Using Grapevine Water Status Measurements for Irrigation Scheduling of Table Grapes - A Review

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Water is becoming an increasingly scarce resource, so agriculture competes with urban and industrial needs for water. The production of table grapes with high export potential is the objective of South African producers. Vegetative growth, production, ripening aspects and quality parameters of table grapes can potentially be manipulated by means of irrigation. Consequently, it is an important management practice to help ensure economically viable table grape production. The objective for optimum irrigation scheduling should be to combine soil and plant water status measurements to calibrate grapevine water potential against reliable soil water monitoring instruments. Considering previously reported literature, poorer vegetative growth was related to lower levels of leaf water potential (Ψ_L). Given that berry size is a crucial aspect for yield as well as quality, it was evident that low levels of water potential can restrict berry development, thereby reducing berry size. Bunch mass was lower where there were lower levels of Ψ_L and pre-dawn leaf water potential (Ψ_{PD}). Poorer yield was generally related to lower levels of Ψ_L experienced throughout the season. However, lower levels of Ψ_L in the post-véraison period did not affect grapevine yield. The juice total soluble solids (TSS) did not respond to levels of Ψ_L but juice total titratable acidity (TTA) was related to lower levels of Ψ_L. Grape colour was affected where wet soil conditions induced higher levels of Ψ_L as well as where dry soil conditions induced lower levels of Ψ_L.

INTRODUCTION

Water is becoming an increasingly scarce resource. Furthermore, agriculture has to compete with urban and industrial needs for water. Climate changes could lower rainfall which would reduce natural water resources and higher air temperatures could increase the water requirements of table grapes. Even if climate change does not realise, table grape growers still need to use irrigation water more efficiently, *i.e.* to maintain existing yields using less water, or to produce more grapes with the water available. Therefore, it is important to distinguish between over-irrigation and the right amount of water, particularly in the case of table grapes. Grapevine water status classifications for high levels of plant available water (PAW) will enable table grape growers to identify situations where over-irrigation occurs. Applying less water, but without the risk of yield and/or quality losses, could result in huge electricity savings if less water has to be pumped. This is an important consideration in light of the proposed steep increases in electricity costs in the future.

The production of table grapes with high export potential is the objective of producers in South Africa. The export of table grapes also earns valuable foreign valuta. Therefore, high yields of tasty grapes with an attractive appearance have to be produced. Many factors, notably climate, soil, water and vineyard management can influence the growth and yield of export table grapes (Pérez-Harvey, 2008). Water and nutrients are essential for plant growth and yield (Keller, 2005). Therefore, growth, production, ripening and quality parameters of table grapes can potentially be manipulated by means of irrigation and nutrients (Howell & Conradie, 2013; Howell *et al.*, 2013). Consequently, irrigation is an important management practice to help ensure economically viable production of export grapes.

THE DEVELOPMENT OF WATER POTENTIAL IN GRAPEVINES

To manage the water supply to grapevines by means of irrigation, it is essential to understand the diurnal water status of grapevines (Myburgh, 2018). On a normal sunshine day, water uptake by roots is slower than water lost by transpiration. A water deficit, or negative water potential gradient, occurs between the grapevine's roots and its

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leaves. Water is extracted temporarily from plant cells into the transpiration stream to maintain adequate transpiration during the daytime. Consequently, plant cells begin to shrink causing grapevine organs such as trunks, shoots, petioles and laminae to also shrink during the daytime. When the transpiration rate begins to decline in the late afternoon, water uptake by the roots continues and the water potential gradient becomes less. At the same time, water flows back into the plant cells and they begin to expand. During night time when there is almost no transpiration, roots continue to absorb water from the soil, and the water potential gradient continues to decline throughout the night. By predawn, the cell water is replenished and the cells have regained full turgidity, *i.e.* if sufficient soil water is available. As soon as the sun comes out, the water potential gradient begins to increase as transpiration exceeds water absorption from the soil, and the next diurnal water status cycle begins. It must be noted that water potential actually reflects the suction by which water is held by the plant cells. Therefore, it has a negative numeric value. Under normal atmospheric conditions, the highest water potential, *i.e.* the least negative value, occurs during the predawn period around 04:00 whereas the lowest water potential usually occurs between 12:00 and 14:00. There are a number of factors that can influence water potential in grapevines. These include atmospheric conditions, soil water status, soil salinity, trellis system, canopy management, crop load, cultivar and leaf damage by pests.

CLASSIFICATION OF WATER STATUS

Threshold values for grapevine water constraints based on predawn leaf water potential (Ψ_{PD}) were proposed by Ojeda *et al*. (2002) and Deloire *et al*. (2004). A further refinement of these Ψ_{PD} constraint classes for Merlot was reported by Myburgh (2011a). The latter classification was also extended to include leaf water potential (Ψ_L) and stem water potential (Ψ_S), as well as total diurnal water potential (Ψ_{Tot}). Similar classifications were also developed for Cabernet Sauvignon (Mehmel, 2010) and Shiraz (Lategan, 2011). The optimum water status in wine grapes is medium to strong constraints, *e.g.* -0.4 ≥ Ψ_{PD} ≥ -0.6 MPa if predawn water potential is measured (Myburgh, 2018) Table grapes will need to be subjected to low levels of water constraints. In this regard, Myburgh and Howell (2012) recommended that an “ultra-low” class, *i.e.* Ψ_{PD} > -0.1 MPa, should be included in the water constraint classification. Other than this, no information or recommendations regarding water constraint classes for table grapes could be found. It is evident that the water status classification based on grapevine water potential should be extended for table grapes to classify plant water status when the PAW in the soil is in the high range. Due to the problems with taking Ψ_L measurements on horizontal canopies (Myburgh & Howell, 2022), only Ψ_{PD} and Ψ_S should be considered to develop water status classes for table grape responses to low levels of PAW depletion. There are also different rates of water constraint evolution for wine grapes in soils having different hydraulic conductivities (Myburgh, 2011b). Such water constraint evolution curves should also be refined for high levels of PAW.

In a study to determine a water potential threshold to set soil water refill lines for table grape irrigation, the relationship between Ψ_S and Ψ_L was determined for ten selected table grape cultivars (Myburgh & Howell, 2022). A single equation could be used to convert midday Ψ_L measured in previous studies with table grapes to Ψ_S. Vegetative growth, berry mass, colour and juice total soluble solids (TSS) data was related to midday Ψ_S. Results showed that -0.8 MPa seemed to be a Ψ_S threshold for water constraints in the pre-harvest period that would allow sustainable growth and berry size. The optimum Ψ_S for berry colour was between -0.8 MPa and -1.0 MPa.

TABLE GRAPE RESPONSES TO WATER POTENTIAL

Numerous studies have addressed the effect of irrigation on table grape responses, which include plant water status as quantified by water potential measurements such as Ψ_{PD}, Ψ_L, Ψ_S and Ψ_{Tot} (Myburgh, 1996; Williams & Ayars, 2005; El-Ansary & Okamoto, 2007; Reynolds *et al.*, 2009; Williams *et al.*, 2010a; Williams *et al.*, 2010b; Myburgh, 2012; Myburgh & Howell, 2012; Silva-Contreras *et al.*, 2012; Williams *et al.*, 2012; Howell *et al.*, 2013; Gálvez *et al.*, 2014; Mabrouk, 2014; Conesa *et al.*, 2015; Conesa *et al.*, 2018; Al-Fadheel *et al.*, 2018). These studies have shown that vegetative growth, yield components, juice characteristics and fruit quality can be related to water constraints in table grapes.

Vegetative growth

Micro-sprinkler irrigation applied at different levels of PAW depletion throughout the season resulted in different levels of Ψ_L in Barlinka grapevines growing in sandy soil (Myburgh, 1996). In response, poorer vegetative growth was related to lower levels of Ψ_L. Likewise, reduced levels of irrigation decreased Ψ_L in Thompson Seedless grapevine, thereby causing a concomitant reduction in cane mass, total shoot length and leaf area (Williams *et al.*, 2010a). Applying 50% of the normal irrigation requirement decreased Ψ_{PD}, as well as midday Ψ_L and Ψ_S, which subsequently reduced vegetative growth of Italia grapevines growing on 1103 P rootstock (Mabrouk, 2014). Daily fertigation reduced Ψ_{Tot} compared to weekly fertigation of drip irrigated Dan-ben-Hannah grapevines (Myburgh & Howell, 2012). Consequently, daily fertigation increased cane mass compared to grapevines that were fertigated weekly (Howell *et al.*, 2013). Irrigation increased Ψ_L in Sovereign Coronation grapevines compared to no irrigation (Reynolds *et al.*, 2009). As expected, the higher water constraints in the non-irrigated grapevines reduced cane mass at pruning compared to the irrigated grapevines. In contrast, reduced drip irrigation decreased Ψ_L in Victoria grapevines, but had no effect on the cane mass at pruning (Al-Fadheel *et al.*, 2018). Likewise, lower Ψ_{PD} in Crimson Seedless grapevines did not reflect in reduced pruning mass (Conesa *et al.*, 2018). However, the water constraints reduced leaf area index and trunk cross-sectional area.

Yield and its components

Berry mass: Berry size is not only a crucial yield aspect, but is also an important quality factor. Water constraints, *i.e.* low levels of water potential, can restrict berry development, thereby reducing berry size (Myburgh, 1996; Reynolds *et* *al.*, 2009; Williams *et al.*, 2010b; Mabrouk, 2014; Conesa *et al.*, 2015; Al-Fadheel *et al.*, 2018). In particular, smaller berries are primarily caused by early season water deficits (Myburgh & Howell 2007a and references therein).

Daily fertigation during berry ripening reduced accumulated water constraints over the course of the day (Ψ_{Tot}) in Dan-ben-Hannah grapevines compared to weekly irrigated grapevines (Myburgh & Howell, 2012). Consequently, the berry mass of the daily fertigated grapevines was bigger than those produced by weekly irrigation (Howell *et al.*, 2013). In contrast, a higher level of PAW depletion and irrigation cut off during berry ripening decreased Ψ_{PD} substantially in Sunred Seedless grapevines (Myburgh & Howell, 2006), but did not reduce berry size (Myburgh & Howell, 2007a). Likewise, berry diameter did not respond to lower Ψ_S where less irrigation was applied to Thompson Seedless grapevines (Gálvez *et al.*, 2014).

Bunch mass: Micro-sprinkler irrigation applied at different levels of PAW depletion from véraison and irrigation either continued or cut off at 12°B or 15°B resulted in different levels of Ψ_L, Ψ_{PD} and Ψ_{Tot} in Sunred Seedless grapevines growing in sandy soil (Myburgh & Howell, 2006). In response, bunches were smaller where there were lower levels of Ψ_L and Ψ_{PD} (Myburgh & Howell, 2007a). Similarly, irrigation of Crimson Seedless grapevines applied at 25% crop evapotranspiration (ET_c) from véraison induced lower levels of Ψ_{PD} compared to irrigation applied at 50% ET_c from véraison and the control (Pinillos *et al.*, 2016). This tended to increase bunch mass where irrigation was applied at 25% ET_c. Likewise, lower Ψ_{PD} in Crimson Seedless grapevines (Conesa *et al.*, 2018) was reflected in reduced bunch mass (Conesa *et al.*, 2016). Bunch mass of the control in that particular study was similar to where regulated deficit irrigation (RDI) was applied at 50% in the post véraison period but grapevines that did not receive any irrigation throughout the season had substantially smaller bunches than the control. Applying 50% of the normal irrigation requirement decreased Ψ_{PD}, as well as midday Ψ_L and Ψ_S, which subsequently reduced the bunch mass of Italia grapevines (Mabrouk, 2014).

During berry ripening, grapevines that were fertigated daily experienced less water constraints in the morning, late afternoon and during the night than weekly irrigated ones and their Ψ_{Tot} was lower than grapevines that were irrigated weekly during berry ripening (Myburgh & Howell, 2012). In addition, daily fertigation reduced Ψ_{Tot} compared to weekly fertigation of drip irrigated Dan-ben-Hannah grapevines. Consequently, bunches from daily fertigated treatments were heavier compared to weekly irrigated grapevines (Howell *et al.*, 2013). These trends were probably the result of differences in berry mass which indicated the importance of near-optimal grapevine water status experienced by daily fertigated grapevines (Myburgh & Howell, 2012).

Yield: Micro-sprinkler irrigation applied at different levels of PAW depletion throughout the season resulted in different levels of Ψ_L in Barlinka grapevines (Myburgh, 1996). In response, poorer yield was related to lower levels of Ψ_L. Similarly, micro-sprinkler irrigation applied at different levels of PAW depletion from véraison and irrigation either continued or cut off at 12°B or 15°B resulted in different levels of Ψ_L, Ψ_{PD} and Ψ_{Tot} in Sunred Seedless grapevines (Myburgh & Howell, 2006), and yield tended to be less at lower levels of Ψ_L and Ψ_{PD} (Myburgh & Howell, 2007a). Likewise, increased levels of irrigation increased Ψ_L in Thompson Seedless grapevine, thereby causing a concomitant increase in the yield (Williams *et al.*, 2010a; Williams *et al.,* 2010b).

Drip irrigation applied at 40% PAW depletion throughout the season resulted in lower levels of Ψ_L in Barlinka grapevines compared to micro-sprinkler irrigated ones and this reduced yield of drip irrigated grapevines substantially (Myburgh, 1996). Daily fertigation reduced Ψ_{Tot} compared to weekly fertigation of drip irrigated Dan-ben-Hannah grapevines (Myburgh & Howell, 2012). Consequently, daily fertigation increased yield compared to grapevines that were fertigated weekly (Howell *et al.*, 2013).

Although irrigation of Crimson Seedless grapevines applied at 25% ET_c from véraison induced lower levels of Ψ_{PD} compared to irrigation applied at 50% ET_c from véraison and the control (Pinillos *et al.*, 2016), yield was not affected. Similarly, lower Ψ_{PD} in Crimson Seedless grapevines did not reflect in reduced yield (Conesa *et al.*, 2016; Conesa *et al.*, 2018). The yield of the control was similar to where RDI was applied at 50% in the post véraison period, but grapevines that did not receive any irrigation throughout the season had substantially less yield than the control. Irrigation increased Ψ_L in Sovereign Coronation grapevines compared to no irrigation (Reynolds *et al.*, 2009). As expected, the higher water constraints in the non-irrigated grapevines reduced the yield compared to the irrigated grapevines. In contrast, reduced drip irrigation decreased Ψ_L in Victoria grapevines, but did not affect on yield at harvest (Al-Fadheel *et al.*, 2018). It should be noted that the reduced drip irrigation received 152 mm of water for the season.

Fruit quality

Juice composition: Although micro-sprinkler irrigation applied at different levels of PAW depletion throughout the season resulted in different levels of Ψ_L, there were no differences in TSS at harvest (Myburgh, 1996). Likewise, micro-sprinkler irrigation applied at different levels of PAW depletion from véraison resulted in different levels of Ψ_L, Ψ_{PD} and Ψ_{Tot} in Sunred Seedless (Myburgh & Howell, 2006), but TSS was similar (Myburgh & Howell, 2007a). According to Conesa *et al.* (2016), the TSS of control grapevines was similar to those where RDI of 50% was applied after véraison. In contrast, where daily fertigation reduced Ψ_{Tot} compared to weekly fertigation of drip irrigated Dan-ben-Hannah grapevines, juice TSS was reduced (Myburgh & Howell, 2012; Howell *et al.*, 2013). Reduced drip irrigation also decreased Ψ_L in Victoria grapevines, but did not affect the TSS (Al-Fadheel *et al.*, 2018).

In a glasshouse study, Muscat of Alexandria table grapes that experienced severe post- véraison water deficits had lower Ψ_S compared to a well-watered control (El-Ansary *et al.*, 2005), which led to higher TSS for grapevines that experienced severe water deficits. This could be due to concentration of the TSS during berry desiccation. In addition there could have been a reallocation of carbohydrates to the grapes.

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Micro-sprinkler irrigation applied at different levels of PAW depletion throughout the season resulted in different levels of Ψ_L in Barlinka grapevines growing in sandy soil (Myburgh, 1996). In response, lower levels of TTA were related to lower levels of Ψ_L. Similarly, micro-sprinkler irrigation applied at different levels of PAW depletion from véraison resulted in different levels of Ψ_L, Ψ_{PD} and Ψ_{Tot} in Sunred Seedless (Myburgh & Howell, 2006), and TTA tended to be lower where there were lower levels of Ψ_L and Ψ_{PD} but juice pH was similar (Myburgh & Howell, 2007a). Likewise, although daily fertigation reduced Ψ_{Tot} compared to weekly fertigation of drip irrigated Dan-ben-Hannah grapevines (Myburgh & Howell, 2012), juice pH was similar (Howell *et al.*, 2013). This was expected, since there were no pronounced differences in juice TTA and cation composition, particularly K (Howell & Conradie, 2012).

Export percentage: Different levels of Ψ_L, Ψ_{PD} and Ψ_{Tot} in Sunred Seedless grapevines were obtained where micro-sprinkler irrigation was applied at different levels of PAW depletion from véraison (Myburgh & Howell, 2006). However, the percentage of exportable grapes was similar (Myburgh & Howell, 2007b).

Although there were no differences in water constraints of fertigated Dan-ben-Hannah grapevines growing near Paarl up to harvest (Myburgh & Howell, 2012), during berry ripening, grapevines that were fertigated daily experienced less water constraints in the morning, late afternoon and during the night than weekly irrigated ones. Consequently, the Ψ_{Tot} of Dan-ben-Hannah grapevines which were fertigated daily during berry ripening was lower than grapevines that were irrigated weekly. Berry crack following rainfall was substantially more where Dan-ben-Hannah grapevines were irrigated weekly compared to daily fertigation, and this contributed to the low export percentages compared with daily fertigated treatments (Howell *et al.*, 2013).

Colour: Micro-sprinkler irrigation applied at different levels of PAW depletion throughout the season resulted in different levels of Ψ_L in Barlinka (Myburgh, 1996). In response, grape colour was affected where wet soil conditions induced high levels of Ψ_L as well as where dry soil conditions induced low levels of Ψ_L. Similarly, irrigation applied at different levels of PAW depletion from véraison resulted in different levels of Ψ_L, Ψ_{PD} and Ψ_{Tot} in Sunred Seedless (Myburgh & Howell, 2006), grape colour tended to be better at lower levels of Ψ_L and Ψ_{PD} (Myburgh & Howell, 2007b). The positive colour response of Sunred Seedless to lower dry soil conditions was in agreement with earlier findings.

Daily fertigation reduced Ψ_{Tot} compared to weekly fertigation of drip irrigated Dan-ben-Hannah grapevines (Myburgh & Howell, 2012). Consequently, daily fertigation with a high crop load produced grapes of inferior colour compared to weekly irrigated grapevines (Howell *et al.*, 2013). Since vegetative growth of the grapevines was comparable, it is unlikely that less bunch exposure to sunlight could have contributed to the poorer colour but, rather, poorer colouring was probably related to lower water constraints experienced by daily fertigated grapevines (Myburgh & Howell, 2012) resulting in larger berries in conjunction with a dilution effect due to the higher yield.

Irrigation of Crimson Seedless grapevines applied at 25% ET_c from véraison induced lower levels of Ψ_{PD} compared to irrigation applied at 50% ET_c from véraison and the control (Pinillos *et al.*, 2016). In response, grape colour was enhanced by lower levels of Ψ_{PD}. Lower Ψ_{PD} in Crimson Seedless grapevines also enhanced berry colouration and provided a higher crop yield in the first pick compared to the control (Conesa *et al.*, 2016; Conesa *et al.*, 2018). In terms of subjective colour, for RDI there was a lower percentage in the pale pink category and a higher percentage in the moderate colour category.

Storage capability

Micro-sprinkler irrigation applied at different levels of PAW depletion throughout the season resulted in different levels of Ψ_L in Barlinka grapevines growing in sandy soil (Myburgh, 1996). In response, the grape taste was best when the levels of Ψ_L were moderate rather than too high or low. Lower Ψ_S and Ψ_{PD} for Crimson Seedless grapevines (Conesa *et al.*, 2018) that were not irrigated compared to a control reflected in poorer sensory scores (Conesa *et al.*, 2015).

During berry ripening, grapevines that were fertigated daily experienced less water constraints in the morning, late afternoon and during the night than weekly irrigated ones (Myburgh & Howell, 2012). In response, firmness and taste resulted in the lower overall grape quality of daily fertigated grapevines (Howell *et al.*, 2013). However, despite the poorer overall quality of the daily fertigated high crop load grapes, they were still within the norms for export standard.

In a glasshouse study, Muscat of Alexandria table grapes that experienced severe post-véraison water deficits had lower Ψ_S compared to a well-watered control (El-Ansary *et al.*, 2005), which led to lower firmness.

MEASURING WATER POTENTIAL

Water potential measurements must be carried out according to the prescribed protocol (Myburgh, 2010; Myburgh, 2018). As in the case of the wine industry, the objective should be to combine soil and plant water status measurements. However, it will not always be possible, or practical, for growers to measure grapevine water potential since human resources, as well as specialised equipment are required. Fortunately, grapevine water potential can be calibrated against any reliable soil water monitoring instruments used on farms (Bruwer, 2010; Mehmel, 2010; Lategan, 2011; Myburgh, 2011a). However, a prerequisite is that such instruments sense the actual soil water reliably. Furthermore, it is recommended that the technical irrigation advisors carry out these calibrations in the field by using pressure chambers according to previously described protocol (Scholander *et al.*, 1965; Hardie & Hinckley, 1975; Myburgh, 2010). Following the calibrations, table grapes can be irrigated to a certain pre-determined Ψ_{PD} or Ψ_S threshold by only monitoring soil water status.

As the measurement of water potentials can be costly, slow and labour intensive, De Bei *et al.* (2011) investigated the possibility of using near-infrared (NIR) spectroscopy to estimate Ψ_S of three wine grape cultivars. Results showed that it may be possible for NIR to be used as a non-destructive method for determining Ψ_S. In another study, there was a high correlation between the measured Ψ_L using a Scholander pressure chamber and Ψ_L estimated using a handheld fluorescence detector (Barnard *et al.*, 2019).

CONCLUSIONS

Considering previously reported literature, poorer vegetative growth was related to lower levels of Ψ_L. Given that berry size is a crucial aspect for yield as well as quality, it was evident that low levels of water potential can restrict berry development, thereby reducing berry size. Bunch mass was lower where there were lower levels of Ψ_L and Ψ_{PD}. Poorer yield was generally related to lower levels of Ψ_L throughout the season. However, lower levels of Ψ_L in the post-véraison period did not affect grapevine yield. Juice TSS did not respond to levels of Ψ_L, but juice TTA was related to lower levels of Ψ_L. The grape colour was adversely affected where wet soil conditions induced higher levels of Ψ_L as well as where dry soil conditions induced lower levels of Ψ_L. Since only Ψ_{PD} or Ψ_L was measured in most of the above-mentioned studies with table grapes, there is no information that directly relates table grape responses in terms of Ψ_S. This is a huge shortcoming. Since it is impractical to measure Ψ_L in leaves that are fully exposed to sunlight in the case of horizontal trellis systems, and Ψ_L was poorly related to soil water status compared to Ψ_S in a warm, arid region, it would be better to use Ψ_S for irrigation scheduling.

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