than on the Avalon soil. This was confirmed by the accumulated diurnal water stress of grapevines on the Tukulu soil, which was significantly more over the 24-hour period than for grapevines on the Avalon soil (Fig. 4.11). This was also the case during the day-time and night-time hours, respectively. The atmospheric conditions were milder than on 5 to 6 December, *i.e.* lower air temperatures and VPD’s, which indicated that the more severe water stress was a result of the soil water status.

Due to the low root density of the Tukulu soil at Papegaaiberg, adequate water could not be absorbed, and the Ψ_l were higher than on the Avalon soil from 05:00 until 07:00. On the Avalon soil, a sap flow reduction at 11:00 coincided with a slight increase in Ψ_l (Fig. 4.15B). A slight increase in sap flow from 11:00 until 16:00 followed by a decrease at 17:00 indicated that stomatal control occurred to such an extent that Ψ_l was higher than in grapevines on the Tukulu soil. Grapevines on the Tukulu soil also showed signs of stomatal control (Fig. 4.15B). The low root density (Table 4.2) probably caused the lower Ψ_l in grapevines on the Tukulu soil compared to those on the Avalon soil.

Grapevines at Helshoogte continued to experience more water stress compared to those at Papegaaiberg during ripening (Fig. 4.10C). At this stage, the soils at both localities had become significantly drier compared to the first part of the season, and water content of all the soils had decreased below the RAW level. However, Ψ_m of the two soils at Helshoogte was considerably lower compared to the two soils at Papegaaiberg. The pre-dawn Ψ_l was comparable at the two localities. Air temperature and VPD were lower at both localities than at pea size, but the Ψ_l were lower. This again illustrated that even when the atmospheric conditions are milder, the decrease in Ψ_m will cause more water stress in grapevines.

At Papegaaiberg the Ψ_l values were lower than -0.90 MPa during most of the day-time period on both soils, but never decreased below -1.20 MPa (Fig. 4.9C). However, Ψ_l came close to -1.20 MPa on the Tukulu soil. At Helshoogte, Ψ_l values not only decreased lower than -0.90 MPa for most of the day, but actually below -1.20 MPa for a major part of the day (Fig. 4.8C). Again, on the Hutton soil at Helshoogte the leaf water potentials decreased sharply until mid-morning and then stabilized before recovering from early afternoon. On the Tukulu soil at Helshoogte the minimum Ψ_l values were below -1.40 MPa during midday and early afternoon (Fig. 4.8C). These results indicated that the grapevines at Helshoogte were probably subjected to more than just slight "material" water stress on this day, especially on the Tukulu soil.

Post harvest

During the post harvest period, Ψ_l at Helshoogte again showed that grapevines on the Tukulu soil experienced more water stress compared to ones on the Hutton soil during the warmest part of the day (Fig. 4.8D). The Ψ_l was significantly lower for grapevines on the Tukulu soil at 12:00, 14:00 and from 16:00 to 18:00 (Fig. 4.8D). However, unlike the diurnal cycle prior to harvest, the pre-dawn Ψ_l of the two soils were similar, *i.e.* approximately -0.51 MPa. By this time, both soils had relatively low SWC and Ψ_m (Fig. 3.5 and Fig. 3.7). The VPD was almost as low as during the first cycle (30 to 31 October) (Fig. 4.7). Despite the fact that the atmospheric conditions were equally mild during the two cycles, the Ψ_l differed widely. The accumulated water stress over the full diurnal cycle (Fig. 4.11A) and the day-time hours (Fig. 4.11B) showed that grapevines on the Tukulu soil experienced significantly more water stress than grapevines on the Hutton soil. During the night (Fig. 4.11C), however, there was no significant water stress difference between the grapevines on the Tukulu and Hutton soils, respectively. This again illustrated that soil water status dominated grapevine water stress compared to atmospheric conditions.

On the Tukulu soil, a sap flow reduction from 10:00 to 11:00 caused a slight increase in Ψ_l measured at 11:00 (Fig. 4.16A). This also occurred at 13:00. On the other hand, the high sap flow at 15:00 could have caused the substantial increase in Ψ_l at 15:00. Due to stomatal control, Ψ_l never decreased lower than -1.50 MPa. On the Hutton soil, the higher Ψ_m and higher sap flow rates caused higher Ψ_l than on the Tukulu soil.

During the post harvest period, the difference in water stress between grapevines on the Avalon and Tukulu soils, respectively, became more pronounced at Papegaaiberg (Fig. 4.9D). The SWC and Ψ_m were considerably lower than during the previous cycles (Fig. 3.6 and Fig. 3.7). The VPD at Papegaaiberg was substantially lower than during pea size, as well as during the pre-harvest stage. Even though the atmospheric conditions were less severe than during the previous cycles, lower Ψ_l

values were obtained (Fig. 4.7). On the Tukulu soil at Papegaaiberg, the reduced sap flow from 13:00 to 14:00 caused an increase in Ψ_l at 14:00, indicating stomatal control (Fig. 4.16B). On the Avalon soil the fluctuation in sap flow suggested that stomatal control had occurred, and that it could be the reason why Ψ_l tended to remain fairly constant from 10:00 until 16:00.

Grapevines on the Tukulu soil experienced significantly more water stress than those on the Avalon soil at 05:00 to 07:00, 09:00, 21:00, 00:00 and 03:00. The pre-dawn Ψ_l was -0.26 MPa and -0.45 MPa for the Avalon and Tukulu soil respectively. The minimum Ψ_l reached was -1.48 MPa for grapevines on the Tukulu soil at 15:00 and -1.28 MPa for grapevines on the Avalon soil at 12:00 and 13:00. The most dramatic difference in Ψ_l during this cycle in comparison to the previous three cycles was at night and early morning, when grapevines on the Tukulu soil experienced considerably more stress than grapevines on the Avalon soil. Grapevines on the Tukulu soil did not recover before 01:00, whereas the grapevines on the Avalon soil seemed to have recovered already at 20:00. This corresponds to the data of the previous three cycles. It is during this stage when the RAW in the soil has already been used that the shallow root system of grapevines on the Tukulu soil caused more water stress. The total accumulated water stress of grapevines on the Tukulu soil were significantly more than in those on the Avalon soil during the full diurnal cycle, as well as during the day and night (Fig. 4.11). In fact, it was the highest of all four soils, although it was not significantly higher than the Tukulu soil at Helshoogte.

During the post harvest period grapevines at Papegaaiberg seemed to endure more water stress than the ones at Helshoogte, at least during the day (Fig. 4.10D). The pre-dawn Ψ_l was, however, still lower in the grapevines at Helshoogte. The SWC and Ψ_m of all the soils had decreased considerably at this stage. The pre-dawn Ψ_l is determined mainly by the soil water status (Van Zyl, 1987). Since both the soils at Helshoogte had much lower Ψ_m (*ca* -0.77 MPa) than the two soils at Papegaaiberg (Ψ_m = -0.13 MPa), this could explain the lower pre-dawn Ψ_l in grapevines at Helshoogte. The Ψ_l values at Helshoogte were lower than -1.20 MPa at 12:00 and 13:00, whereafter the grapevines seemed to recover. Partial stomatal closure in grapevines at Helshoogte prevented excessive water stress (*i.e.* Ψ_l < -1.20 MPa) during the warmest part of the day compared to the ones at the Papegaaiberg where almost no stomatal control occurred. Unlike at pre-dawn, the Ψ_l during the midday is largely influenced by both the soil water status and the climate of the locality (Carey *et al.*, 2004). Since Papegaaiberg had slightly higher temperatures and higher VPD during the midday than Helshoogte (Fig. 4.7), it is expected that the grapevines at Papegaaiberg would experience more water stress during the warmest part of the day compared to those at Helshoogte. The accumulated VPD was also higher at Papegaaiberg than at Helshoogte (Fig. 4.12).

At this stage, the Ψ_l in grapevines on the Tukulu soils at both localities decreased considerably below -1.20 MPa for significant parts during day-time, indicating that the plants could possibly suffer significant material stress on these soils, despite the mild atmospheric conditions. Leaf water potential of grapevines on the Tukulu soil at Helshoogte dropped below -1.20 MPa much earlier in the day than in the case of Papegaaiberg. On the Avalon soil at Papegaaiberg, Ψ_l maintained a consistent value of slightly below -1.20 MPa for most of the day-time, indicating the possibility of some material stress. The Ψ_l pattern on the Hutton soil at Helshoogte was very interesting on this mild day. It decreased sharply to just above -1.20 MPa early in the morning and then recovered. By early afternoon it recovered sharply, so that from 14:00 onwards the values were above -0.90 MPa for the rest of the day. Thus on this soil the grapevines on this day had little, if any, material stress. Due to favourable physical soil properties, grapevines on the Hutton soil at Helshoogte were able to recover earlier from water stress experienced during the day. In contrast, due to unfavourable soil physical conditions and a low root density leading to a decrease in water uptake, grapevines on the Tukulu soil at Papegaaiberg were not able to recover fully early during the night.

It should be kept in mind that these post harvest conditions would not have affected the yield or the quality of the wines produced during this season, but it could have a significant effect on reserve accumulation and the general conditioning of the grapevines for the next season.

4.3.2.3 Yield

Long-term (1994-2001) yield measurements at Helshoogte showed that grapevines on the Tukulu soil tended to yield less than those on the Hutton soil (Table 4.2). On the contrary, the grapevines on the Tukulu soil yielded more than those on the Hutton soil during 2002/03. During the dry 2002/03 season, grapevines on the Tukulu soil yielded 19% more than during previous years. Tukulu soils tend to be wetter than most soils during normal years, which through higher vigour levels, could impact negatively on their production potential, as a result of more canopy shading. During a dry season, such as 2002/03, the extra water storage capacity of the Tukulu soils could be advantageous as shown by its substantially higher yield compared to normal years. It is interesting that the Hutton soil, a relatively dry soil, did succeed in maintaining its normal yield level during this dry season. The fact that the grapevines on the Tukulu soil had more vegetative growth and a 10% higher crop load than those on the Hutton soil could explain why the Ψ_m of the Tukulu soil decreased more than that of the Hutton soil.

At Papegaaiberg, the long-term crop measurements show that the average yield was less for grapevines on the Tukulu soil than for grapevines on the Avalon soil (Table 4.2). Similar to the long-term measurements, the grapevines yielded more on the Avalon soil than those on the Tukulu soil during the 2002/03 season. The physical properties of Avalon soils allow a better water regime for most crops in seasons with sub average rainfall. The fact that grapevines on the Avalon soil had substantially higher yields than grapevines on all the other soils during the dry 2002/03 season is thus not surprising. The Avalon soil maintained the highest soil water potential towards the end of the season (Fig. 3.7C). It is interesting that the Avalon soil produced an abnormally high crop in the 2002/03 season, while having poor vegetative growth in that season. The low yield of grapevines on the Tukulu soil could be ascribed to a combination of factors, the most important being the severe soil compaction at a shallow depth, seriously limiting rooting depth and root density (Table 4.2). This would be devastating in such a dry season, when less soil water would be available to grapevines which will lead to excessive water stress in the grapevines. In a normal season this soil is probably excessively wet, but in an abnormally dry season, like 2002/03, its low plant-available water capacity, caused by its high gravel fraction becomes an over-riding negative factor.

In Chapter 3 the different lower subsoil regimes, as derived from soil morphological features, indicated the following order of subsoil wetness for the four soils in the study: Hutton < Avalon <Tukulu (Helshoogte) < Tukulu (Papegaaiberg). The long-term (1994-2001) yield averages reported by Conradie *et al*. (2002) had exactly the reverse order, *viz.* Hutton > Avalon > Tukulu (Helshoogte) > Tukulu (Papegaaiberg), indicating an adverse effect of elevated subsoil wetness on grapevine yield. Probably not unexpectedly in the lower than normal rainfall 2002/03, yields on the Avalon soil rose to the top, followed by the Tukulu at Helshoogte and the drier Hutton soil. As indicated earlier, yields on the Tukulu at Papegaaiberg were adversely affected by low root densities affecting soil water utilization.

4.3.2.4 Wine quality

During the 2002/03 season, the fresh vegetative character appeared to be lower than usual for wine made from grapevines on the Tukulu soil at Helshoogte, whereas the cooked vegetative and tropical fruit characters were higher than in previous years, *i.e.* 1994 to 2001 (Table 4.3). The overall wine quality was also lower than usual. This was probably due to more water stress experienced by grapevines on this soil during the relatively dry season in comparison to previous seasons. Wine made from grapes produced on the Hutton soil was similar to wines in previous years. Thus the Hutton soil maintained consistency in regard to both yield and wine quality during the relatively dry season. On the other hand, grapevines on the Tukulu soil produced higher than normal yield, but lower than usual wine quality.

Wine quality for the 2002/03 season was similar to those for previous years for wines from grapes produced on the Avalon and Tukulu soils at Papegaaiberg. The tropical fruit character was, however, lower than usual for wine from grapes produced on the Tukulu soil. Usually, the quality of Papegaaiberg wine was lower due to the low potential of this terrior for Sauvignon blanc (Conradie *et al*., 2002).

When the interaction between atmospheric conditions, soil water status, vegetative growth, grapevine water status during the day and wine quality parameters were summarised, distinct patterns emerged. At both localities, the combination of lower Ψ_m, lower Ψ_l and more vigorous growth resulted in the fresh vegetative aroma to be dominant (Table 4.4). On these soils the more vigorous growth was due to wetter conditions during the earlier part of the season. This vigorous growth could have depleted soil water to a larger extent which resulted in more water stress in the grapevines during ripening as discussed earlier.

On the other hand, higher Ψ_m, less water stress and less vigorous growth caused the tropical fruit aroma to be the dominant one at Helshoogte as well as at Papegaaiberg (Table 4.4). These results showed that the less vigorous growth enhanced the tropical fruit aroma, whereas more shading of the bunches tended to increase the fresh vegetative aroma of Sauvignon blanc. This is in agreement with the findings of Marais *et al*. (1999).

Furthermore, it was clear that the cooler, more humid atmospheric conditions at Helshoogte resulted in the highest fresh vegetative aroma intensity (Table 4.4). At the warmer locality the tropical fruit aroma intensity was higher than at Helshoogte. Marais *et al.* (1999) reported similar aroma trends with respect to atmospheric conditions. According to these results, it seems that atmospheric conditions and shading, *i.e.* more dense canopies, played a deciding role in the intensity of the dominant aroma and that the combination of soil and grapevine water status had a distinct, but more subdued, effect on the aroma character of Sauvignon blanc. However, considering all variables involved, the combination of cool, humid atmospheric conditions where grapevines were subjected to more water stress without reducing vegetative vigour seemed to produce the highest overall wine quality.

4.4 CONCLUSIONS

The 2002/03 growing season at the localities studied, was relatively hot and dry in comparison to the long-term averages of previous seasons. These atmospheric conditions accentuated the effects of certain soil properties that may not come forward during normal, wetter seasons.

Relative to the Hutton soil, the usually wet Tukulu soil at Helshoogte was drier than expected during the 2002/03 season, leading to higher water stress in the grapevines on this Tukulu soil. Due to greater root efficiencies on the Hutton soil, because of its more favourable soil physical conditions, grapevines experienced less water stress than on the Tukulu soil and were able to recover earlier from water stress experienced during the day. The Hutton soil maintained consistency with regards to both yield and wine quality compared to previous seasons. On the other hand the Tukulu soil supported a higher yield, but with lower than normal wine quality.

The Avalon soil at Papegaaiberg maintained the highest soil water potential towards the end of the season. Avalon soils have soil water regimes that usually cause them to outperform most other soils during seasons with less rain. This was confirmed by the fact that this soil far outperformed all three other soils in terms of yield during the dry 2002/03 season, which is not the case during normal rainfall seasons. In addition, it maintained the same wine quality as during the 1994 to 2001 seasons. Grapevines on the Tukulu soil at Papegaaiberg experienced much higher water stress than grapevines on the Avalon soil, and even compared to the soils at Helshoogte, especially during the latter part of the season. The high water stress and low yield of grapevines on the Tukulu soil could be ascribed to a combination of factors, the most important being the severe soil compaction at a shallow depth, seriously limiting rooting depth and root efficiency, which is detrimental to grapevine performance in dry seasons. During a normal season this soil is excessively wet, but in an abnormally dry season, like 2002/03, its low plant-available water capacity, caused by its high gravel fraction, becomes an overriding negative factor.

During the Ψ_l cycle measurement at pea size the air temperatures and VPD were extremely high and values decreased to material stress levels, despite the fact that soil water content and soil water potential were not limiting. This indicated that even when there was still enough soil water available, harsh atmospheric conditions induced stress in the grapevines. Although the atmospheric conditions were much milder during the ripening period prior to harvest and the post harvest period than during pea size, the diurnal Ψ_l values on all the soils were much lower at these stages than at pea size. This demonstrated that the low soil water status late in the season had a major impact on the amount of stress grapevines experienced, even though atmospheric conditions were mild. Both the soil water status and climate played important roles in determining the amount of water stress that the grapevines experienced at different stages.

The air temperature and VPD throughout the season were consistently lower at Helshoogte, the cooler terroir, compared to Papegaaiberg, the warmer terroir. At flowering, Ψ_l showed that Sauvignon blanc grapevines were subjected to more water stress throughout the day at Helshoogte compared to those at Papegaaiberg. At that stage, Ψ_m of the well drained soils at Helshoogte was *ca* -0.03 MPa compared to -0.01 MPa at Papegaaiberg. This showed that diurnal grapevine water status was primarily controlled by soil water content. The difference in grapevine water status between the two terroirs gradually diminished until it was reversed at the post harvest period when Ψ_l in grapevines at Helshoogte tended to be higher compared to those at Papegaaiberg. The relatively low pre-dawn Ψ_l at Helshoogte indicated that the grapevines were subjected to excessive water stress resulting from the low soil water content (*i.e.* $\Psi_m = -0.77$ MPa). However, grapevines at this locality did not suffer material water stress (*i.e.* $\Psi_l < -1.20$ MPa) during the warmest part of the day, suggesting that partial stomatal closure prevented the development of excessive water stress in the grapevines.

The foregoing suggests that low pre-dawn Ψ_l values do not necessarily imply that grapevines will experience more water stress over the warmer part of the day, or *visa versa*. This does not rule out the possibility that side-effects of partial stomatal closure, such as reduced photosynthesis, can have negative effects on grapevine functioning in general. These results also suggest that measurement of diurnal Ψ_l cycles at various phenological stages is required to understand, and quantify terroir effects on grapevine water status.

4.4 LITERATURE CITED

Allen, R.G., Pereira, L.S, Raes, D. & Smith, M. (1998). Crop evapotranspiration. Guidelines for computing crop water requirements. FAO irrigation and drainage paper **56**. 299pp.

Bosen, J.F. (1958). An approximation formula to compute relative humidity from dry bulb and dew point temperatures. *Monthly Weather Rev*. **86**, 486.

Choné, X., Van Leeuwen, C., Chéry, P. & Ribéreau-Gayon, P. (2001). Terroir influence on water status and nitrogen status of non-irrigated Cabernet Sauvignon (*Vitis vinifera*). Vegetative development, must and wine composition (Example of a Medoc Top Estate Vineyard, Saint Julien Area, Bordeaux, 1997). *S. Afr. J. Enol. Vitic*. **22**, 8-15.

Conradie, W.J., Carey, V.A., Bonnardot, V., Saayman, D. & Van Schoor, L.H. (2002). Effect of different environmental factors on the performance of Sauvignon blanc grapevines in the Stellenbosch/Durbanville districts of South Africa. I. Geology, soil, climate, phenology and grape composition. *S. Afr. J. Enol. Vitic*. **23**, 78-91.

Doorenbos, J. & Pruitt, W.O. (1977). Crop water requirements. FAO Irrigation and Drainage Paper 24. 144 pp.

Fregoni, M. (1977). Effects of soil and water on the quality of the harvest. In: Proc. Int. Sym. Quality of the Vintage, February 1977, Cape Town, South Africa. pp 151-168.

Granville, W.A., Smith, P.F. & Longley, W.R. (1941). Elements of the differential and integral calculus. Revised edition. 556 pp.

Hensley, M. and De Jager, J.M. (1982). The determination of the profile available water capacities of soils. Alice, University of Fort Hare. 282 pp.

Kramer, P.J. (1969). Plant and soil water relationships: A modern synthesis. McGraw-Hill, New York.

Kramer, P.J. (1983). Water relations of plants. Academic Press, London.

Marais, J., Hunter, J.J. & Haasbroek, P.D. (1999). Effect of canopy microclimate, season and region on Sauvignon blanc grape composition and wine quality. *S. Afr. J. Enol. Vitic.* **20**, 19-30.

Myburgh, P.A. (1998). Water consumption of South African vineyards: A modelling approach based on the quantified combined effects of selected viticultural soil and meteorological parameters. Ph.D. dissertation, University of Stellenbosch, Private bag X1, Matieland 7602 (Stellenbosch), South Africa.

Myburgh, P.A. (2003). Responses of *Vitis vinifera* L. cv. Sultanina to level of soil water depletion under semi-arid conditions. *S. Afr. J. Enol. Vitic* **24**, 16-25.

Myburgh, P.A., Van Zyl, J.L. & Conradie, W.J. (1996). Effect of soil depth on growth and water consumption of young *Vitis Vinifera* L. cv. Pinot noir. *S. Afr. J. Enol. Vitic.* **17**, 53-62.

Myburgh, P.A. & Coetzee, F. (2004). Apparatus for non-destructive measurement of grapevine trunk cross-sectional area. *S. Afr. J. Enol. Vitic* **21**, 67-69.

Saayman, D. (1992). Natural influences and wine quality Part 2. The role of soil. *Wynboer* Aug. 1992, 49-51.

Saayman, D. & Van Huyssteen, L. (1980). Soil preparation studies: I. The effect of depth and method of soil preparation and of organic material on the performance of *Vitis vinifera* (var. Chenin blanc) on Hutton/Sterkspruit soil. *S. Afr. J. Enol. Vitic.* **1**, 107-121.

Scholander, P.F., Hammel, H.T., Bradstreet, E.D. & Hemmingsen, E.A. (1965). Sap flow in vascular plants. *Science* **148**, 339-346.

Seguin, G. (1983). The influence of vineyard soils on the composition and quality of harvested grapes. Bulletin de l'OIV **56**, 3-18.

Seguin, G. (1986). "Terroirs" and pedology of wine growing. *Experientia* **42**, 861-873.

Slayter, R.O. (1967). Plant water relationships. Academic Press, New York.

Van Schoor, L.H. (2001). Geology, particle size distribution and clay fraction mineralogy of selected vineyard soils in South Africa and the possible relationship with grapevine performance. M.Sc. Thesis, University of Stellenbosch, Private bag X1, Matieland 7602 (Stellenbosch), South Africa.

Van Zyl, J.L. (1987). Diurnal variation in grapevine water stress as a function of changing soil water status and meteorological conditions. *S. Afr. J. Enol. Vitic*. **8**, 45-52.

Van Zyl, J.L. & Van Huyssteen, L. (1984). Soil and water management for optimum grape yield and quality under conditions of limited or no irrigation. In: Proc. 5th Australian Wine Industry Technical Conf., November - December 1983., University of Western Australia, Perth, Australia. pp. 25-66.

Van Zyl, J.L. & Weber, H.W. (1977). Irrigation of Chenin blanc in the Stellenbosch area within the framework of the climate-soil-water-plant continuum. In: Proc. Int. Sym. Quality of the Vintage. February 1977, Cape Town, South Africa. pp 331-349.

Williams, L.E., Dokoozlian, N.K. & Wample, R. (1994). Grape. In: Shaffer, B. & Anderson, P.C. (eds). Handbook of environmental physiology of fruit crops, Vol I, Temperate crops. CRC Press, Boca Raton. pp 85-133.

Table 4.1 Distribution of wind direction at two localities in the Stellenbosch district during the 2002/03 season compared to the long-term mean.

Wind direction	Helshoogte		Papegaaiberg	
	2002/03 (%)	Mean (%)	2002/03 (%)	Mean (%)
N	5.1	7.6	4.5	4.7
NE	12.9	16.1	6.8	6.2
E	9.1	13.7	15.3	19.5
SE	4.7	9.7	9.0	9.9
S	4.5	7.6	7.9	8.0
SW	8.8	10.1	25.4	24.4
W	22.3	12.4	12.4	9.7
NW	32.2	22.1	18.7	17.6
Windless	0.4	0.7	0	0

Table 4.2 Effect of soil type on the root density, vegetative growth and yield responses of Sauvignon blanc at two localities in the Stellenbosch region during the 2002/03 season, as well as the long-term mean for the 1994 until 2001 seasons.

Locality	Soil type	Root density(1) (roots/m^2)	Cane mass (kg/vine)		Yield (kg/vine)	
			Mean(1)	2002/03(2)	Mean(1)	2002/03(2)
Helshoogte	Tukulu	561	0.9	-	1.7	2.0
	Hutton	369	0.9	-	1.8	1.8
Papegaaiberg	Avalon	863	0.7	0.5	1.8	2.3
	Tukulu	261	0.6	0.9	1.4	1.3

(1) After Conradie *et al*. (2002).
(2) W.J. Conradie, unpublished data.

Table 4.3 Effect of soil type on aroma components and wine quality for Sauvignon blanc at two localities in the Stellenbosch region during the 2002/03 season, as well as mean overall wine quality for the 1994 until 2001 seasons (W.J. Conradie, unpublished data).

Locality	Soil type	Aroma(1)					Overall quality(1)	Mean overall quality(1)
		Intensity	Fresh vegetative	Cooked vegetative	Dry vegetative	Tropical fruit		
Helshoogte	Tukulu	5.9	4.2	2.5	2.2	3.1	5.4	6.0
	Hutton	5.6	3.0	1.9	2.7	3.5	5.3	5.9
Papegaaiberg	Avalon	6.2	3.0	2.0	2.0	4.9	5.0	5.5
	Tukulu	5.6	3.0	2.6	2.7	2.5	5.1	5.3

(1) Aroma and wine quality was judged on a point scale of 1 to 10, where 10 was considered to be ideal.

Table 4.4 Summarised interaction between pre-harvest atmospheric conditions, soil matric potential (Ψ_m), grapevine water stress during the day, aroma characteristics and wine quality of Sauvignon blanc as measured at two localities during the 2002/03 season at Stellenbosch. Values in brackets designate rank order of actual values.

Locality	**Air temperature**	**VPD**	**Soil type**	Ψ_m	**Water stress**	**Growth vigour**	**Dominant aroma**	**Aroma intensity**	**Quality ranking**
Helshoogte	Cooler	Lower	Tukulu	Lower (4)	More (1)	Higher	Fresh vegetative (2)	Higher (2)	1
			Hutton	Higher (3)	Less (2)	Lower	Tropical fruit (3)	Lower (3)	2
Papegaaiberg	Warmer	Higher	Tukulu	Lower (2)	More (3)	Higher	Fresh vegetative (3)	Lower (3)	3
			Avalon	Higher (1)	Less (4)	Lower	Tropical fruit (1)	Higher (1)	4

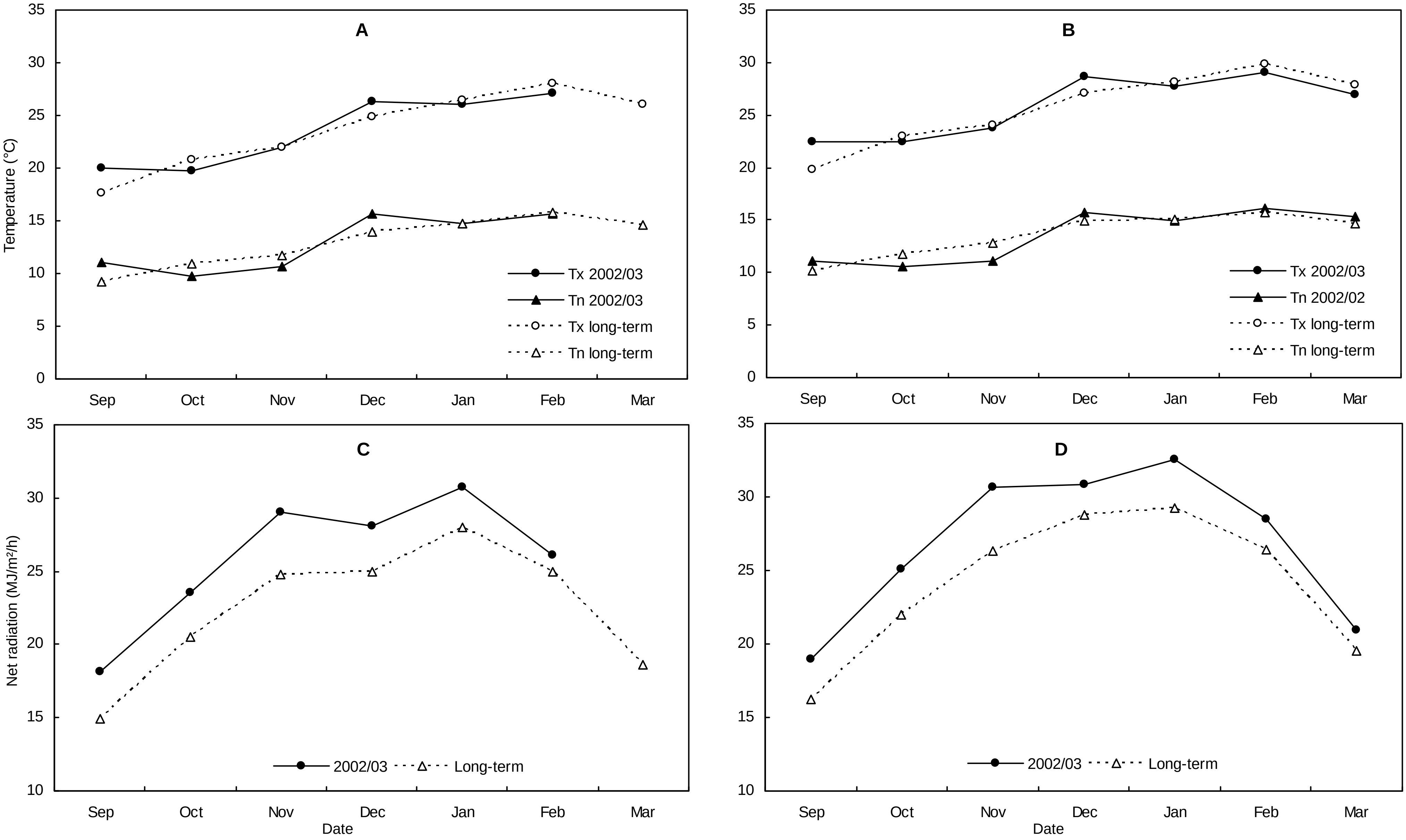

Figure 4.1 Mean monthly maximum (Tx) and minimum (Tn) temperatures at (A) Helshoogte and (B) Papegaaiberg as well as mean monthly net radiation at (C) Helshoogte and (D) Papegaaiberg as measured during the 2002/03 season in comparison to long-term mean values.

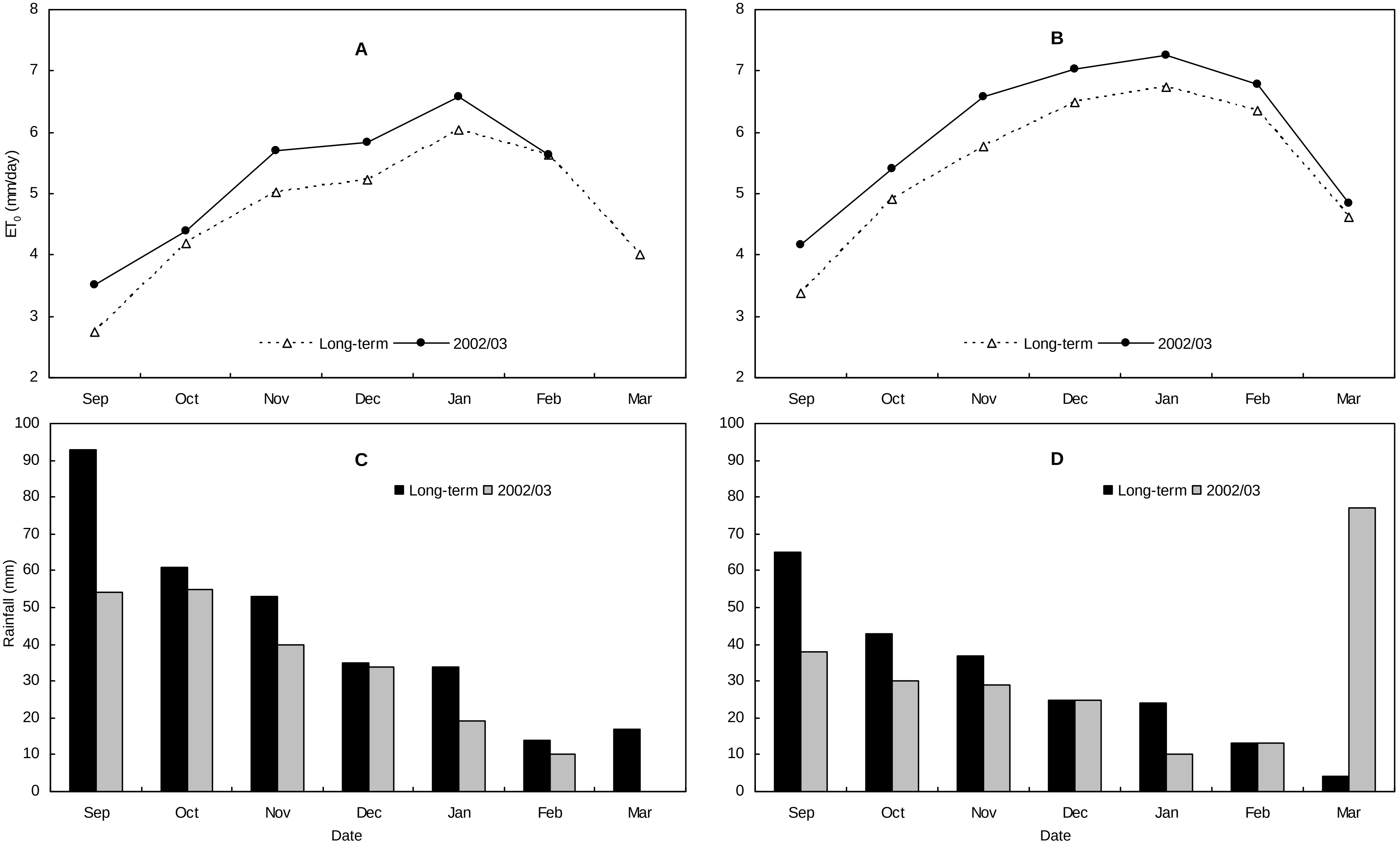

Figure 4.2 Mean monthly reference evapotranspiration (ET$_0$) at (A) Helshoogte and (B) Papegaaiberg as well as mean monthly rainfall at (C) Helshoogte and (D) Papegaaiberg as measured during the 2002/03 season in comparison to long-term mean values.

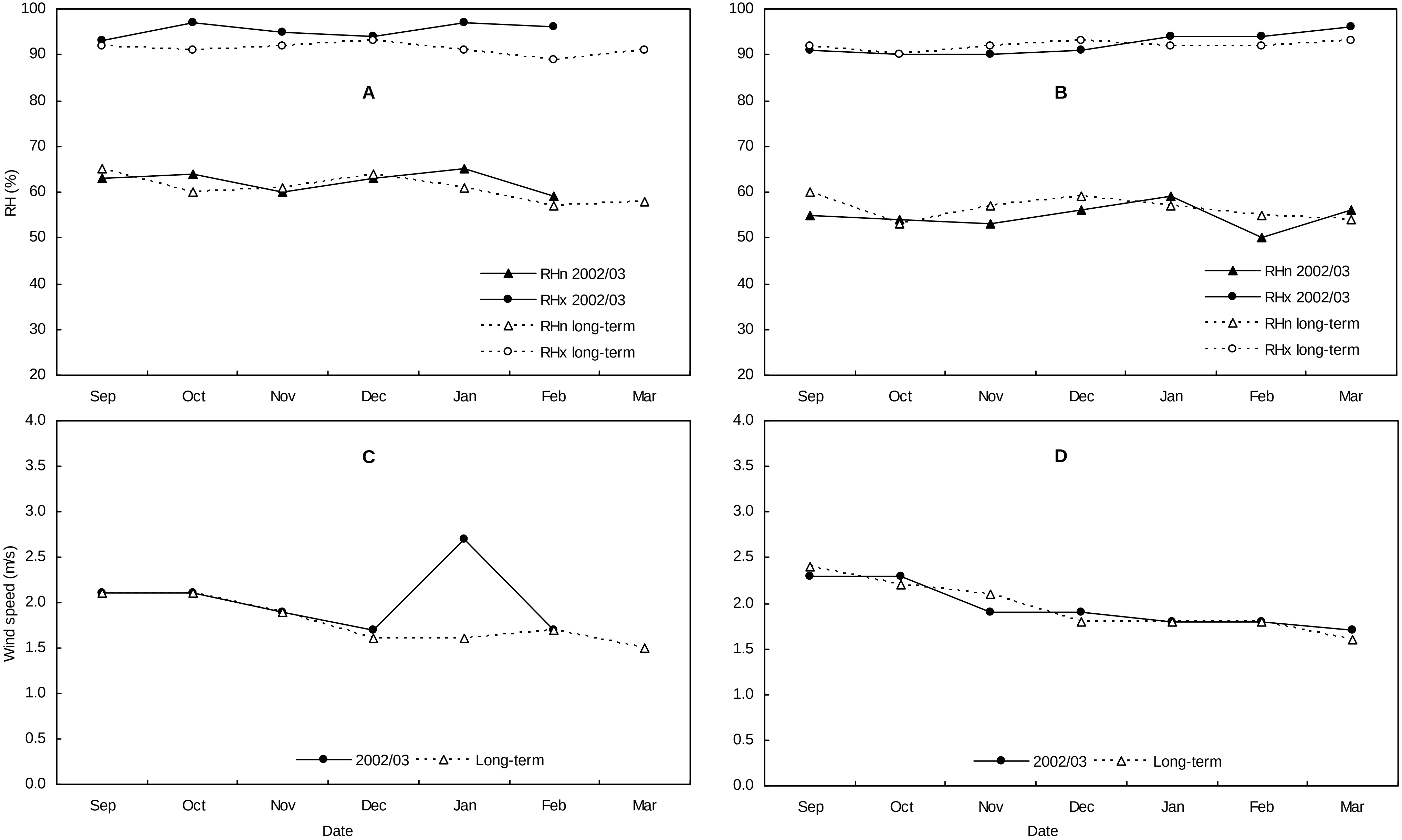

Figure 4.3 Mean monthly maximum (RHx) and minimum (RHn) relative humidity at (A) Helshoogte and (B) Papegaaiberg as well as mean monthly wind speed at (C) Helshoogte and (D) Papegaaiberg as measured during the 2002/03 season in comparison to long-term mean values.

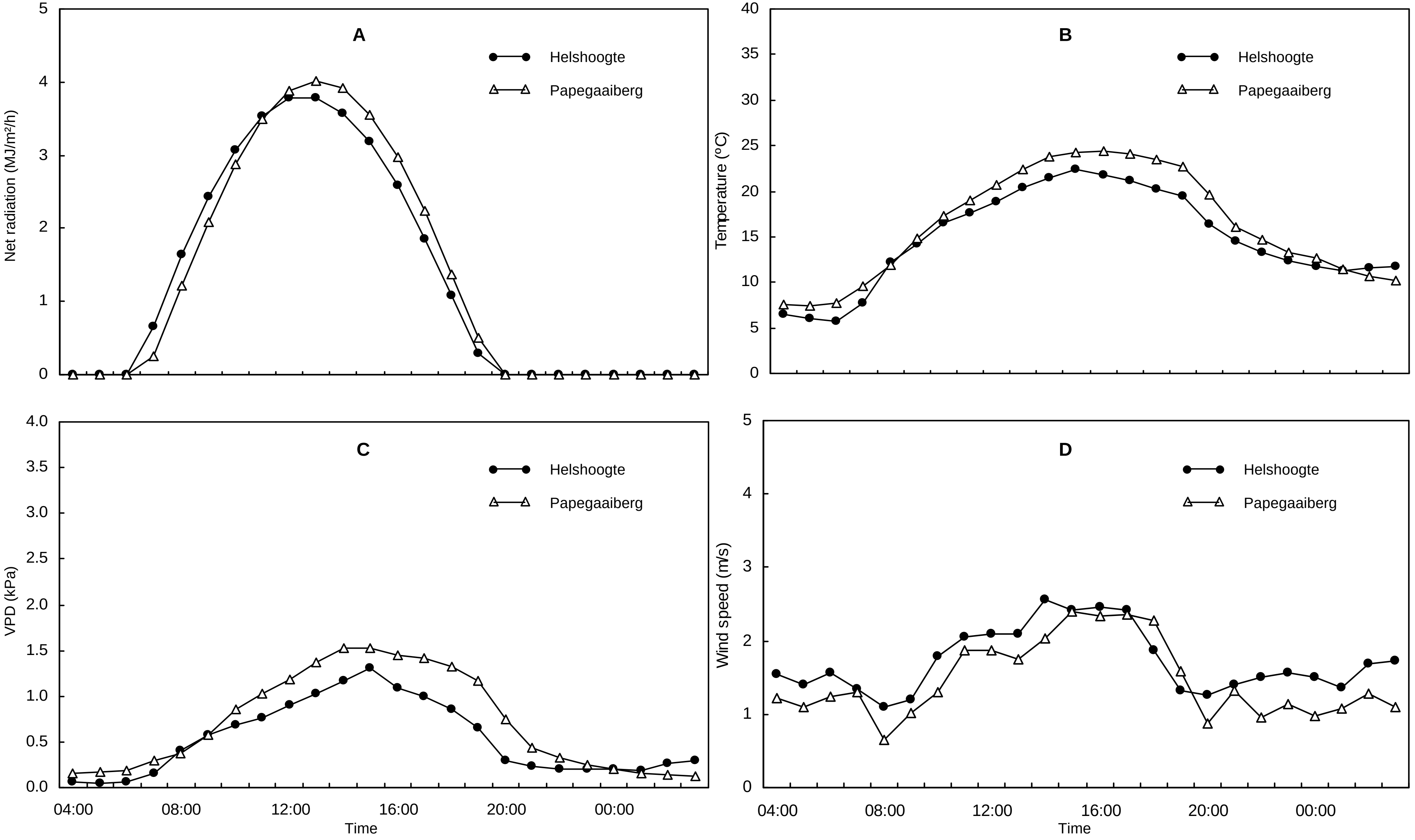

Figure 4.4 Diurnal variation in (A) net radiation, (B) mean air temperature, (C) vapour pressure deficit (VPD) and (D) wind speed as measured at flowering (30 to 31 October 2002) at two localities in the Stellenbosch district.

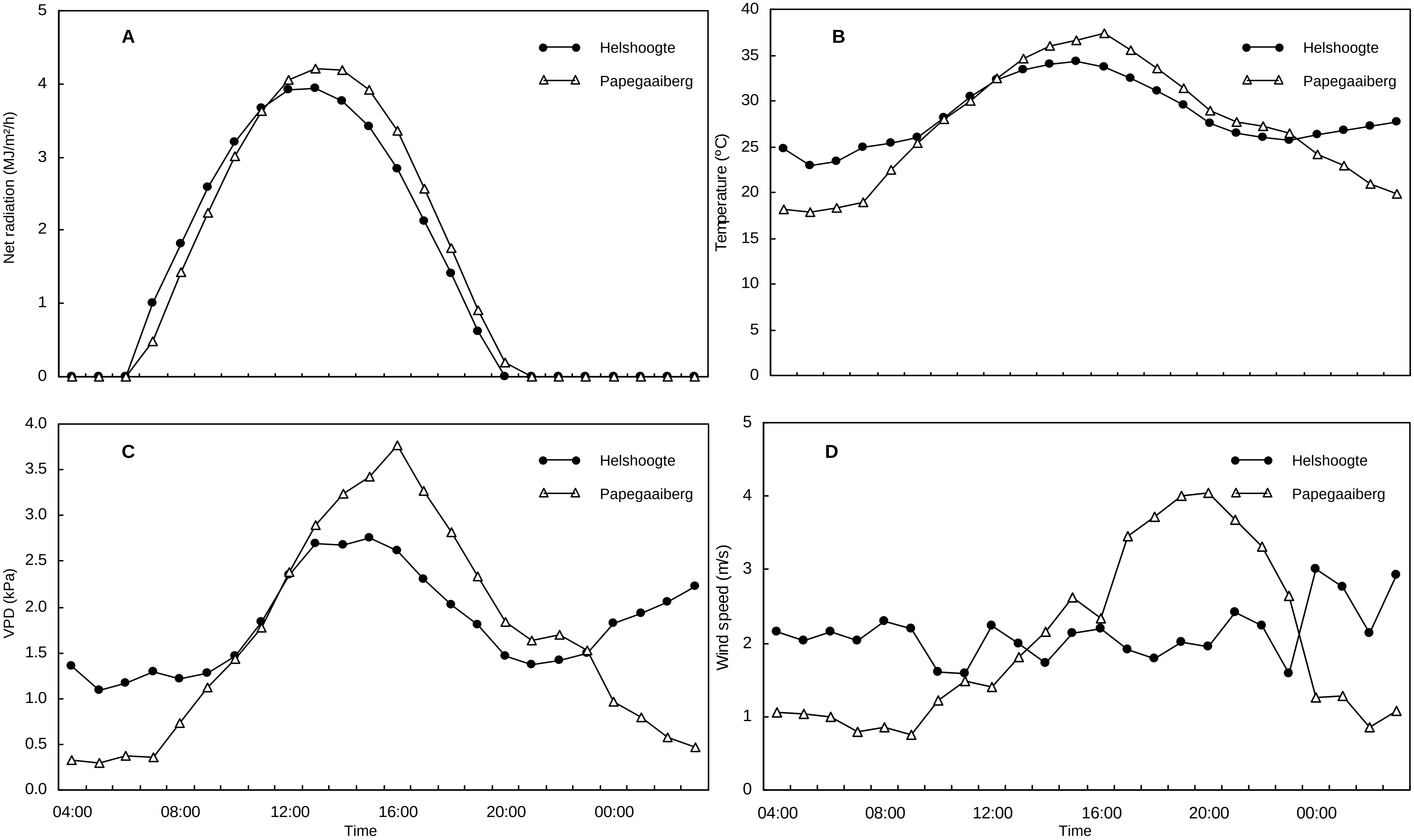

Figure 4.5 Diurnal variation in (A) net radiation, (B) mean air temperature, (C) vapour pressure deficit (VPD) and (D) wind speed as measured at pea size (5 to 6 December 2002) at two localities in the Stellenbosch district.

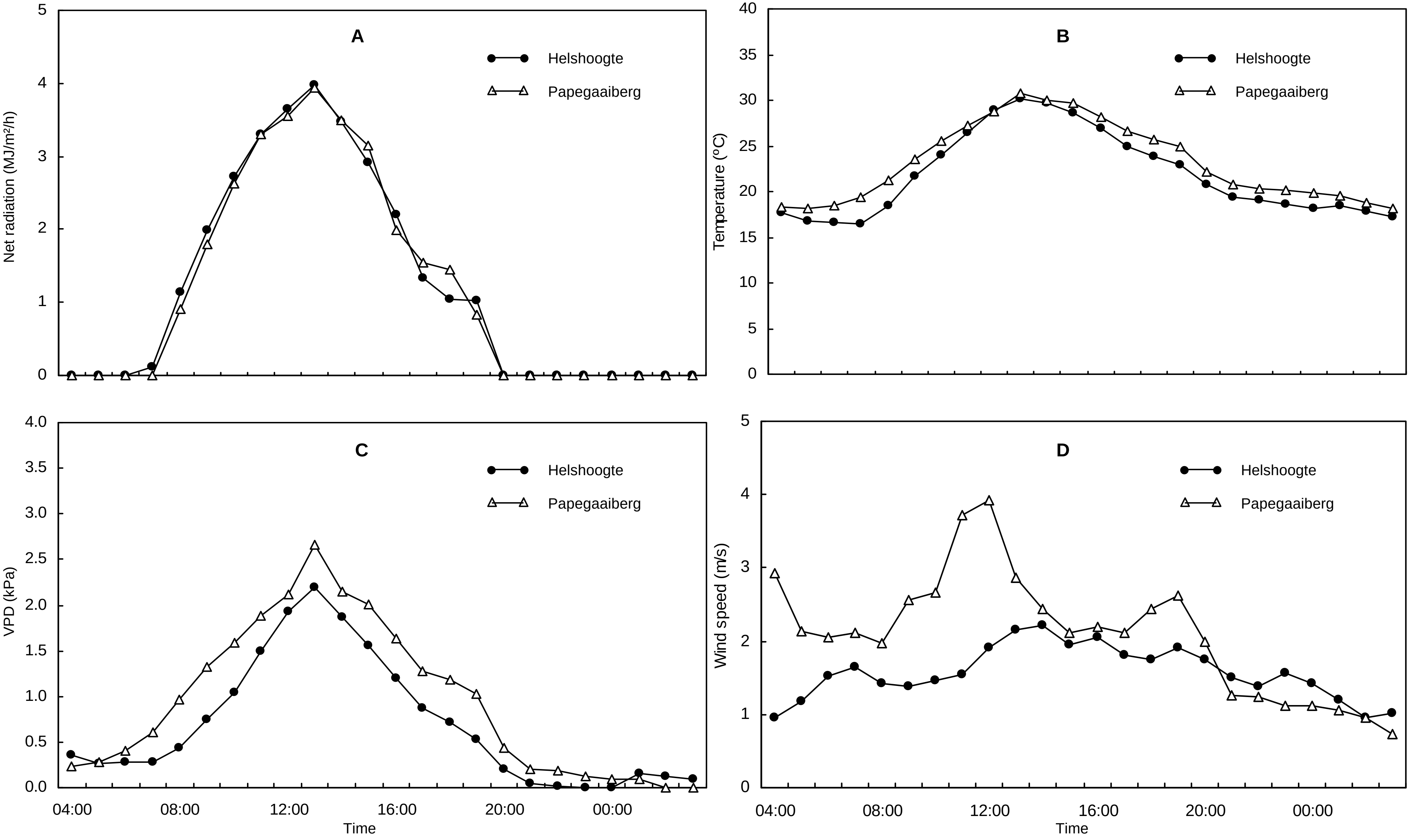

Figure 4.6 Diurnal variation in (A) net radiation, (B) mean air temperature, (C) vapour pressure deficit (VPD) and (D) wind speed as measured during the ripening period prior to harvest (11 to 12 February 2003) at two localities in the Stellenbosch district.

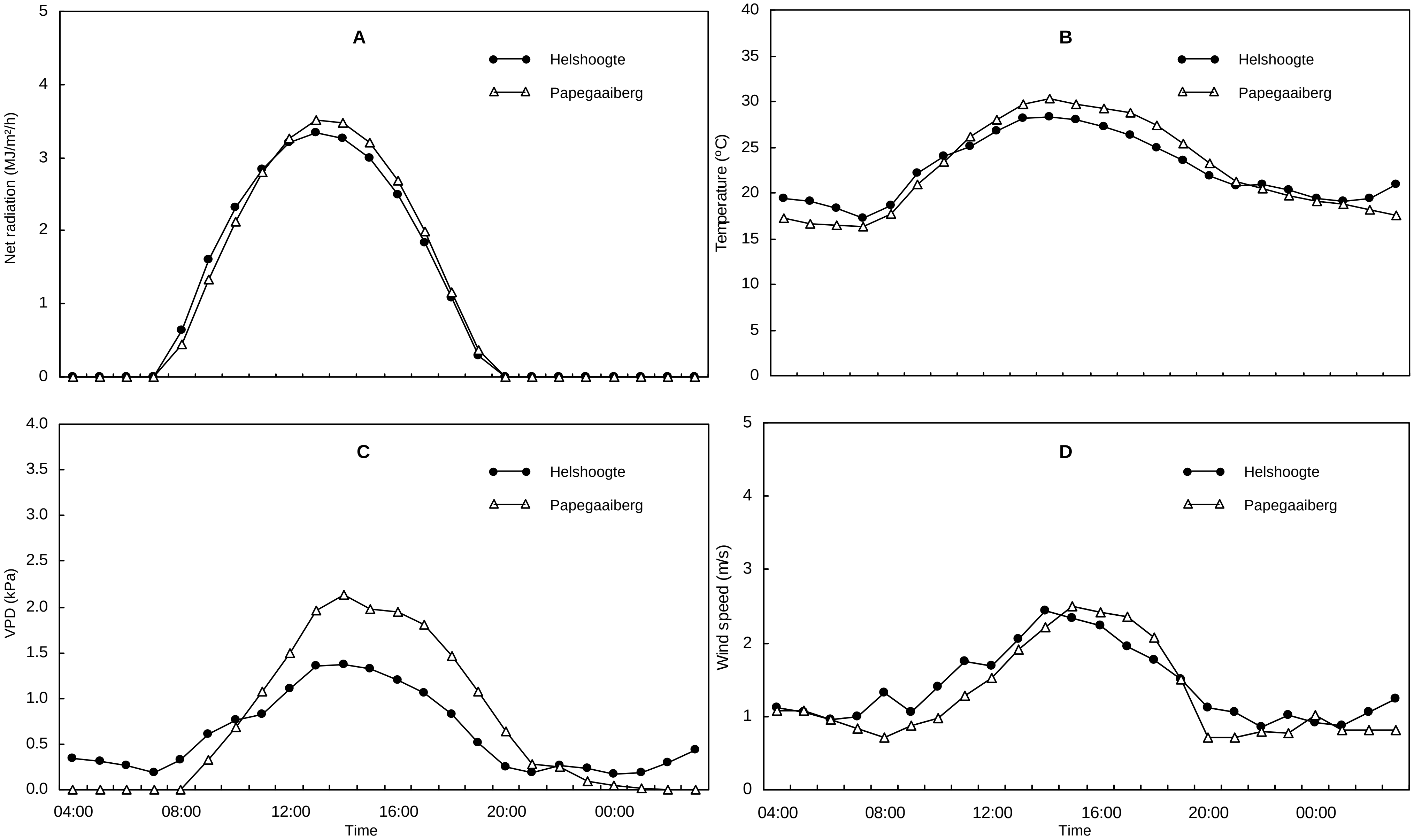

Figure 4.7 Diurnal variation in (A) net radiation, (B) mean air temperature, (C) vapour pressure deficit (VPD) and (D) wind speed as measured in the post harvest period (11 to 12 March 2003) at two localities in the Stellenbosch district.

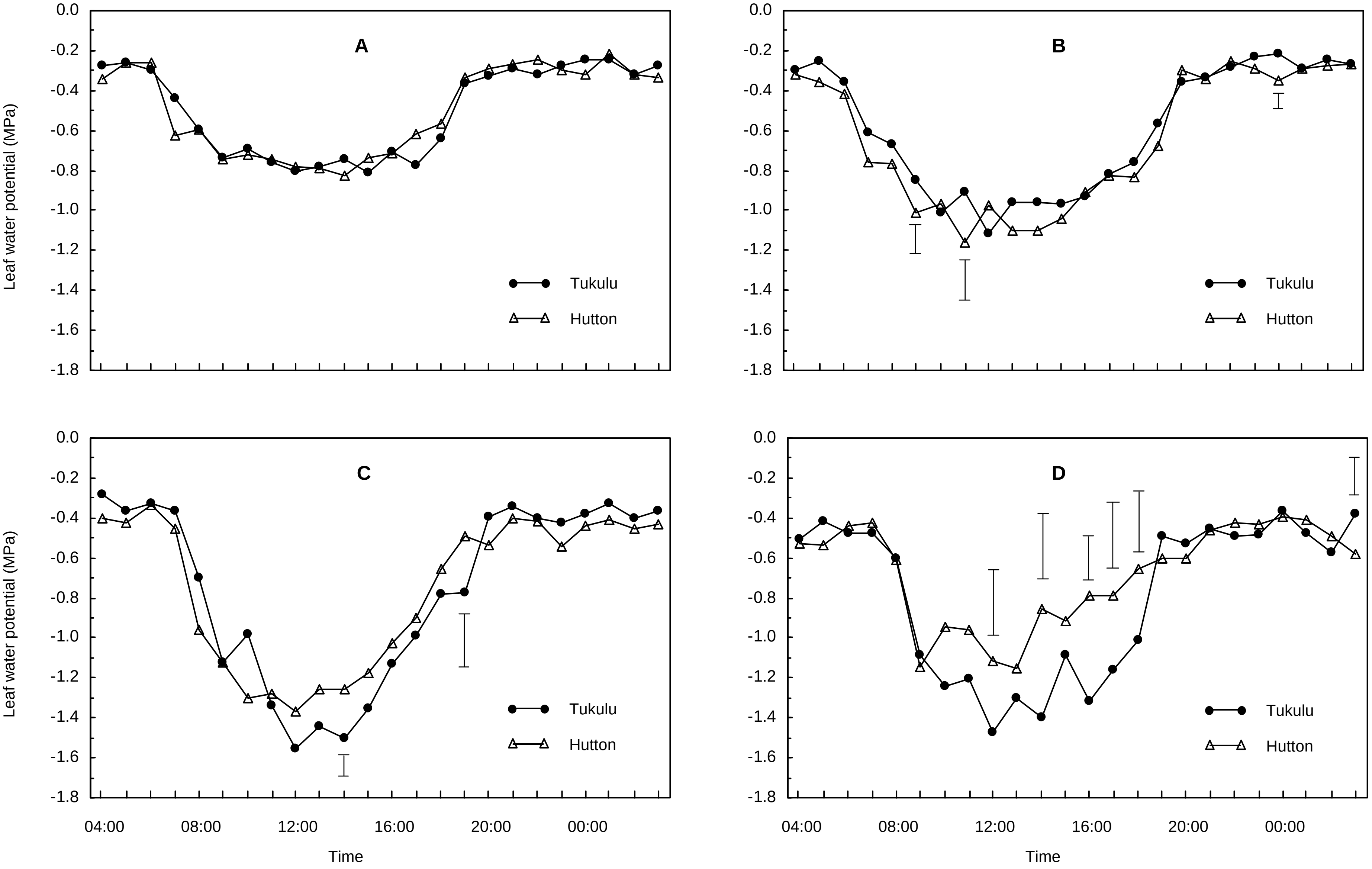

Figure 4.8 Diurnal variation of leaf water potential in Sauvignon blanc at Helshoogte for two soil types measured (A) at flowering, (B) at pea size, (C) during the ripening period prior to harvest and (D) during the post harvest period. Vertical bars designate significant differences ($p \leq 0.05$).

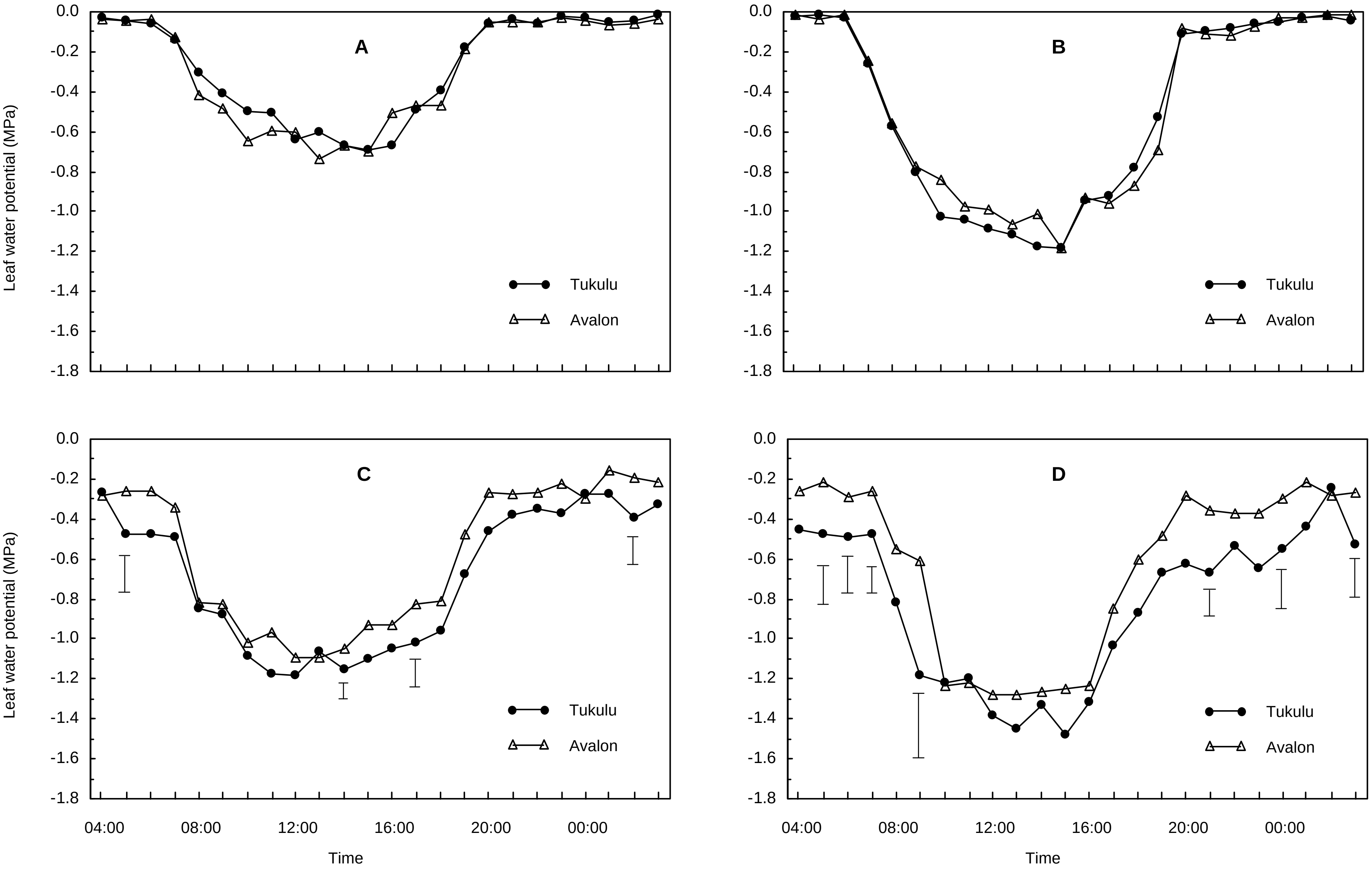

Figure 4.9 Diurnal variation of leaf water potential in Sauvignon blanc at Papegaaiberg for two soil types measured (A) at flowering, (B) at pea size, (C) during the ripening period prior to harvest and (D) during the post harvest period. Vertical bars designate significant differences ($p \leq 0.05$)

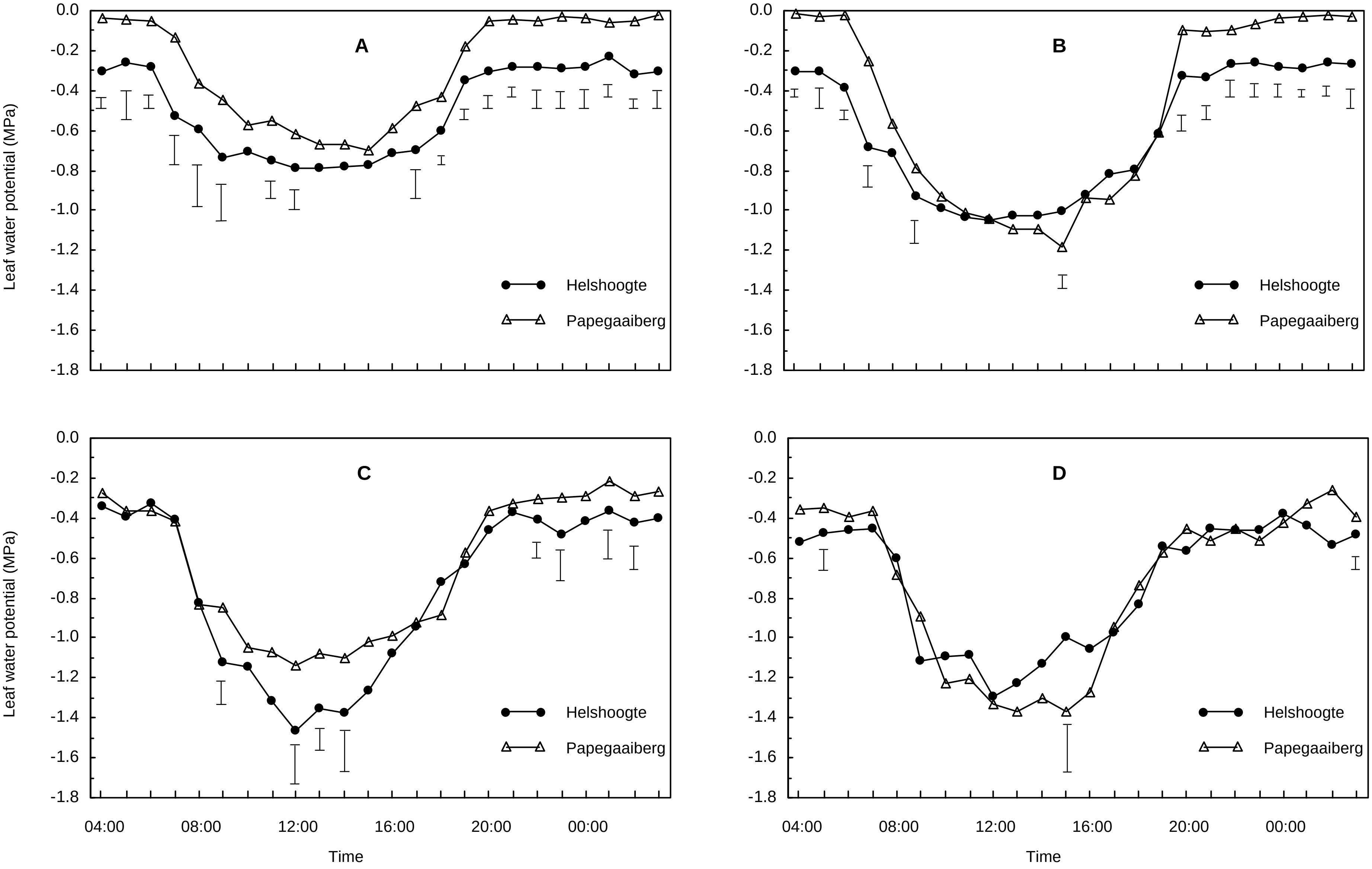

Figure 4.10 Diurnal variation of leaf water potential in Sauvignon blanc at two localities measured (A) at flowering, (B) at pea size, (C) during the ripening period prior to harvest and (D) during the post harvest period. Vertical bars designate significant differences ($p \leq 0.05$).

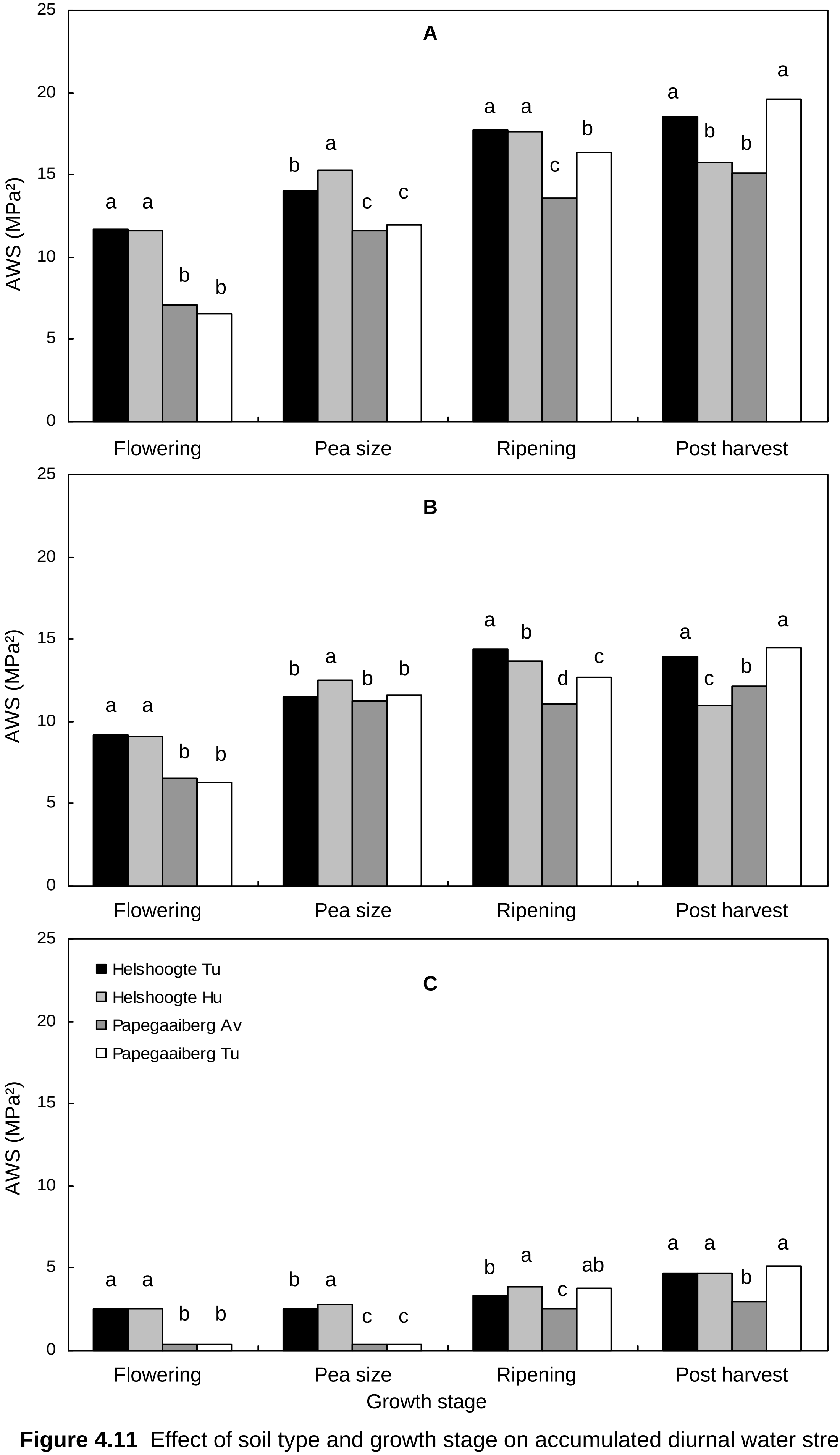

Figure 4.11 Effect of soil type and growth stage on accumulated diurnal water stress (AWS) in Sauvignon blanc grapevines during (A) the full diurnal cycle, (B) the day and (C) the night measured at two localities in the Stellenbosch district. Data for each stage were analysed separately. Values designated by the same letter do not differ significantly ($p \leq 0.05$).

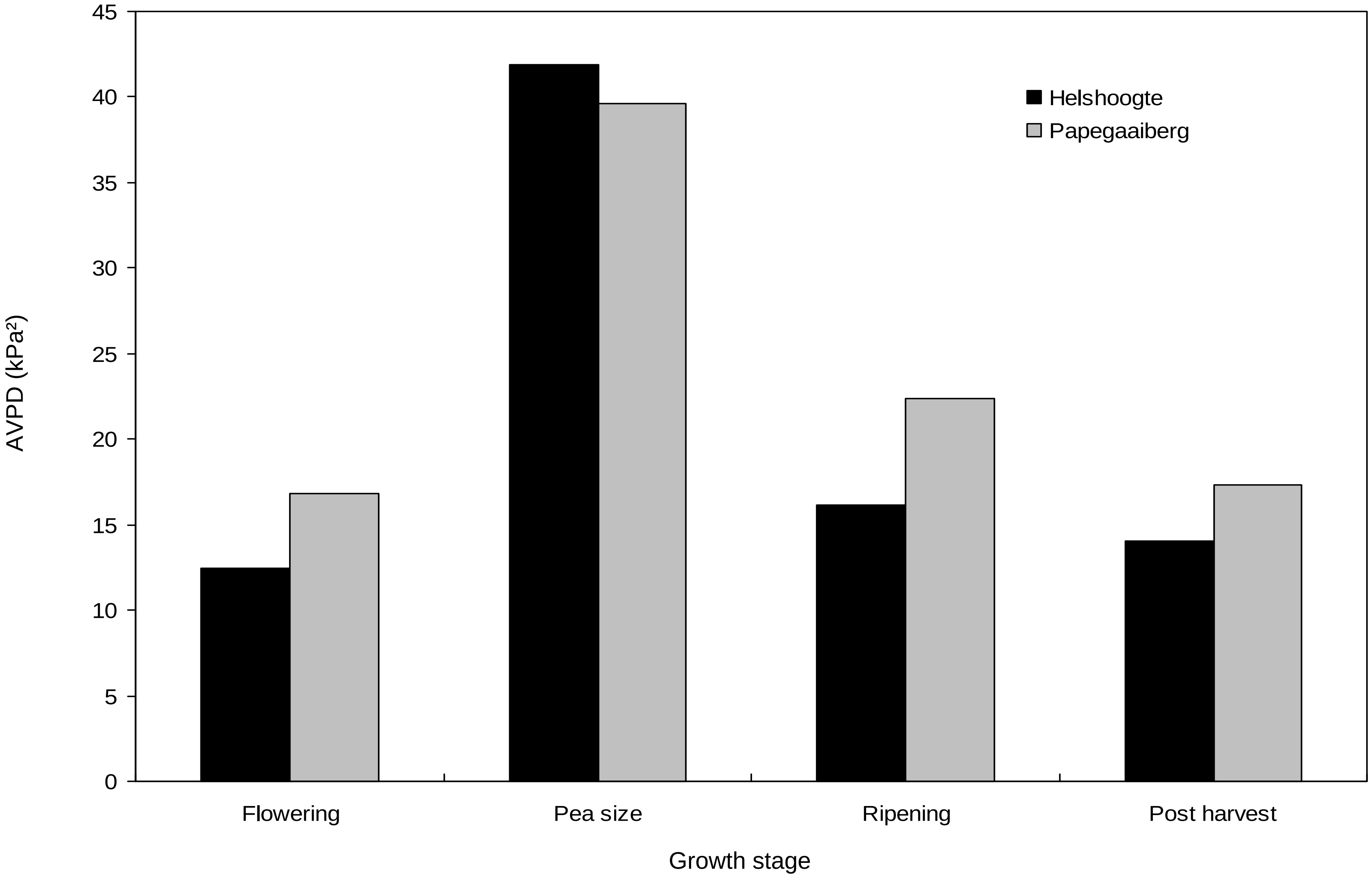

Figure 4.12 Accumulated vapour pressure deficit at different growth stages measured at two localities in the Stellenbosch district.

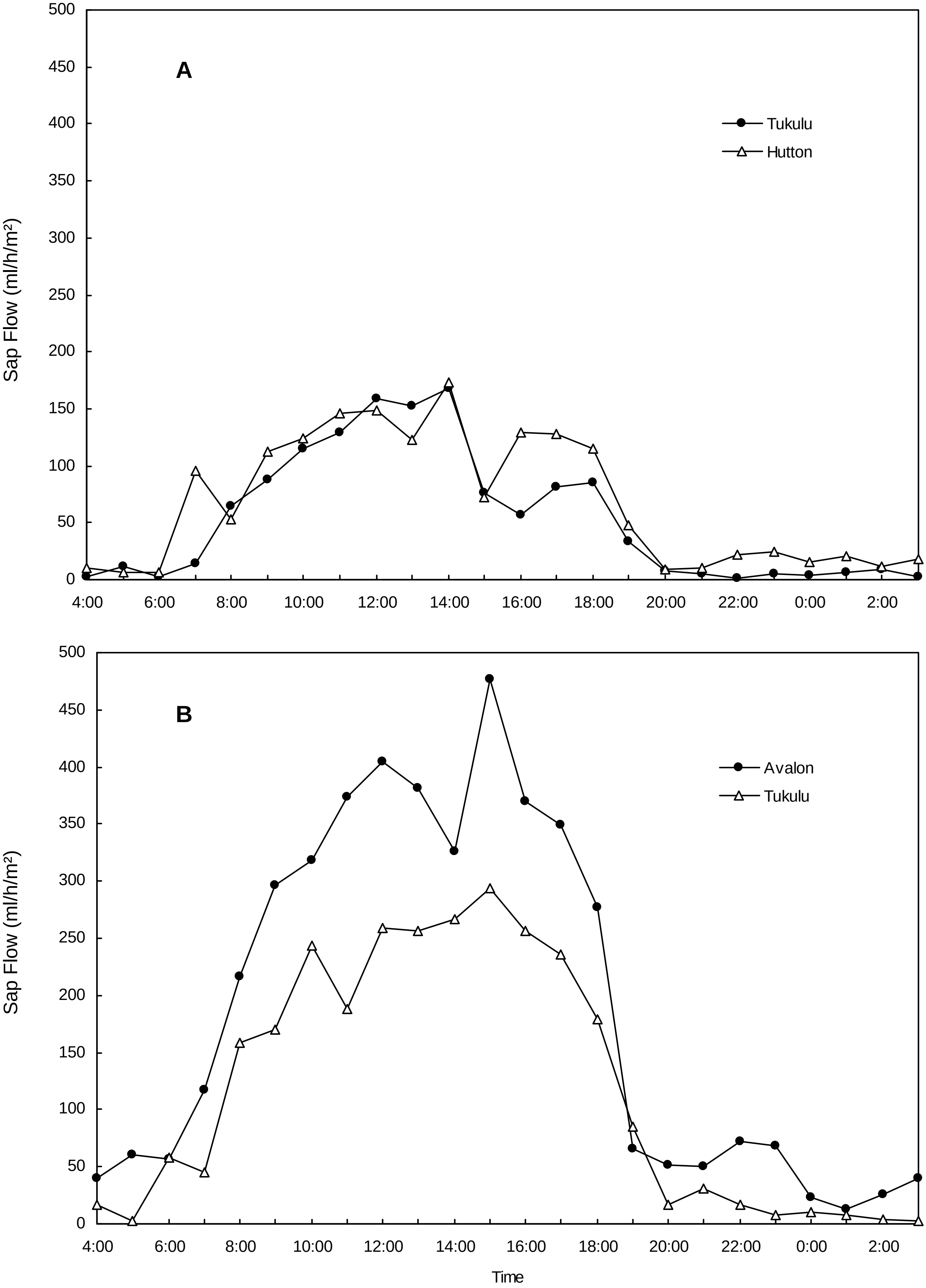

Figure 4.13 Diurnal sap flow in Sauvignon blanc grapevines as measured during flowering (30 to 31 October 2002) on the different soils at (A) Helshoogte and (B) Papegaaiberg in the Stellenbosch district.

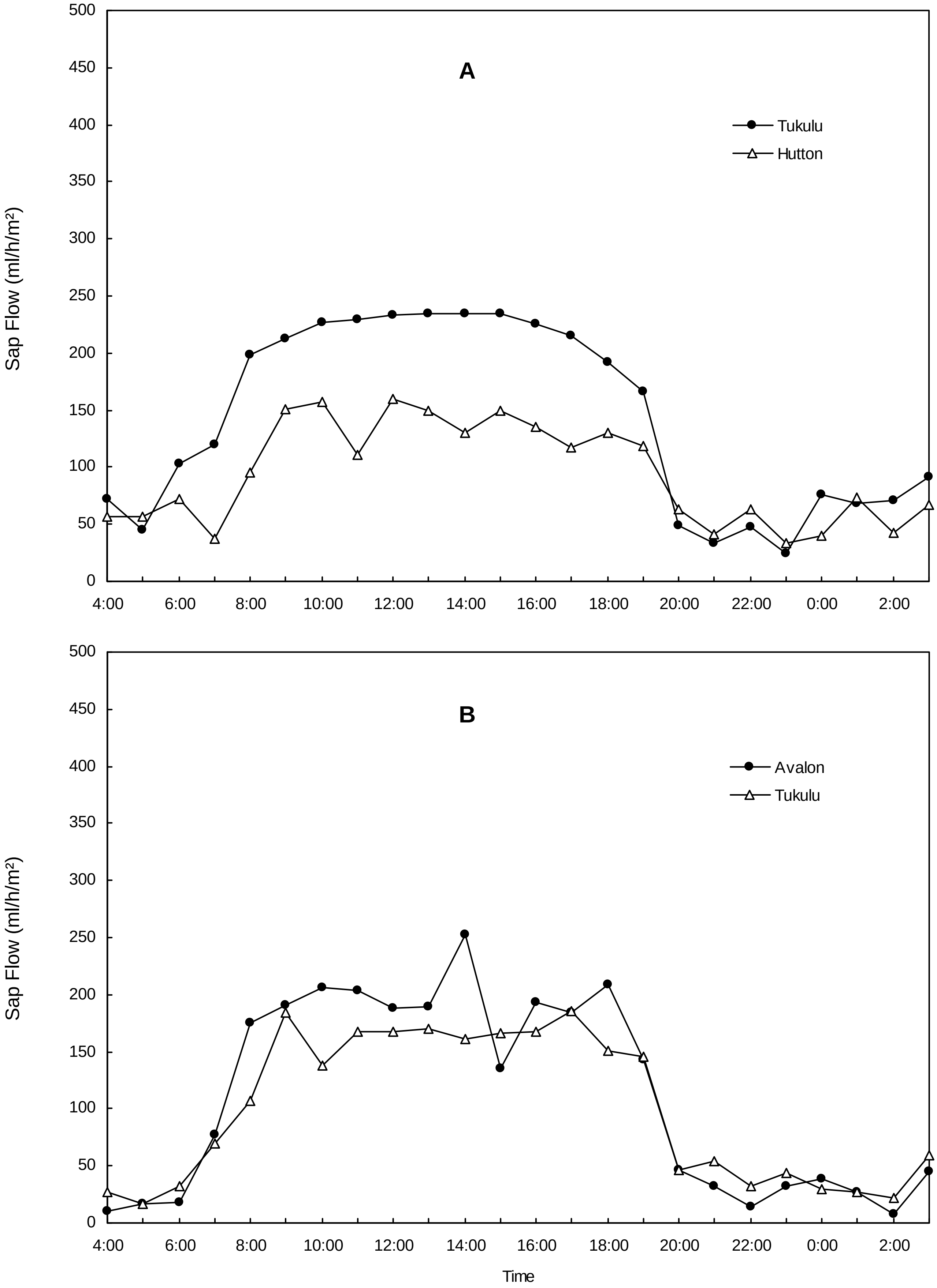

Figure 4.14 Diurnal sap flow in Sauvignon blanc grapevines as measured during pea size (5 to 6 December 2002) on the different soils at (A) Helshoogte and (B) Papegaaiberg in the Stellenbosch district.

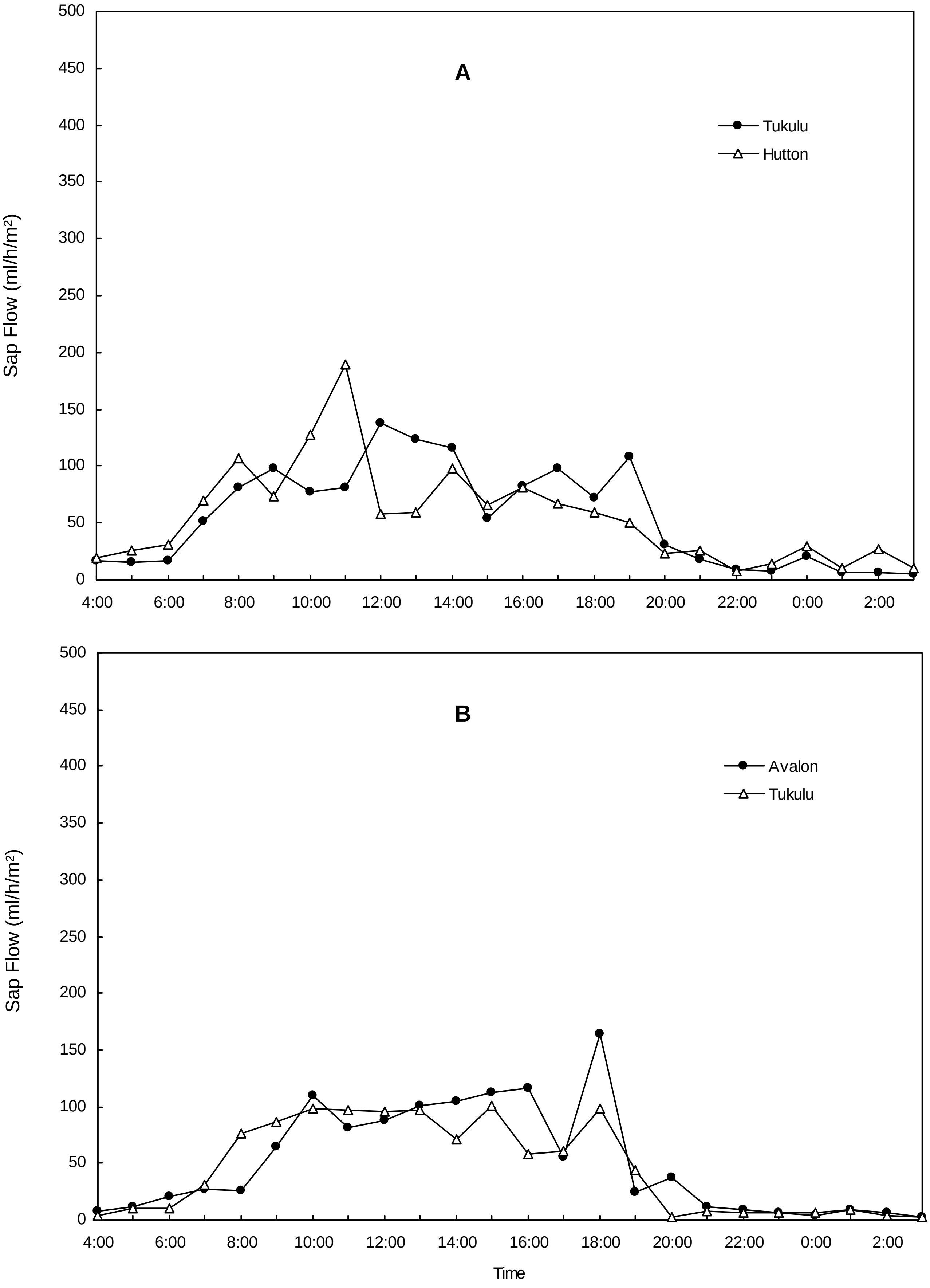

Figure 4.15 Diurnal sap flow in Sauvignon blanc grapevines as measured during harvest (11 to 12 February 2003) on the different soils at (A) Helshoogte and (B) Papegaaiberg in the Stellenbosch district.

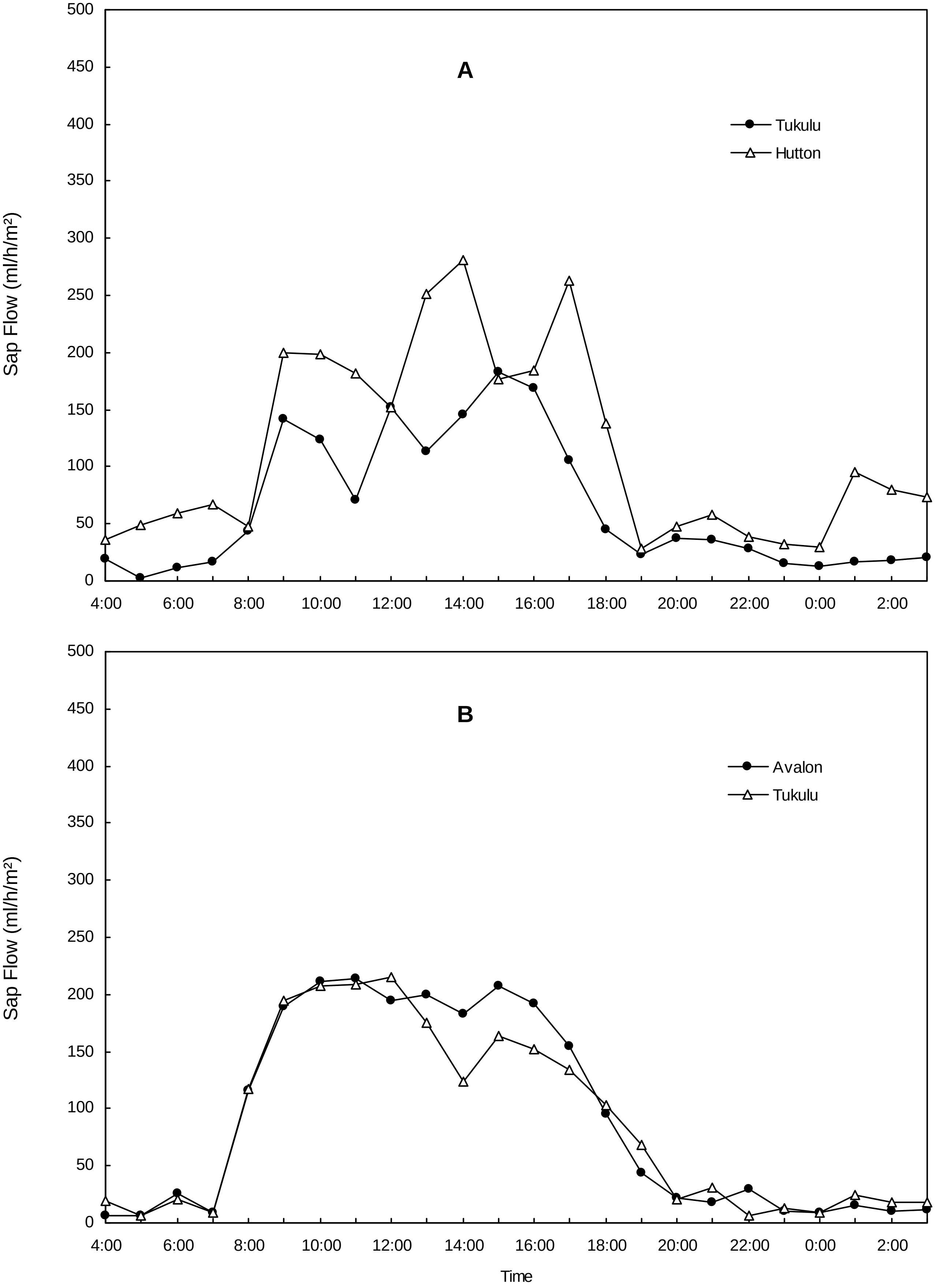

Figure 4.16 Diurnal sap flow in Sauvignon blanc grapevines as measured during the post harvest period (11 to 12 March 2003) on the different soils at (A) Helshoogte and (B) Papegaaiberg in the Stellenbosch district.

CHAPTER 5

CONCLUSIONS

CONCLUSIONS

During the 2002/03 growing season, atmospheric conditions were relatively warm and dry in comparison to the long-term averages of previous seasons. These conditions accentuated the effects of certain soil properties that may not come forward during wetter, normal seasons.

The usually wet Tukulu soil at Helshoogte was drier than expected during the 2002/03 season compared to the Hutton soil. Due to more vigorous growth on the Tukulu soil, grapevines extracted more soil water early in the season, leading to a low Ψ_m and more water stress in the grapevines. Due to the higher vigour, resulting in more canopy shading, and more water stress, the dominant aroma in wines from the Tukulu soil was fresh vegetative. Greater root efficiencies on the Hutton soil because of its more favourable soil physical conditions resulted in grapevines experiencing less water stress than on the Tukulu soil. The Hutton soil maintained consistency with regards to both yield and wine quality compared to previous seasons. On the other hand the Tukulu soil supported a higher yield, but with lower than normal wine quality.

The Avalon soil at Papegaaiberg maintained the highest soil water potential towards the end of the season, probably due to capillary supplementation from the sub-soil. Grapevines on the Tukulu soil at Papegaaiberg experienced much higher water stress than ones on the other three soils, especially during the later part of the season. The Tukulu soil also had higher than normal growth vigour during the 2002/03 season, leading to more canopy shading which resulted in a fresh vegetative aroma in the wine. The high water stress and low yield of grapevines on this soil could be ascribed to a combination of factors, the most important being the severe soil compaction at a shallow depth, seriously limiting rooting depth and root distribution, which is detrimental to grapevine performance.

Both the soil water status and atmospheric conditions played important roles in determining the amount of water stress that the grapevines experienced at different stages. The air temperature and VPD throughout the season were consistently lower at Helshoogte, the cooler terroir, compared to Papegaaiberg, the warmer terroir. At flowering, Ψ_l was lower for grapevines at Helshoogte than at Papegaaiberg, showing that diurnal grapevine water status was primarily controlled by soil water content. The difference in grapevine water status between the two terroirs gradually diminished until it was reversed during the post harvest period when Ψ_l in grapevines at Papegaaiberg tended to be lower compared to those at Helshoogte. The relatively low pre-dawn Ψ_l at Helshoogte indicated that the grapevines were subjected to excessive water stress resulting from the low soil water content. However, grapevines at Helshoogte did not suffer material water stress (*i.e.* $\Psi_l < -1.20$ MPa) during the warmest part of the day, suggesting that partial stomatal closure prevented the development of excessive water stress in the grapevines.

This suggests that low pre-dawn Ψ_l values do not necessarily imply that grapevines will experience more water stress over the warmer part of the day, or *visa versa*. This does not rule out the possibility that side-effects of partial stomatal closure, such as reduced photosynthesis, can have negative effects on grapevine functioning in general. These results also suggest that measurement of diurnal Ψ_l cycles at various phenological stages is required to understand and quantify terroir effects on grapevine water status.