RESEARCH NOTE
Determining a Midday Stem Water Potential Threshold for Irrigation of Table Grapes

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Sustainable table grape production depends on sufficient water supply. Water potential is a useful indicator of water constraints in grapevines. In this regard, midday stem water potential (Ψ_S) is considered to be a better indicator of grapevine water status than leaf water potential (Ψ_L). The objective of the study was to determine a water potential threshold to set soil water refill lines for table grape irrigation. However, in previous studies carried out locally, only Ψ_L was measured. The relationship between Ψ_S and Ψ_L was determined for ten selected table grape cultivars. Since there were no differences between cultivars, 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 and colour, as well as juice total soluble solids (TSS) data were pooled, and related to midday Ψ_S. This showed that -0.8 MPa seems to be a Ψ_S threshold for water constraints in the pre-harvest period that will allow sustainable growth and berry size for anisohydric table grape cultivars. The optimum Ψ_S for berry colour is between -0.8 MPa and -1.0 MPa. Consequently, a midday Ψ_S threshold of -0.8 MPa can be used to set refill points for irrigation where soil water content is measured on a regular basis in table grape vineyards.

INTRODUCTION

Water plays an important role in grapevine physiology. Consequently, management of grapevine water status to avoid water constraints in table grapes is essential to ensure optimum yield and grape quality. Predawn (Ψ_{PD}), as well as midday Ψ_L and Ψ_S are proven measures to assess the water status in table grapes (Myburgh, 1996; Myburgh, 2003; Selles *et al.*, 2004; Williams & Ayars, 2005; Myburgh & Howell, 2006a; 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, 2012; Williams *et al.*, 2012; Howell *et al.*, 2013; Gálvez *et al.*, 2014; Mabrouk, 2014; Conesa *et al.*, 2015; Zúñiga-Espinoza *et al.*, 2015; Pinillos *et al.*, 2016; Conesa *et al.*, 2018; Al-Fadheel *et al.*, 2018; Weiler *et al.*, 2019). These studies have shown that water potential relates to important grapevine responses such as physiological processes, vegetative growth, berry size, yield and grape quality. This implies that water potential can be used to establish guidelines for irrigation scheduling of table grapes. However, there is a need to determine a water potential threshold that will prevent unnecessary irrigation, but still allows optimum yield and grape quality.

Midday Ψ_S is considered to be a more sensitive indicator of grapevine water status than Ψ_L (Van Leeuwen *et al.*, 2009; Tuccio *et al.*, 2019). Hence, a classification was proposed according to midday Ψ_S for wine grapes where water constraints were defined as none (> -0.6 MPa), weak (-0.6 to -0.9 MPa), weak to moderate (-0.9 to -1.1 MPa), moderate to severe (-1.1 to -1.4 MPa) and severe (< -1.4 MPa). Since Ψ_S measurements are time consuming and require skilled persons, it might not be suitable for irrigation scheduling at the commercial level. A more practical approach would be to monitor soil water content (SWC) and apply irrigation when grapevines experience a critical level of water constraints, or reach a Ψ_S threshold. The refill points can be set by measuring SWC and Ψ_S simultaneously as the soil dries out until Ψ_S reaches the threshold. Once the SWC refill point is set, no further Ψ_S measurements would be necessary. Using water potential thresholds was previously proposed for irrigation scheduling of wine grapes (Baeza *et al.*, 2007; Acevedo-Opazo *et al.*, 2010; Centeno *et al.*, 2010 and references therein, Charrier *et al.*, 2018). Likewise, pre- and post véraison midday Ψ_L thresholds of -0.8 MPa and -1.1 MPa, respectively, were proposed for table grapes in Tunisia (Mabrouk, 2014).

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ARC Infruitec-Nietvoorbij carried out several irrigation studies with table grapes where only midday Ψ_L was measured. The preferred trellis systems for table grape production in South Africa are Slanting, Gable and Factory trellises (Ferreira, 2020). Since it is difficult to access sun-exposed leaves on the upper side of these horizontal canopies, measuring midday Ψ_S in bagged leaves on the underside of canopies provides a more practical option than Ψ_L. It is also easier to standardize by picking mature leaves opposite bunches or close to bunches when leaves are removed as the season progresses. This is an important consideration where measurement of grapevine Ψ_S is required to set SWC refill points for irrigation scheduling in commercial vineyards. However, in order to relate the previously reported grapevine responses to midday Ψ_S to determine an optimum threshold, the midday Ψ_L values need to be converted to Ψ_S. Grapevines were subjected to different levels of plant available water depletion in the previous studies. In addition to midday Ψ_L, vegetative growth, berry size and grape colour responses were measured.

It is well established that grapevine water potential is affected by VPD (Williams & Baeza, 2007; Gálvez *et al.*, 2014; Conesa *et al.*, 2018; Suter *et al.*, 2019). Similar to Ψ_L (Williams & Baeza, 2007), Ψ_S becomes less susceptible to the effect of VPD as water constraints develop when the soil dries out (Gálvez *et al.*, 2014). In fact, the latter study showed that there was no relationship between Ψ_S and VPD where table grapes were irrigated at 50% plant available water depletion. Furthermore, the effect of VPD was not considered where water potential thresholds for grapevines were determined in previous studies (Baeza *et al.*, 2007; Acevedo-Opazo *et al.*, 2010; Centeno *et al.*, 2010 and references therein; Mabrouk, 2014). Air temperature can also affect Ψ_S (Williams & Baeza, 2007; Suter *et al.*, 2019). In this regard it was shown that modelling can be used to standardize Ψ_S when climatic conditions differ (Suter *et al.*, 2019). However, growers might find it difficult to implement such models, particularly with respect to obtaining real time weather data.

The objectives of the study were (i) to determine the relationship between Ψ_S and Ψ_L, (ii) convert existing Ψ_L data to Ψ_S and (iii) find a stem water potential threshold for table grape irrigation.

MATERIALS AND METHODS

The study to establish the relationship between Ψ_S and Ψ_L was carried out during the 2015/16 season in full bearing commercial vineyards in the Noorder-Paarl region of the Western Cape. Five white and five red cultivars were included in the study (Table 1). The cultivars were seedless, except for Tropical Delight, Victoria and Waltham Cross. All vineyards were irrigated by means of micro-sprinklers and trained onto Gable trellises (Ferreira, 2020). In each vineyard, a plot comprising an experiment row and two buffer rows were selected. The experiment rows consisted of at least eight grapevines. From the beginning of berry ripening, the water supply to the experiment plots was cut off for approximately four weeks. As the soil dried out, midday Ψ_S and Ψ_L were measured weekly between 12:00 and 14:00 mean solar time according to the protocol described by Myburgh (2010) using a pressure chamber (Scholander *et al.*, 1965). A custom-made pressure chamber mounted on a motor cycle was used. In the case of Ψ_S, leaves were covered using aluminium bags with black linings one hour before measurements were made. The bags were not removed during the measurements. Since the vineyards were approximately 5 km apart, water potentials were only measured in three grapevines per plot to stay within the midday time limit.

The irrigation studies carried by ARC Infruitec-Nietvoorbij included Barlinka (Myburgh, 1996), Thompson Seedless (Myburgh, 2003; Myburgh, 2012), Sunred Seedless (Myburgh & Howell, 2006a; Myburgh & Howell, 2006b; Myburgh & Howell, 2007) and Dan-ben-Hannah (Myburgh & Howell, 2012; Howell *et al.*, 2013). In these studies, Ψ_L was generally measured before irrigations, thereby indicating the maximum water constraints the grapevines would

TABLE 1
Viticultural characteristics of the vineyards where the relationship between stem (Ψ_S) and leaf (Ψ_L) water potential was determined in ten selected table grape cultivars.

Cultivar		Plant spacing	Row direction
Scion	Rootstock		
Prime Seedless	Ramsey	3 x 1.5 m	NNW-SSE
Regal Seedless	Ramsey	3 x 1.5 m	NNW-SSE
Thompson Seedless	99Richter	3 x 1.5 m	NE-SW
Victoria	Ramsey	3 x 1.5 m	NNE-SSW
Waltham Cross	99Richter	3 x 1.5 m	NNE-SSW
Crimson Seedless	Ramsey	3 x 1.8 m	WNW-ESE
Sugranineteen	Ramsey	3 x 1.5 m	NNE-SSW
Starlight	Ramsey	3 x 1.5 m	WNW-ESE
Sunred Seedless	Ramsey	3 x 1.5 m	WNW-ESE
Tropical Delight	Ramsey	3 x 1.5 m	WNW-ESE

have been subjected to by various treatments. Vegetative growth was quantified by weighing cane mass at pruning and berry mass at harvest. Juice TSS and sensorial berry colour were also determined at harvest. Berry colour was evaluated using the colour chart for each cultivar as prescribed by the table grape industry. To allow more data for relating grapevine responses to water status, data of the different experiments were pooled. Due to differences in locality and cultivar, relative values for cane mass, berry mass and grape colour were calculated for each experiment.

Regression analyses were carried out using STATGRAPHICS® version XV (StatPoint Technologies, Warrenton, Virginia, USA). To allow comparison between the regression lines of the different cultivars, upper and lower 95% confidence limits for the slope of each regression line were calculated as ±1.96 times the standard error of the slope (Ott, 1998).

RESULTS AND DISCUSSION

For each cultivar, Ψ_S and Ψ_L correlated linearly (Fig. 1). However, in the case of Sugranineteen two distinct outlier values occurred which suggested that the water potential in this cultivar might be more susceptible to variability in atmospheric conditions as was previously shown (Williams & Baeza, 2007; Suter *et al.*, 2019). The linearity between Ψ_S and Ψ_L agrees with previous reports for grapevines (Williams & Araujo, 2002; Montoro *et al.*, 2012; Williams, 2012). The linear relationship also applies to predawn Ψ_S and Ψ_L in table grapes (Mabrouk, 2014). When the soil was wet, the difference between Ψ_L and Ψ_S ($\Delta\Psi$) was notably bigger compared to drier conditions (Fig. 1). For well-watered wine grapes, $\Delta\Psi$ is *c.* 0.6 MPa compared to *c.* 0.1 MPa when severe water constraints occur due to low soil water contents (Choné *et al.*, 2001). Grapevine transpiration is high when water is readily available, and decreases as the soil dries out (Winkel & Rambal, 1993; Centeno *et al.*, 2010; Rogiers *et al.*, 2010). Since transpiration declines linearly as $\Delta\Psi$ decreases, $\Delta\Psi$ provides an indirect assessment of grapevine transpiration as it varies with soil water content and atmospheric VPD (Choné *et al.*, 2001).

The linear correlations between Ψ_L and Ψ_S were highly significant for all cultivars (Table 2). Furthermore, comparison of the regression lines for the ten cultivars showed that there were no statistical differences (Fig. 2). The latter indicated that the development of water constraints as the soil dried out did not differ between cultivars. Furthermore, it appeared that row direction did not affect grapevine water status. Consequently, the data for all cultivars were pooled to obtain the following equation:

$$\Psi_S = 1.33\Psi_L + 0.68 \text{ (n = 130; } R^2 = 0.9076\text{; s.e. = 0.003; } p < 0.0001\text{)} \qquad \text{(Eq. 1)}$$

Equation 1 was used to convert the midday Ψ_L to Ψ_S for the previous table grape irrigation studies mentioned earlier.

The foregoing results implied that the selected cultivars showed anisohydric behavior under the prevailing conditions. This means that Ψ_L follows a distinct diurnal pattern, and decreases in response to soil water deficits (Schultz, 2003 and references therein). In contrast, Ψ_L remains more or less constant during the day in isohydric or near-isohydric grapevines and does not respond to changes in soil water status (Schultz, 2003). This suggested that Equation 1 is most likely not applicable to isohydric table grape cultivars.

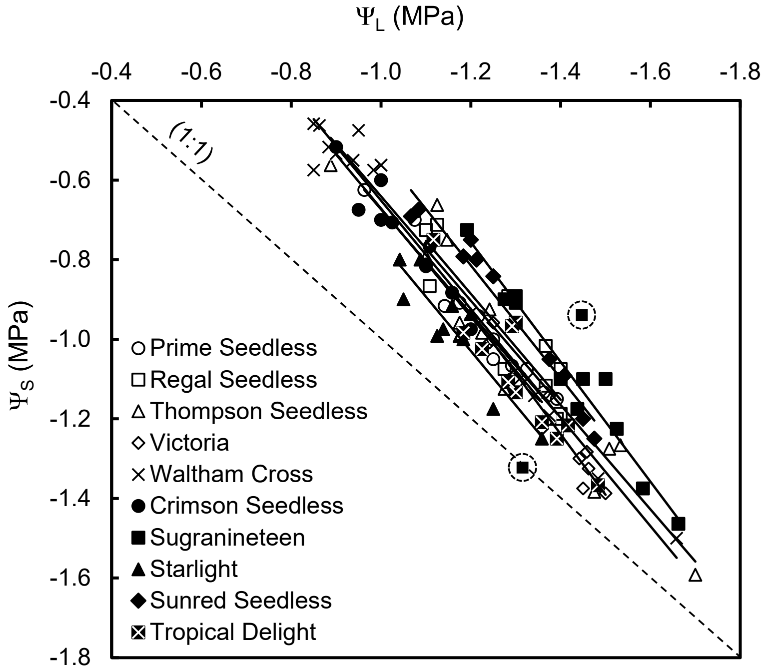

FIGURE 1

Relationship between midday stem (Ψ_S) and leaf (Ψ_L) water potential for ten table grape cultivars. The encircled outliers for Sugranineteen were not included in the regression equation. The equations are presented in Table 2.

However, it must be noted that there is some controversy about the consistent hydric behavior, and subsequent classification, of grapevine cultivars (Hugalde & Vila, 2014; Charrier *et al.*, 2018; Levin *et al.*, 2020).

Vegetative growth vigour, *i.e.* as quantified in terms of cane mass at pruning, began to decline when midday Ψ_S fell below *c.* 0.8 MPa (Fig. 3). This value corresponded more or less with the transition from weak to moderate water constraints (Van Leeuwen *et al.*, 2009). Below this threshold, relative cane mass declined at a rate of *c.* 11% per 0.1 MPa decrease in Ψ_S. Although grapevine shoot growth and cane mass declined linearly as Ψ_L decreased, no distinct threshold was observed (Baeza *et al.*, 2007; Williams *et al.*, 2010a). This was probably due to the highest Ψ_L being c. -0.7 MPa in both studies. These results indicate that irrigation applied before midday Ψ_S reaches -0.8 MPa is likely to induce excessive vegetative growth. The latter could cause unfavourable micro-climatic conditions in the bunch zone. Furthermore, excessive growth will require more canopy management inputs that could increase production costs. Similar to vegetative growth, berry mass also remained unaffected up to a Ψ_S threshold of *c.* -0.8 MPa (Fig. 4). The decline in berry mass with decreasing grapevine water potential agrees with earlier findings (Baeza *et al.*, 2007; Williams *et al.*, 2010b). The rate of berry mass decline below the threshold was *c.* 8% per 0.1 MPa decrease in Ψ_S. This suggested that berry size appeared to be less sensitive to water constraints than vegetative growth.

In contrast to vegetative growth and berry size, grape colour did not have a prominent threshold with respect to Ψ_S. In fact, berry colour responded curvilinear to Ψ_S and seemed to reach an optimum between -0.8 MPa and -1.0 MPa (Fig. 5). The poor colour score of Thompson Seedless was due to the presence of yellow coloured berries that are

TABLE 2
Equations for the relationship between stem (Ψ_S) and leaf (Ψ_L) water potential determined for ten selected table grape cultivars.

Cultivar	Equation for Ψ_S versus Ψ_L					
	Slope	Intercept	n	R^2	s.e.	p
Prime Seedless	1.358	0.686	12	0.9070	0.044	< 0.001
Regal Seedless	1.332	0.712	11	0.8126	0.083	< 0.001
Thompson Seedless	1.311	0.669	13	0.9093	0.095	< 0.001
Victoria	1.525	0.897	10	0.9169	0.046	< 0.001
Waltham Cross	1.364	0.712	16	0.9763	0.058	< 0.001
Crimson Seedless	1.358	0.686	10	0.9070	0.044	< 0.001
Sugranineteen	1.471	0.999	10	0.9373	0.052	< 0.001
Starlight	1.36	0.607	11	0.8180	0.062	< 0.001
Sunred Seedless	1.418	0.886	10	0.9618	0.044	< 0.001
Tropical Delight	1.496	0.864	11	0.8409	0.073	< 0.001

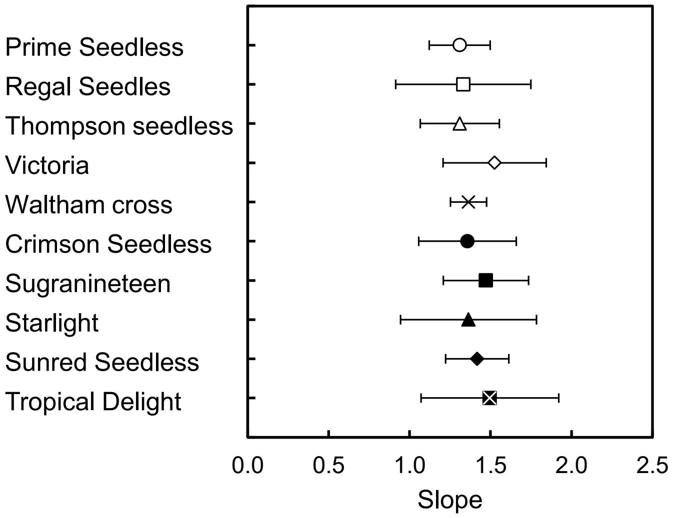

FIGURE 2
Upper and lower 95% confidence limits for the slope of the regression line for each of the ten cultivars.

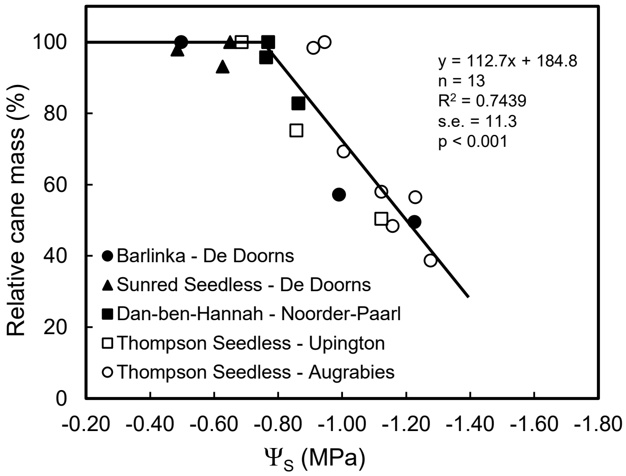

FIGURE 3

Relationship between relative cane mass and midday stem water potential (Ψ_S) for four table grape cultivars at four localities. Regression equation is for data points where Ψ_S falls below -0.8 MPa.

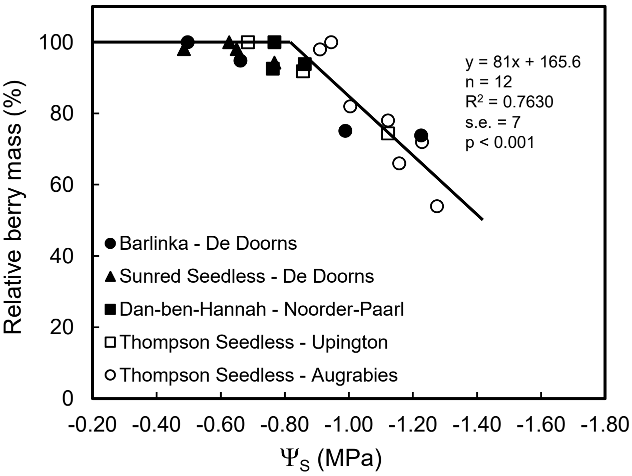

FIGURE 4

Relationship between relative berry mass and midday stem water potential (Ψ_S) for four table grape cultivars at four localities. Regression equation is for data points where Ψ_S falls below -0.8 MPa.

not suitable for the fresh market. It was previously shown that Thompson Seedless produced more yellow berries where water constraints reduced vegetative growth and solar radiation interception (Zúñiga-Espinoza *et al.*, 2015). Although the colour of Crimson Seedless grapes improved where Ψ_S was lower than -0.8 MPa throughout most of the pre-harvest period, berry mass was reduced (Pinillos *et al.*, 2016). Furthermore, this response was not consistent over seasons. Excessively high berry temperatures reduced the total monomeric anthocyanin concentrations in berry skins, but cooling of sun-exposed grapes had the opposite effect (Spayd *et al.*, 2002). The foregoing suggested that the effect of over-irrigation, as well as excessive water constraints on berry exposure could have a negative effect on berry colour development. Juice sugar content at harvest did not correlate well with midday Ψ_S (data not shown). The insensitivity of juice TSS where table grapes were subjected to different irrigation regimes was in agreement with previous findings (Serman *et al.*, 2004; Blanco *et al.*, 2010; Mabrouk, 2014; Zúñiga-Espinoza *et al.*, 2015; Pinillos *et al.*, 2016; Al-Fadheel *et al.*, 2018). This is probably due to table grapes being harvested at relatively low TSS for export. Yet, this does not rule out the possibility that irrigation induced water constraints have no effect on TSS in table grapes (Selles *et al.*, 2004; El-Ansary & Okamoto, 2007; Tangolar *et al.*, 2007; Reynolds *et al.*, 2009). Inconsistent juice TSS responses to water deficits were also reported for a number of table grape cultivars (Permanhani *et al.*, 2016 and references therein). If the midday Ψ_L thresholds proposed by Mabrouk (2014) are converted to Ψ_S by means of Equation 1, the pre-véraison threshold of -0.4 MPa appears to be too high for table grapes in South Africa. However, the post-véraison threshold of -0.8 MPa for table grapes in Tunisia will be applicable for local conditions. Based on the foregoing, the following water

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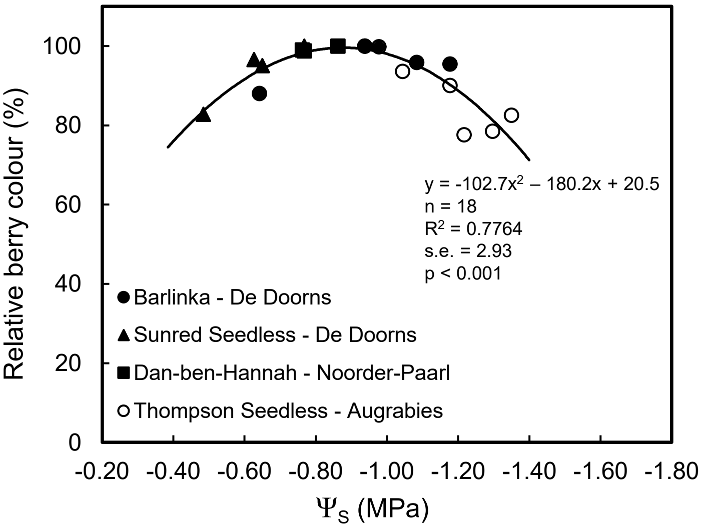

FIGURE 5

Relationship between relative berry colour and midday stem water potential (Ψ_S) for four table grape cultivars at three localities. Regression equation is for all data points.

constraint classification according to midday Ψ_S is proposed for table grape production: none ($\Psi_S > -0.6$ MPa), weak ($-0.6 \leq \Psi_S > -0.8$ MPa), moderate ($-0.8 \leq \Psi_S > -1.0$ MPa), strong ($-1.0 \leq \Psi_S > -1.2$ MPa) and severe ($\Psi_S < -1.2$ MPa).

CONCLUSIONS

Within the constraints of the methodology, -0.8 MPa seems to be a water status threshold that will allow sustainable growth and berry size for anisohydric table grape cultivars. If midday Ψ_S is consistently above -0.8 MPa or below -1.0 MPa, it could restrict berry colour development. It is recommended that irrigation advisors and managers set soil water refill lines for table grape vineyards when midday Ψ_S reaches -0.8 MPa in the pre-harvest period. Adjusting Ψ_S thresholds for the post-harvest period is part of an ongoing study.

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