DIURNAL CYCLES OF GRAPEVINE LEAF WATER POTENTIAL UNDER FIELD CONDITIONS

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Key words: Soil water matric potential, diurnal cycles, leaf water potential, accumulated water stress

Abstract

Diurnal cycles of leaf water potential (Ψ_l) were established on an hourly basis at various phenological stages at two localities with different air temperature and vapour pressure deficit (VPD). Lower air temperature and VPD values were recorded consistently throughout the season at the cooler locality. Leaf water potential measurements at flowering showed that Sauvignon blanc grapevines at this cooler locality were subjected to a higher degree of water stress throughout the day compared to grapevines at the warmer locality. At this phenological stage, soil water matric potential (Ψ_m) of the well-drained soil at the cooler locality was *ca* -0.03 MPa compared to *ca* -0.01 MPa at the warmer locality. This suggested that diurnal grapevine water status was primarily controlled by soil water content. The difference in grapevine water status between the two localities gradually diminished as the growth season progressed until the post harvest period when Ψ_l in grapevines at the cooler locality tended to be higher compared to those at the warmer one. The relatively low pre-dawn Ψ_l at the cooler locality during this measurement cycle indicated that the grapevines were exposed to excessive water stress as a result of the low soil water content (*i.e.* Ψ_m = -0.77 MPa). Partial stomatal closure in grapevines at the cooler locality, however, prevented excessive water stress (*i.e.* Ψ_l < -1.2 MPa) during the warmest part of the day compared to grapevines at the warmer terroir where almost no stomatal control occurred.

It appears from these results that low pre-dawn Ψ_l values do not necessarily imply that grapevines will experience more water stress during the warmest part of the day, or *vice versa*. Hence, determination of daily water status cycles, as well as the accumulated water stress over the full diurnal cycle at various phenological stages is invaluable in order to understand and quantify terroir effects on grapevine water status.

Resumé

Les cycles journaliers du potentiel hydrique foliaire (Ψ_l) ont été établis toutes les heures, pour différents stades phénologiques, sur deux localités et en fonction de différentes mesures de la température de l'air et du déficit en pression de vapeur (VPD). De faibles valeurs pour ces 2 paramètres ont été enregistrées tout au long de la saison à l'endroit le plus frais. Les mesures du potentiel hydrique foliaire obtenues au stade floraison montrent que les vignes de Sauvignon blanc à l'endroit le plus frais, ont subi un stress hydrique plus important au cours de la journée par rapport aux vignes situées à l'endroit plus chaud. De plus le potentiel hydrique du sol (Ψ_m) obtenu sur les sols bien drainés de la localité plus fraîche, à ce même stade, était d'environ -0.03 MPa comparés au -0.01 MPa de la localité plus chaude. Ceci laisse à penser que le statut hydrique de la vigne durant la journée est d'abord contrôlé par la teneur en eau du sol. Les différences de statut hydrique entre les deux endroits diminuent progressivement durant la phase de croissance végétative et ce, jusqu'à la période suivant les vendanges durant laquelle le potentiel foliaire obtenu à l'endroit plus frais devenait supérieur à celui obtenu à l'endroit plus chaud. Les valeurs relativement faibles du potentiel hydrique obtenues à l'aube à l'endroit plus frais, indiquent que les vignes étaient exposées à un important stress hydrique comme le montre la faible teneur en eau du sol (Ψ_m= -0.77 MPa). La fermeture stomatique partielle observée sur les vignes de l'endroit plus frais, ont permis d'éviter de trop sévères stress hydriques (Ψ_l < -1.2 MPa) durant les plus chaudes heures de la journée. Cependant ce mécanisme de résistance fut à peine observé à l'endroit plus chaud.

On peut donc conclure sur ces résultats, qu'un faible potentiel hydrique obtenu à l'aube, ne conduira pas forcément à un stress hydrique plus important durant les plus chaudes heures de la journée, et *vice versa.* La détermination des cycles hydriques journaliers, ainsi que le stress hydrique observés sur une journée entière à différents stades phénologiques sont donc indispensables si l'on veut comprendre et quantifier l'effet du terroir sur le statut hydrique de la vigne.

Introduction

The South African Wine Industry is compelled to increase wine quality because of increasing competitive national and international markets (Hunter & Myburgh, 2001). Wine grape quality depends on both the grape 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 of totally 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 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. The measurement of grapevine water status is therefore important if the cultivar x terroir interaction is to be better understood (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. Measuring 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. Under comparable atmospheric conditions leaf water potential is normally well related to soil water content (Williams *et al*., 1994), as well as to soil water matric potential (Van Zyl, 1987). Pre-dawn or covered leaf water potential is usually preferred for detection of the 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 each 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 clear (Saayman, 1977). That soil has marked effects on grapevine performance, phenological characteristics and production is commonly observed 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 which exists between them (Saayman, 1977).

The aim of this study was to (i) determine the level of water stress of grapevines on each soil at each locality over the full diurnal cycle, and (ii) determine the effect of the atmospheric conditions and the soil water status on the level of water stress in the grapevines.

Materials and Methods

The experiment was conducted during the 2002/03 season in two, 20-year old Sauvignon blanc vineyards in the Stellenbosch district. The vineyards were at Helshoogte and Papegaaiberg, approximately 9 km apart. Two experiment plots (approximately 60 m apart) with contrasting soil types in terms of soil water regime were selected in each vineyard. At Helshoogte the two soils represented the Tukulu (Entunja family) and Hutton (Hayfield family) forms, respectively (Van Schoor, 2001). The soils at Papegaaiberg were of the Avalon (Vryheid family) and Tukulu (Mostertshoek family) forms, respectively.

Air temperature, rainfall, relative humidity, precipitation, net radiation as well as wind speed and direction were recorded by means of automatic weather stations (MC Systems, Cape Town). These were erected midway between the two plots at each locality. Vapour pressure deficit (VPD) was calculated from data recorded by the automatic weather stations.

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 determined by taking hourly measurements at each site. Measurements were made between 04:00 and 03:00 on days which fell within the four main growth stages (flowering, pea size, 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:

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

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

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.

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.

Results and Discussion

Lower air temperatures and VPD values were consistently recorded throughout the season at the cooler locality, Helshoogte, compared to Papegaaiberg. At Papegaaiberg the vineyard consistently received more radiation, and temperatures were higher than those at Helshoogte. This observation was consistent with the fact that the Papegaaiberg vineyard rested on a north-west facing slope at low altitude (148 m), whereas the Helshoogte vineyard faced south-east and were located at an appreciably greater altitude. During the 2002/03 growing season less rainfall occurred than the long-term mean at both localities. The relatively dry growing season of 2002/03 was, however, preceded by a winter with normal rainfall.

During flowering there were no significant differences in the diurnal Ψ_l in grapevines from the two different soils at Helshoogte, and grapevines experienced the same amount of water stress at this stage, as could be seen from the accumulated diurnal water stress (Fig. 1). Since the Ψ_m of the two soils were similar at this stage (Fig. 2), 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 the period of measurement.

During the diurnal Ψ_l cycle at flowering there was also no significant difference in the accumulated diurnal water stress between grapevines on the Avalon and Tukulu soils at Papegaaiberg, respectively (Fig. 1). Since the Ψ_m of both soils were still high at this time (Fig. 2), and the air temperatures and VPD were low, the grapevines at Papegaaiberg did not experience significant water stress at this stage.

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 during most of the diurnal cycle (Fig. 3), even though the accumulated VPD and the air temperature 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. 1). 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 levels of water stress that would have negatively affected grapevine functioning.

At pea size (5 to 6 December), both the soils at Helshoogte were still relatively wet (Fig. 2). The pre-dawn Ψ_l was approximately -0.30 MPa in grapevines on both soils. The diurnal Ψ_l of grapevines on the Tukulu and Hutton soils tended to be similar and the only significant difference was at 09:00, 11:00 and 24:00 (Fig. 4). However, grapevines on the Hutton soil experienced significantly more accumulated diurnal water stress than those on the Tukulu soil (Fig. 1). 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 (Fig. 4). 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 slight increase in Ψ_l at 10:00 and at 12:00 suggested that several stomatal control cycles occurred to prevent excessively high Ψ_l in the grapevines (Fig. 4). 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 an increase at 11:00, Ψ_l in grapevines on the Tukulu soil at Helshoogte seemed to follow the normal diurnal pattern.

The accumulated diurnal water stress in grapevines on the Avalon and Tukulu soils did not differ significantly (Fig. 1). The grapevines at Helshoogte still seemed to experience significantly more accumulated water stress during pea size than the ones at Papegaaiberg (Fig. 1). The VPD, as well as the air temperature, were very high during this day, and this shows that even when there is still enough soil water available (Fig. 2), harsh atmospheric conditions can induce water stress in grapevines.

During the diurnal Ψ_l cycle measured prior to harvest the grapevines on the Tukulu soil at Papegaaiberg were subjected to slightly more water stress than those on the Avalon soil (Fig. 5). 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 only experienced significantly more water stress than grapevines on the Avalon soil at 05:00, 14:00 and 02:00. Grapevines on the Avalon soil 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. Due to the lower Ψ_m of the Tukulu soil at this stage (Fig. 2), 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 than for grapevines on the Avalon soil

(Fig. 1). The atmospheric conditions were milder than during pea size, *i.e.* lower air temperatures and VPD's, which indicated that the more severe water stress was a result of the low soil water status. The accumulated diurnal water stress during the ripening period prior to harvest did not differ significantly in grapevines on the Tukulu and Hutton soil at Helshoogte (Fig. 1).

Grapevines at Helshoogte continued to experience more accumulated water stress compared to those at Papegaaiberg during ripening (Fig. 1). At this stage, the soils at both localities had become significantly drier compared to the first part of the season. However, Ψ_m of the two soils at Helshoogte was considerably lower compared to the two soils at Papegaaiberg (Fig. 2).

During the post harvest period the accumulated water stress (Fig. 1) showed that grapevines on the Tukulu soil at Helshoogte experienced significantly more water stress than grapevines on the Hutton soil. 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 (Fig. 2) 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 the more vigorous growth of grapevines on this soil, extracting more water compared to the less vigorous grapevines on the Hutton soil. This illustrated that soil water status dominated grapevine water stress compared to atmospheric conditions.

The Ψ_m of all four soils were considerably lower during the post harvest period than during the previous cycles (Fig. 2). 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, higher accumulated water stress values were obtained (Fig. 1). The total accumulated water stress of grapevines on the Tukulu soil at Papegaaiberg were significantly more than in those on the Avalon soil (Fig. 1). 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. 6). The pre-dawn Ψ_l was, however, still lower in the grapevines at Helshoogte. The 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.* $\Psi_l < -1.20$ 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 atmospheric conditions of the locality (Carey *et al.*, 2004). Since Papegaaiberg had slightly higher temperatures and higher VPD during the midday than Helshoogte, 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.

Conclusions

The 2002/03 growing season at the localities studied, was relatively hot and dry in comparison to the long-term average. These atmospheric conditions accentuated the effects of certain soil properties that may not be expressed 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. 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. 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.

During the Ψ_l cycle measurement at pea size the air temperatures and VPD were extremely high and grapevines experienced water stress, 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 accumulated water stress of grapevines on all the soils were higher 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 lower compared to those 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. 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. Hence, determination of daily water status cycles, as well as the accumulated water stress over the full diurnal cycle at various phenological stages is required to understand, and quantify terroir effects on grapevine water status.

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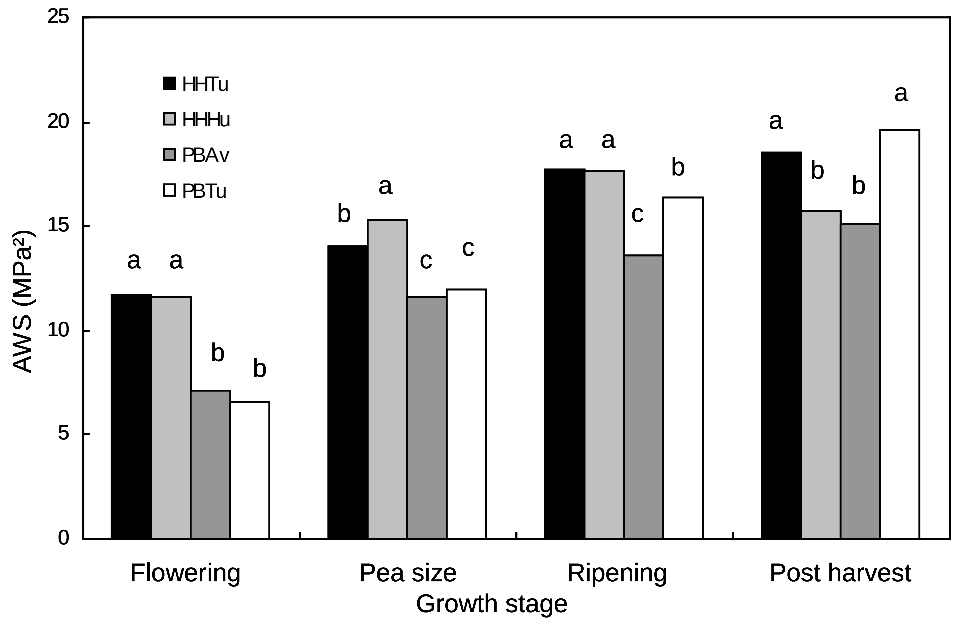

Figure 1 Effect of soil type (Helshoogte Tukulu = HHTu; Helshoogte Hutton = HHHu; Papegaaiberg Avalon = PBAv; Papegaaiberg Tukulu = PBTu) and growth stage on accumulated diurnal water stress (AWS) in Sauvignon blanc grapevines during the diurnal cycle measured at two localities in the Stellenbosch district. Data for each stage were analysed separately. Values designated by the same letter do not differ significantly ($p \leq 0.05$).

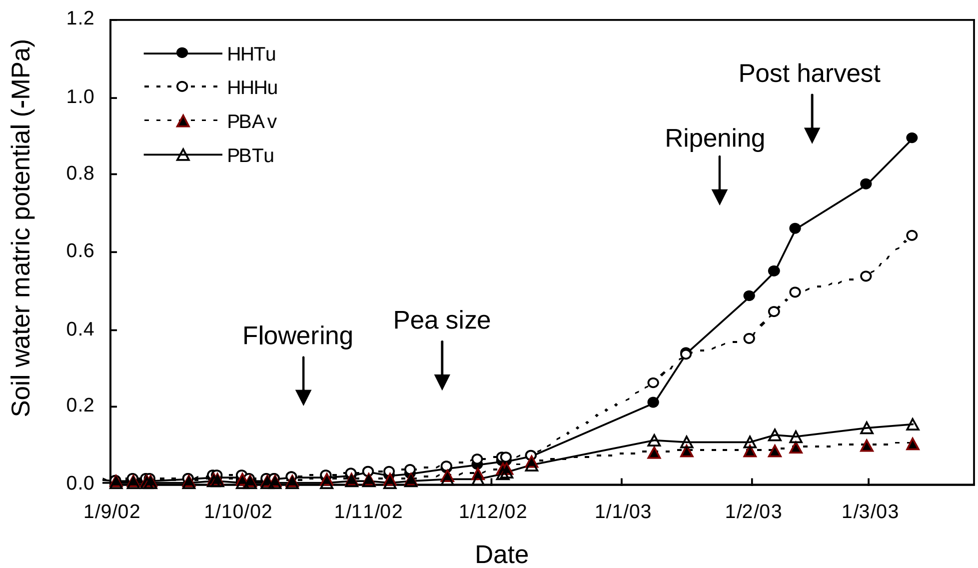

Figure 2 Variation in soil matric potential during the 2002/03 season at Helshoogte for the Tukulu (HHTu) and the Hutton soils (HHHu), as well as at Papegaaiberg for the Avalon (PBAv) and the Tukulu soils (PBTu). Arrows indicate when diurnal cycles were measured.

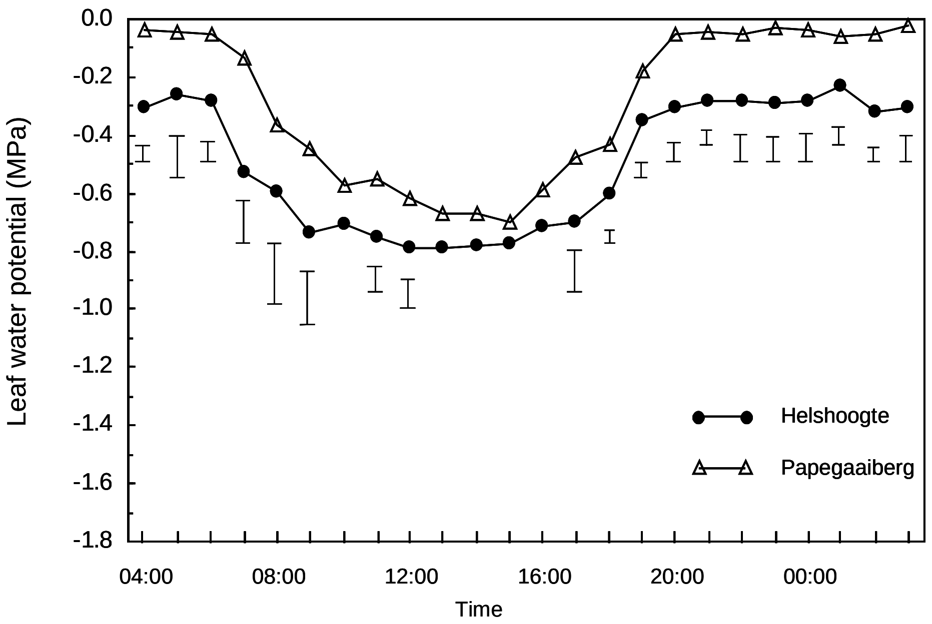

Figure 3 Diurnal variation of leaf water potential in Sauvignon blanc at two localities measured at flowering. Vertical bars designate significant differences ($p \leq 0.05$).

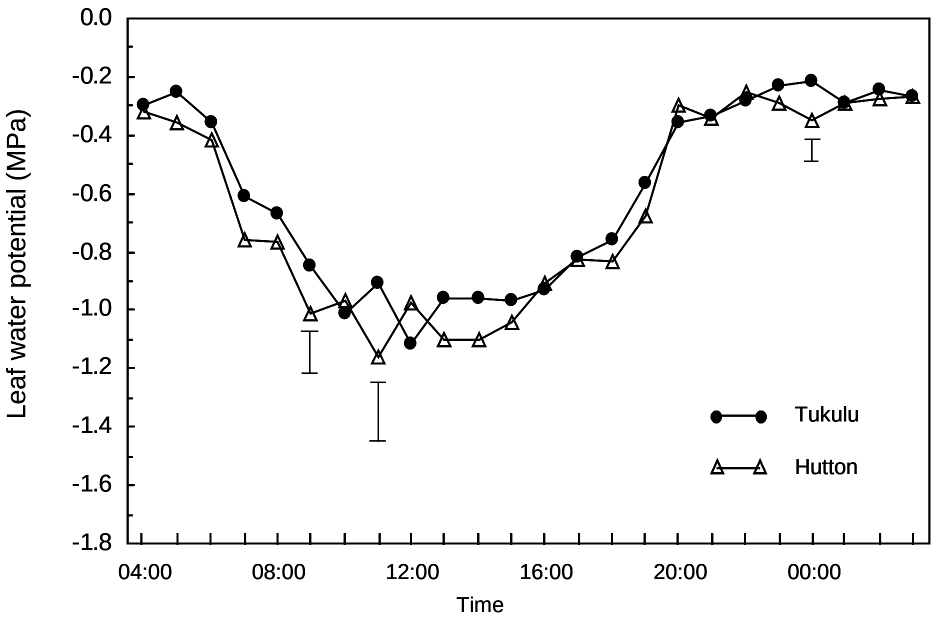

Figure 4 Diurnal variation of leaf water potential in Sauvignon blanc at Helshoogte for two soil types measured at pea size. Vertical bars designate significant differences ($p \leq 0.05$).

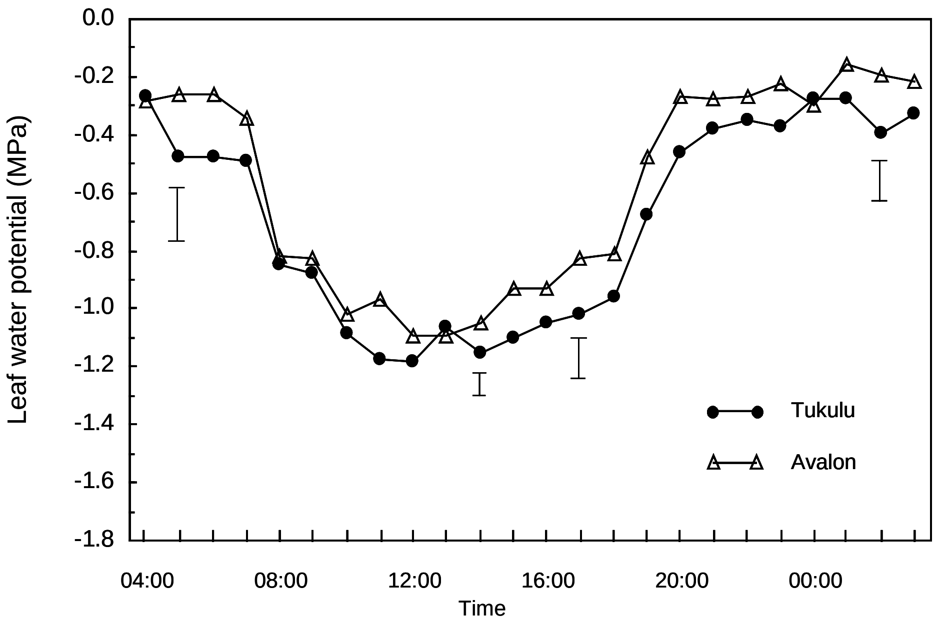

Figure 5 Diurnal variation of leaf water potential in Sauvignon blanc at Papegaaiberg for two soil types measured during the ripening period prior to harvest. Vertical bars designate significant differences ($p \leq 0.05$).

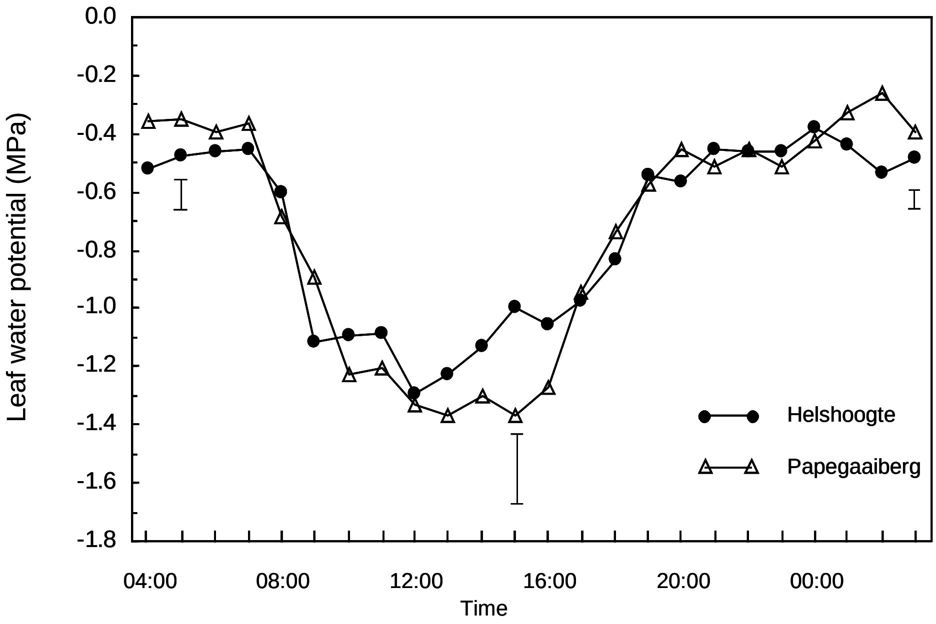

Figure 6 Diurnal variation of leaf water potential in Sauvignon blanc at two localities measured during the post harvest period. Vertical bars designate significant differences ($p \leq 0.05$).