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Short communication

Usefulness of early morning stem water potential as a sensitive indicator of water status of deficit-irrigated grapevines (*Vitis vinifera* L.)

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ABSTRACT

A study was conducted to investigate the practical use of early morning stem water potential ($\Psi_{stem\text{-}em}$) as a measure of water status of *Vitis vinifera* L. cv. Tempranillo under field conditions within the Southern Oregon American Viticultural Area (AVA). Midday leaf water potential ($\Psi_{leaf\text{-}md}$), midday stem water potential ($\Psi_{stem\text{-}md}$), and $\Psi_{stem\text{-}em}$ were each measured on vines being irrigated at 70% of crop evapotranspiration (ET_c) and 35% of ET_c. Predawn leaf water potential (Ψ_{pd}) and $\Psi_{stem\text{-}em}$ were also measured on the same cultivar with the same irrigation treatments at a different vineyard within the same AVA. In comparing $\Psi_{leaf\text{-}md}$, $\Psi_{stem\text{-}md}$, and $\Psi_{stem\text{-}em}$ over the growing season, early morning measurements showed differences between irrigation treatments on three of four measurement dates while midday measurements on the same vines showed differences on only one of four dates. Linear regression analysis of $\Psi_{stem\text{-}em}$ versus Ψ_{pd}, $\Psi_{stem\text{-}md}$, and $\Psi_{leaf\text{-}md}$ indicated significant positive correlations. $\Psi_{stem\text{-}em}$ measurements also had a high degree of repeatability as indicted by their low coefficients of variance. The results of this study indicate that $\Psi_{stem\text{-}em}$ could be a useful parameter for the assessment of grapevine water status due to its high sensitivity compared to other commonly used metrics.

1. Introduction

Irrigation scheduling in most horticultural crops requires growers to decide on a method to determine both the timing and quantity of water to be applied (Pritchard, 2000). Numerous methods are available to determine the water requirements of crops including soil-based, water balance, and plant-based methods (van Leeuwen et al., 2009). Plant-based methods have the advantage of taking into account more of the factors influencing plant water status, including soil moisture, evaporative demand, and the plant's physiological responses to both (Jones, 2004). The use of a pressure chamber to measure the water potential (Ψ_w) of the leaf has become one of the most popular and well-established methods for directly measuring plant water status (Williams and Araujo, 2002). A number of variations on the measurement of plant water potential (Ψ_w) have been proposed and validated, primarily predawn leaf water potential (Ψ_{pd}), midday leaf water potential ($\Psi_{leaf\text{-}md}$), and midday stem water potential ($\Psi_{stem\text{-}md}$) (Williams and Trout, 2005). However, there remains disagreement within the literature as to which of these three methods best characterizes vine water status under field conditions (Chone et al., 2001; Gruber and Schultz, 2005; Williams and Trout, 2005).

Ψ_{pd} is generally considered to be a good indicator of soil or root Ψ_w since this measurement is taken during a period in which both canopy Ψ_w and root Ψ_w come into equilibrium with soil Ψ_w (Jones, 2007), but may be inaccurate in soils with strongly heterogeneous water content if a portion of the soil provides enough available water to rehydrate the entire plant during this period (Ameglio et al., 1999). $\Psi_{leaf\text{-}md}$ is considered an indicator of the minimum leaf water potential experienced by the plant during daylight hours and under maximum transpiration (van Leeuwen et al., 2009). Studies have confirmed that $\Psi_{leaf\text{-}md}$ can show significant differences between soil water availability (Matthews et al., 1987; Williams and Trout, 2005) and is well-correlated with other indicators of vine water stress (Baeza et al., 2007). $\Psi_{leaf\text{-}md}$ is widely used by grape growers due to its simple and quick procedure, and since established $\Psi_{leaf\text{-}md}$ thresholds for irrigation scheduling exist (Baeza et al., 2007). However, $\Psi_{leaf\text{-}md}$ may not always reflect the true water status of the vine because each measurement represents the Ψ_w of only a single leaf, and, in several grape cultivars, Ψ_{leaf} is

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regulated by the vine under high levels of water stress (Schultz, 2003). Stem water potential (Ψ_{stem}) integrates the water status of all the leaves on the stem and is, therefore, less sensitive to environmental fluctuations affecting individual leaves compared to day-time measurements of Ψ_{leaf} (Jones, 2007). $\Psi_{stem\text{-}md}$ was found to be least susceptible to local environmental fluctuations compared to $\Psi_{leaf\text{-}md}$ (Patakas et al., 2005; Shackel, 2007). Chone et al. (2001) found that $\Psi_{stem\text{-}md}$ measured in grapevines provided the earliest indication of water stress and correlated well to leaf transpiration.

Several researchers have recently suggested that Ψ_{stem} measured in the early morning hours between 0700 and 0800 h solar, known as early morning stem water potential ($\Psi_{stem\text{-}em}$), may be a useful and practical method for measuring the water status of grapevines (Intrigliolo and Castel, 2006, 2010; Intrigliolo et al., 2005; Salon et al., 2004, 2005). When measured on Tempranillo grapevines, $\Psi_{stem\text{-}em}$ was shown to be more sensitive in distinguishing differences between irrigation treatments over a range of seasonal conditions and vine water stress levels compared to midday measurements (Intrigliolo and Castel, 2010). $\Psi_{stem\text{-}em}$ was also better correlated with stomatal conductance compared to other Ψ_w measurements (Intrigliolo and Castel, 2006). In addition, $\Psi_{stem\text{-}em}$ was well-correlated with berry weight, berry sugar content, yield, and wine characteristics when measured on both Tempranillo and *V. vinifera* cv. Bobal (Salon et al., 2004, 2005). Results from these published studies suggest that early morning measurements of stem water potential may provide yet another option for accurately assessing plant water status. In this paper, we validate the utility of $\Psi_{stem\text{-}em}$ as a sensitive indicator of grapevine water stress as affected by irrigation level, and compare it to other widely-used Ψ_w metrics in a semi-arid growing region.

2. Materials and methods

2.1. Plant material and vineyard site

This study was conducted in the 2012 growing season in a commercial vineyard located near Roseburg, OR, USA (43.218° N; 123.356° W), part of the Southern Oregon American Viticulture Area (AVA). The vineyard block had a slope of approx. 30% and consisted of soils that belong to the Philometh–Dixonville complex, predominantly silty clay with moderate water holding capacity. All measurements were taken from an ongoing irrigation trial being conducted on mature (12-year old) *Vitis vinifera* L. cv. Tempranillo grafted onto 101-14 (*V. riparia* × *V. rupestris*) rootstock. Rows in the vineyard block were oriented east to west, and spacing was 2.4 m (within rows) × 3.0 m (between rows). The vines were trained to a bilateral cordon, spur pruned, and shoot thinned to a shoot density of 9–10 shoots per linear meter of cordon. The crop level was adjusted to two clusters per shoot just prior to véraison, approximately August 28, 2012.

2.2. Irrigation regime

Experimental plots consisted of two sustained deficit irrigation (SDI) treatments with three replicates per treatment. The SDI treatments were 70% of crop ET_c and 35% of ET_c, where ET_c was estimated using an on-site evapotranspiration simulator (ETgage Model E; ETgage Company, Loveland, CO, USA). Irrigation was initiated when $\Psi_{leaf\text{-}md}$ on three or more plants within the experimental block reached −1.2 MPa or less, which corresponded to July 31.

2.3. Water potential measurements

Plant water potential was measured using a leaf pressure chamber (PMS Instruments, Model 615D, Albany, OR, USA). Pre-dawn and midday measurements were conducted as described in Williams and Trout (2005), taking into account recommendations by Williams and Araujo (2002). Midday measurements were taken during a 2-h window between 11:00 and 13:00 h solar time (http://www.esrl.noaa.gov/gmd/grad/solcalc), which corresponded to approximately 12:00 to 02:00 pm PDT on dates the measurements were taken. $\Psi_{stem\text{-}em}$ was measured between 07:00 and 08:00 h solar time, as in Intrigliolo and Castel (2006), which corresponded to approximately 08:00 to 09:00 am PDT on dates measurements were taken. Leaves chosen for stem water potential (Ψ_{stem}) were selected according to Chone et al. (2001).

At the primary experimental site, $\Psi_{stem\text{-}em}$, $\Psi_{leaf\text{-}md}$, and $\Psi_{stem\text{-}md}$ were carried out on the same three plants per replicate within the same vineyard block (nine measurements per treatment) on four dates: August 7, August 21, September 11, and September 25. On August 21, at the same site, both Ψ_{stem} and Ψ_{leaf} were measured every 1–2 h on the same three vines to produce diurnal Ψ_w curves. Each set of three measurements was taken within a 10 min time window. At a different experimental site in the same AVA and with the same SDI treatments, $\Psi_{stem\text{-}em}$ and Ψ_{pd} were each carried out on the same three plants per replicate (nine measurements per treatment) on five dates: July 2, July 23, July 30, August 13, and August 27.

On August 19, three adjacent vines irrigated at 70% of ET_c and three adjacent vines irrigated at 35% ET_c were chosen and four leaves from each vine were bagged between approximately 05:00 and 06:00 h (solar). $\Psi_{stem\text{-}em}$ was then measured on all leaves between 07:00 and 08:00 h (solar), with less than 3 min between measurements of leaves on the same vine. Vapor pressure deficits (VPD) were calculated during measurement windows on each date using temperature and relative humidity data from an automatic weather station located on site.

2.4. Statistical analyses

Data was subject to analysis of variance (ANOVA). Means were compared using Duncan's multiple range test ($P \leq 0.05$). Statistical analysis was done using Statistica® version 10 software (Statsoft, Tulsa, OK, USA). Two statistical approaches were used to compare the three methods of measuring vine water status. In order to evaluate the discriminating ability or power of a given method, Discriminant Ratios (DRs) were calculated for each of the three methods compared in this study at each irrigation level as per the method proposed by Levy et al. (1999). DR is the ratio of the underlying between-subject standard deviation (σ_u) to within-subject standard deviation (σ_w; DR = σ_u/σ_w):

$$\sigma_u = \sqrt{\sigma_b^2 - \left(\frac{\sigma_w^2}{k}\right)}$$

where σ_b is the standard deviation between subjects, σ_w is the mean within-subject standard deviation of all subjects in the study, and k is the number of replicate measurements.

Therefore,

$$DR = \frac{\sqrt{\sigma_b^2 - (\sigma_w^2/k)}}{\sigma_w}$$

Homogeneity of variance, or homoscedasticity, was checked by Levene's test using SAS statistical software (v.9.4, SAS Institute Inc., Cary, NC, USA). Heteroscedastic data was corrected using a log transformation. In order to ascertain the similarity of the different methods compared in this study to the measurement of vine water