Relationships among Vine- and Soil-Based Measures of Water Status in a Thompson Seedless Vineyard in Response to High-Frequency Drip Irrigation

Larry E. Williams[1]* and Thomas J. Trout[2]

Abstract: A study was conducted in the field on *Vitis vinifera* L. (cv. Thompson Seedless) to compare various measurements of vine water status under high-frequency drip irrigation. Water use at 100% of vine evapotranspiration (ET_c), was determined with a weighing lysimeter. Vines in the vineyard were irrigated at 0, 0.2, 0.6, 1.0, or 1.4 times the amount of water used by the lysimeter vines. Water applications occurred each time the lysimeter lost 16 L of water (2 mm depth; 8 L vine^{-1}). Soil water content (θ_v) was measured in the 0.2, 0.6, 1.0, and 1.4 irrigation treatments. Predawn (Ψ_{PD}), midday leaf (Ψ_l), and midday stem (Ψ_{stem}) water potentials were measured at the ends of the 1991 and 1992 growing seasons and almost monthly during 1993. Soil water content in 1993 remained constant throughout the growing season for the 1.0 irrigation treatment, increased in the 1.4 treatment, and decreased in the 0.2 and 0.6 treatments. Both Ψ_l and Ψ_{stem} measurements detected differences among irrigation treatments to a greater extent than did Ψ_{PD} until very late in the 1993 growing season. There was a linear relationship between Ψ_l and Ψ_{stem}. All three measurements of water potential were related to soil water content (using a quadratic function); however, the relationship between SWC and Ψ_{PD} had the lowest R^2 value, 0.52 compared to 0.90 and 0.94 for Ψ_l and Ψ_{stem}, respectively. Results indicated that Ψ_{PD} would not be useful in accurately determining vine water status under high-frequency deficit irrigation.

Key words: predawn water potential, midday leaf and stem water potential, soil water content, weighing lysimeter

The majority of grapevines grown in California have to be irrigated because of the high evaporative demand, low amount of rainfall during the growing season, and lack of adequate water reserves in the soil profile (Williams and Matthews 1990). Summer reference evapotranspiration (ET_o) can range from 6 to 9 mm day^{-1} at midseason, depending upon location. Vineyards may be drip irrigated once or twice daily, depending upon the capacity of the irrigation system and the availability of water. Since soil water deficits have been shown to improve grape quality (Williams et al. 1994, Williams and Matthews 1990), deficit irrigation practices in vineyards are gaining in popularity for raisin, table, and wine grapes in California. In addition to monitoring soil water content, plant-based measures of vine water status are being used to assist in making objective irrigation-management decisions. These include determining when to start, the interval between irrigation events, and the amount of stress one achieves in the vineyard.

The pressure chamber commonly is used to determine the water status (water potential: Ψ) of plants in the field (Hsiao 1990, Jones 1990, Koide et al. 1989). Water potential can be determined on leaves measured before sunrise (predawn [Ψ_{PD}]) or at midday (by measuring leaf [Ψ_l] or stem [Ψ_{stem}] water potentials) when daily minimum values occur (Grimes and Williams 1990, Williams et al. 1994). The precision with which two of the above methods, Ψ_{PD} and midday Ψ_l, can accurately determine the water status of a grapevine has recently been questioned (Chone et al. 2001, Naor 1998, Naor and Wample 1994).

Many assume that Ψ_{PD} reflects the availability of water in the soil profile: that the plant's water potential is in equilibrium with that of the soil just before sunrise (Correia et al. 1995, Schultz 1996, Winkel and Rambal 1993). These Ψ_{PD} values are then used as a reference to which other measures of vine water status taken later in the day are compared. However, it has been found that Ψ_{PD} may come into equilibrium with the wettest portion of the soil profile, rather than the entire root zone (Ameglio et al. 1999, Tardieu and Katerji 1991). Therefore, an assessment of water status using Ψ_{PD} may provide erroneous results, especially under an irrigation management program where the crop is deficit irrigated on a high-frequency basis.

[1]Department of Viticulture and Enology, University of California, Davis, and Kearney Agricultural Center, 9240 S. Riverbend Ave., Parlier, CA 93648; [2]Water Management Research Laboratory, USDA-ARS, Parlier, CA 93648.

*Corresponding author [Email: williams@uckac.edu]

Acknowledgments: We thank Peter Biscay, Weigang Yang, and Paul Wiley for their technical assistance. We also thank Dr. Pilar Baeza for reviewing the manuscript.

This research was supported in part by a grant from the American Vineyard Foundation.

Manuscript submitted February 2005; revised May 2005

It also has been shown that midday Ψ_{stem} may be a better measure of plant water status than Ψ_l (Chone et al. 2001, Garnier and Berger 1985, McCutchan and Shackel 1992, Naor 1998). These authors found that Ψ_{stem} appeared to be less affected by environmental conditions at the time of measurement than Ψ_l and that one could detect small but significant differences when using Ψ_{stem} as opposed to Ψ_l. It was recently shown that all three of the above methods of determining grapevine water status were highly correlated with one another and with other measures of vine and soil water status when measured late in the growing season (Williams and Araujo 2002). It is unknown, however, whether such relationships would be correlated with one another earlier in the growing season.

A long-term study was initiated in the San Joaquin Valley of California to determine water use of Thompson Seedless grapevines measured with a weighing lysimeter (Williams et al. 2003a,b). Four years after planting, a replicated trial was established in the vineyard surrounding the lysimeter where vines were irrigated at various amounts of lysimeter water use (from no applied water to 140% in 20% increments). It was expected that these treatments would result in vines under a wide range of water status. The purpose of the study was to determine the relationships among Ψ_{PD}, Ψ_l, and Ψ_{stem} of Thompson Seedless grapevines grown in the San Joaquin Valley under high-frequency drip irrigation. In addition, all measures of Ψ were compared with other measurements of soil and vine water status. Measurements of Thompson Seedless Ψ_{PD} and midday Ψ_l were made at the ends of the 1991 and 1992 growing seasons and Ψ_{PD} and midday Ψ_l and Ψ_{stem} were measured regularly during the 1993 growing season.

Materials and Methods

A weighing lysimeter was installed at the University of California Kearney Agricultural Center located in the San Joaquin Valley of California (lat: 36°48'N; long: 119°30'W) in 1986. Two *Vitis vinifera* L. (cv. Thompson Seedless clone 2A) grapevine cuttings were planted in the lysimeter on 9 April 1987. Cuttings were also planted in the vineyard surrounding the lysimeter with vine and row spacings of 2.15 and 3.51 m, respectively (7.55 m^2/vine). The length allocated to the canopies of the two vines within the lysimeter was similar to that of the vines in the vineyard surrounding the lysimeter. Row direction was 6° north of the east/west axis. The vineyard was ~1.4 ha (168 m x 82 m). The soil was a Hanford fine sandy loam (coarse-loamy, mixed, nonacid, thermic Typic Xerorthent).

The trellis of the vines used in the study consisted of a 2.13-m wooden stake driven 0.45 m into the soil at each vine. A 0.6-m cross arm was placed atop the stake and wires attached at either end of the cross arm to support the vine's fruiting canes. The trellis for the vines in the lysimeter was self-contained and not attached to the trellis system used down the row where the lysimeter was located to ensure it was part of the lysimeter mass.

The soil container of the lysimeter was 2 m by 4 m by 2 m deep. The tank was weighed with a balance beam and load cell configuration, with most of the weight being eliminated using counter weights. A detailed description of the lysimeter and its construction are given in Williams et al. (2003a).

Vines within the lysimeter and the surrounding vineyard were irrigated with 4 L h^{-1} in-line drip emitters, spaced every 0.30 m in the vine row. The drip tubing was attached to a wire suspended 0.4 m above the soil surface. The lysimeter was weighed hourly to determine crop evapotranspiration (ET_c); when the decrease in mass exceeded a 16 L (8 L $vine^{-1}$) threshold value the lysimeter was irrigated. The number of irrigations per day throughout the growing season ranged from 0 to 7.

The irrigation pump for the rest of the vineyard was controlled by the lysimeter datalogger (Campbell Scientific 21X Micrologger; Logan, UT). Whenever the lysimeter was irrigated the vineyard pump was activated and an irrigation event took place. The irrigation treatments were applied water amounts at various fractions of lysimeter water use. Vines were irrigated at 0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, and 1.4 times that used by the lysimeter. Each irrigation treatment plot consisted of 18 vines down a single row. The irrigation treatments within an individual block (replicated eight times) were set up as a line-source, going from lowest to highest. The activation of solenoid valves at the head of each row for various times was used to provide the differing fractions of applied water. In-line water meters downstream from the solenoid valves in each row measured actual applied water amounts.

Soil water content (SWC) in the 0.2, 0.6, 1.0, and 1.4 irrigation treatments was monitored using the neutron backscattering technique with a neutron moisture probe (model 503 DR Hydroprobe Moisture Gauge; Campbell Pacific Nuclear, Martinez, CA). Nine access tubes were placed in one-quarter of an individual vine's rooting volume and inserted to a depth of 3 m at each site. Three access tubes were placed down the vine row (directly below the drip line), one close to the trunk, one midway between vines within the row, and the third midway between the two previously mentioned tubes. Another three tubes were placed midway between rows, perpendicular to each of the three tubes placed within the row. The last three tubes were placed midway between the former two sets of tubes. Readings were taken at a depth of 0.23 and 0.45 m beneath the soil surface and then in increments of 0.3 m to a depth of 2.90 m. Each access tube site was replicated three times, in three of the eight replicated blocks, for each irrigation treatment. The neutron probe was calibrated according to Araujo et al. (1995), and SWC values expressed as percent by volume (θ_v). The SWC content at field capacity of this soil type was ~22.0% by volume while SWC at a soil moisture tension of -1.5 MPa was ~8.0% by volume. Therefore, total available water to a depth of 3 m for this soil was equivalent to 624 mm. The relationship between soil matric potential (Ψ_π) and SWC was determined as described by Araujo et al. (1995) and resulted in the following equation: soil $\Psi_\pi = -20.8 * \theta_v^{-2.22}$ ($R^2 = 0.91$).

Water-potential readings were conducted according to the procedures of Williams and Araujo (2002). Specifically, predawn Ψ (Ψ_{PD}) measurements began at ≈0330 hr and were finished before sunrise using a pressure chamber (model 1000; PMS Instrument Co., Corvallis, OR). Midday measurements of leaf (Ψ_l) and stem (Ψ_{stem}) water potentials generally were taken between 1230 and 1330 hr, PDT. Leaf blades for Ψ_{PD} and Ψ_l determinations were covered with a plastic bag, quickly sealed, and petioles then cut within 1 to 2 seconds. The time between leaf excision and chamber pressurization was generally <10 to 15 seconds. Leaves, chosen for Ψ_{PD}, Ψ_l, and Ψ_{stem} were fully expanded and mature. At midday, Ψ_l was measured on leaves exposed to direct solar radiation located on the south side of the east/west rows. Approximately 90 minutes before midday measurements, leaves for determination of Ψ_{stem} were enclosed in black plastic bags covered with aluminum foil. Leaves chosen for Ψ_{stem} measurements were of similar age and type as those used for Ψ_l but were located on the north side of the vines to minimize any possible heating effects. A single leaf from each of five individual vine replicates was measured and used for data analysis. Leaves for midday determinations of Ψ_l and Ψ_{stem} were not always taken from the same vines. Measurements of leaf Ψ were made in three (same blocks that SWC was measured) of the eight irrigation blocks. One to two leaves were chosen in each block so that n = 5.

Measurements of net CO_2 assimilation rates (A) and stomatal conductance (g_s) were taken subsequent to the measurements of midday Ψ_l and Ψ_{stem} and completed by 1400 hr when measured on the same day or between 1230 and 1330 hr on other days. Both measures of gas exchange were made with a portable infrared gas analyzer (model LCA-2; Analytical Development Co., Hoddeson, UK) using the broad leaf chamber. Leaves chosen for gas exchange were similar to those used for Ψ_l in the same blocks as mentioned above. Environmental and reference ET (ET_o) data were obtained from a California Irrigation Management Information System (CIMIS) weather station located 2 km from the vineyard site.

The Ψ and gas exchange measurements were collected from the 0, 0.2, 0.6, 1.0, and 1.4 irrigation treatments while SWC was only measured in the irrigated treatments. Data were analyzed via regression analysis using linear, quadratic, and cubic terms. Regressions with the best fit are presented. The relationships among water status measurements (Ψ_{PD}, Ψ_l, and Ψ_{stem}) and soil water content were analyzed using the means of an individual irrigation treatment. Differences in water potentials, A, g_s, and SWC among irrigation treatments were analyzed via analysis of variance and means separated using Duncan's multiple range test.

Results

Budbreak occurred on 15, 14, and 10 March in 1991, 1992, and 1993, respectively. Rainfall amounts between 1 Jan and the end of March in 1991, 1992, and 1993 were 236, 201, and 312 mm, respectively. The total amount of rainfall subsequent to 31 March and the end of the growing season each year was no greater than 18 mm.

Grapevine water use, measured with the lysimeter, from budbreak in 1993 to 17 Aug was 624 mm (4,711 L $vine^{-1}$). Water use before the initiation of irrigation was equivalent to 61 mm (464 L $vine^{-1}$). Water applied to the 1.0 irrigation treatment between the commencement of irrigation and 17 Aug was about 4,400 L $vine^{-1}$. Applied water amounts for the 0.2, 0.6, and 1.4 irrigation treatments were 21.3, 61.8, and 143.2% the amount of water applied to the 1.0 irrigation treatment, respectively.

Daily water use of the vines growing in the lysimeter on the dates Ψ measurements were taken ranged from 14 to greater than 50 L day^{-1}, with maximum hourly water use at midday greater than 6 L in July of both 1992 and 1993 (Table 1). Temperature at the time of midday measurements of Ψ ranged from 23 to almost 38°C while vapor pressure deficit (VPD) ranged from approximately 1 to 4 kPa. Solar radiation exceeded 830 W m^{-2} during the time of the midday measurements on all dates.

Despite a record amount of rainfall in early 1993, SWC of the four irrigated treatments were different from one another in April (Figure 1) because the same irrigation treatments had been in use the previous two growing seasons and there were significant differences in SWC at the end of both years (Table 2). Before the initiation of irrigation on 3 May 1993, SWC decreased for all treatments. Once irrigations commenced, SWC continued to decrease throughout the season for the 0.2 and 0.6 treatments, remained constant for the 1.0 treatment, and increased for

Table 1 Daily grapevine water use measured with the weighing lysimeter and ET_o and mean water use rate, ambient temperature, solar radiation (SR), and vapor pressure deficit (VPD) between 1200 and 1400 hr on dates in which Ψ measurements were made in 1991, 1992, and 1993 (see Tables 2 and 3). Water use of the vines divided by 7.55 (m^2 of surface area per vine within the vineyard) is equivalent to mm of water.

Day/Mo/Yr	Daily ET_c (L $vine^{-1}$)	Daily ET_o (mm)	Hourly ET_c (L $vine^{-1}$)	Temp (°C)	SR (W m^{-2})	VPD (kPa)
04/09/1991	41.6	5.44	5.44	34.1	833	3.25
14/07/1992	51.2	7.11	6.08	35.0	914	3.39
18/08/1992	41.6	6.27	5.56	37.7	867	3.98
28/04/1993	14.0	4.83	1.72	25.4	855	1.19
11/05/1993	22.4	5.30	2.64	22.7	899	0.89
09/06/1993	39.0	5.91	4.28	28.1	875	1.95
16/06/1993	46.8	6.81	5.56	29.1	952	2.17
07/07/1993	50.8	6.95	6.01	33.7	927	2.65
16/08/1993	36.8	5.91	4.88	27.4	885	1.96

the 1.4 treatment. There were differences in SWC as a function of depth and irrigation treatment both early and late in the 1993 growing season (Figure 2). There was a decrease in SWC down to a depth of 2.5 m for the 0.2 and 0.6 irrigation treatments from April to August with the decrease more pronounced at the shallower depths. The values of SWC at all depths for the 1.4 treatment remained fairly constant over the same time period, while those for the 1.0 treatment decreased slightly. Soil water content directly beneath the emitters was generally less down to a depth of ~1.5 m for the 0.2 and 0.6 irrigation treatments when compared to SWC measured midway between rows (data not given). This value was the opposite for the 1.0 and 1.4 irrigation treatments, as SWC was greater directly beneath the emitters compared to midrow.

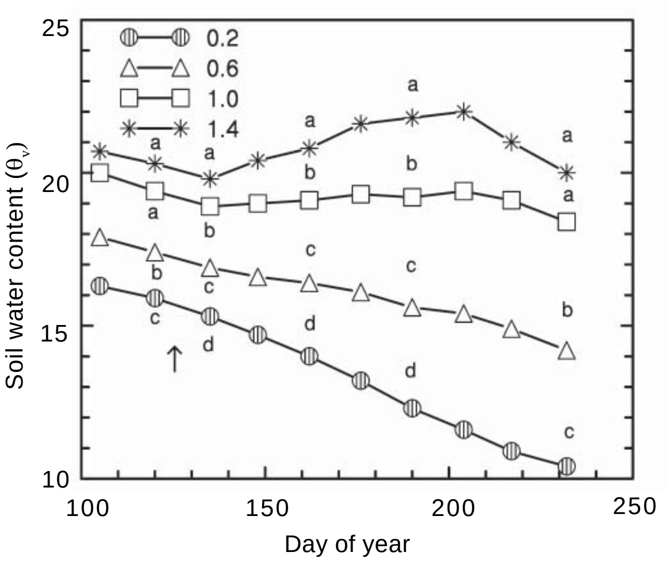

Figure 1 Soil water content for the four irrigated treatments measured during the 1993 growing season. Each data point is the mean of three access tube sites. The arrow represents the date (3 May) irrigations began. Data points accompanied by a different letter on the same date of measurement indicate significant differences among irrigation treatments at $p < 0.05$. Those dates corresponded to 30 April, 15 May, 11 June, 9 July, and 20 Aug 1993.

Measurements of Ψ_{PD}, Ψ_l, and SWC were only taken on 4 Sept in 1991 and 14 July and 18 Aug in 1992 (Table 2). On all three dates, there were significant differences in Ψ_l and SWC among all treatments. There were significant differences in Ψ_{PD} among the deficit-irrigated treatments, but not between the 1.0 and 1.4 treatments in 1991 or among the 0.6, 1.0, and 1.4 irrigation treatments in 1992. In most cases, Ψ_{PD} was lower than the mean soil Ψ_π and the greatest soil Ψ_π (illustrated in Table 2) for all irrigation treatments.

There were no significant differences in Ψ_{PD} among the irrigation treatments on 28 April 1993 (Table 3). The trend in values of midday Ψ_{stem} and Ψ_l on that date, however, resulted in significant differences among several treatments. The values of Ψ_{PD} were always lower than those of

Table 2 Soil water content (SWC), mean soil matric potential (Ψ_π), and Thompson Seedless predawn (Ψ_{PD}) and midday leaf (Ψ_l) water potentials measured on selected dates in 1991 and 1992 as a function of irrigation treatment. Irrigation treatments were applied water amounts at various fractions of lysimeter water use; SWC was measured only for the irrigated treatments; soil Ψ_π was calculated from the mean SWC for each treatment. The greatest soil Ψ_π column represents the matric potential of the wettest portion of the soil profile above the 1.7 m depth.

Calendar date[a]	Irrigation treatment	SWC[b] (θ_v)	Mean soil Ψ_π (MPa)	Greatest soil Ψ_π (MPa)	Ψ_{PD} (MPa)	Midday Ψ_l (MPa)
4 Sept 1991						
	0.2	8.8 d[c]	-0.17	-0.19	-0.18 c	-1.37 d
	0.6	10.5 c	-0.11	-0.09	-0.14 b	-1.15 c
	1.0	14.7 b	-0.05	-0.06	-0.08 a	-0.79 b
	1.4	17.8 a	-0.03	-0.04	-0.07 a	-0.65 a
14 July 1992						
	0.0	—	—	—	-0.66 c	-1.39 e
	0.2	9.1 d	-0.15	-0.19	-0.29 b	-1.27 d
	0.6	11.2 c	-0.10	-0.08	-0.12 a	-1.21 c
	1.0	13.7 b	-0.06	-0.04	-0.09 a	-0.99 b
	1.4	16.0 a	-0.04	-0.03	-0.10 a	-0.86 a
18 Aug 1992						
	0.0	—	—	—	-0.83 c	-1.51 e
	0.2	8.8 d	-0.17	-0.09	-0.19 b	-1.43 d
	0.6	10.9 c	-0.10	-0.08	-0.11 a	-1.05 c
	1.0	13.4 b	-0.07	-0.04	-0.07 a	-0.84 b
	1.4	16.7 a	-0.04	-0.03	-0.07 a	-0.69 a

[a]The last irrigation of the day on 3 Sept 1991, 13 July 1993, and 17 Aug 1993 occurred at 1700, 1700, and 1800 hr, respectively.
[b]SWC measured on 30 Aug 1991, 14 July 1992, and 19 Aug 1992.
[c]Means followed by a different letter within a column for a particular date are significantly different at $p < 0.05$.

soil Ψ_π on all dates for all treatments in 1993. Measurements of Ψ_{stem} and Ψ_l taken in May, June, and July resulted in more significant differences among irrigation treatments than did that of Ψ_{PD}. The use of either Ψ_{stem} or Ψ_l was equally good in discriminating among the irrigation treatments on most dates.

There were fewer significant differences among irrigation treatments in 1993 with regard to A and g_s (Table 4) than differences in measures of water potential. On 17 August, there were no significant differences in A among the three highest irrigation treatments. Differences in g_s among the irrigation treatments were not always reflected in differences among A.

Based on the data collected, Ψ_{stem} varied by as much as 0.6 MPa with less than a 0.1 MPa difference in Ψ_{PD} (Figure 3). The range in Ψ_l measured at midday at a Ψ_{PD} between -0.05 and -0.2 MPa ranged from -0.5 to less than -1.4 MPa (Figure 4). There was a linear relationship between

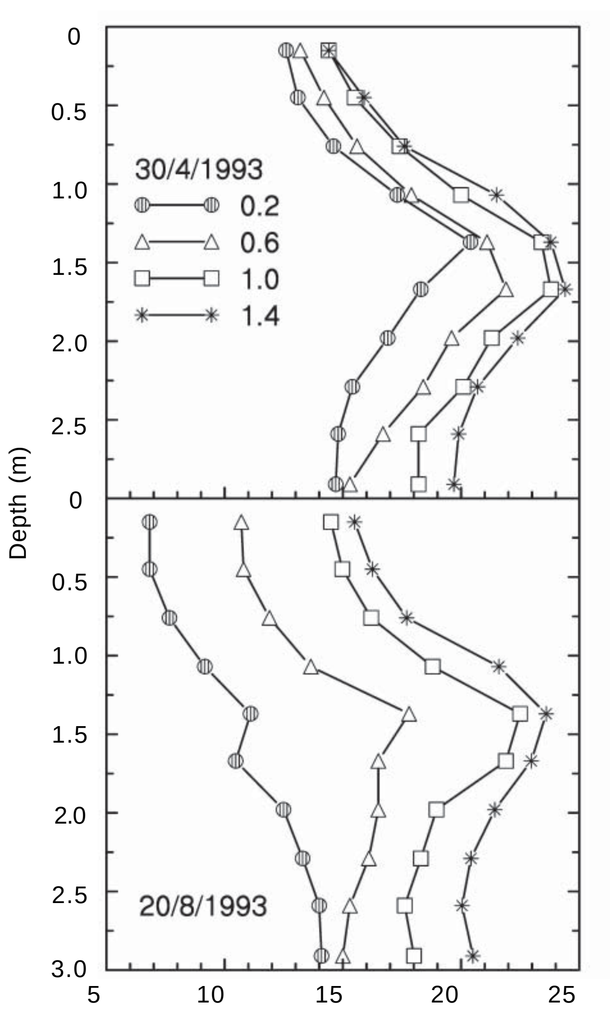

Figure 2 Soil water content as a function of depth below the soil surface and irrigation treatment just before the first irrigation of the 1993 growing season (see Figure 1) and on the last date physiology measurements were taken. Each data point is the mean of 27 values (nine access tubes per site, replicated three times). 30 April and 20 Aug are days of year 120 and 232, respectively.

Table 3 Soil matric potential and Thompson Seedless water potentials measured in 1993 as a function of irrigation treatment. Irrigation treatments were applied water amounts at various fractions of lysimeter water use. Irrigations began on 3 May. Other information as given in Table 2.

Calendar date[a]	Irrigation treatment	Mean soil Ψ_π (MPa)	Ψ_{PD} (MPa)	Midday Ψ_{stem} (MPa)	Midday Ψ_l (MPa)
28 April					
	0.0	—	-0.13 a[b]	-0.48 d	-0.75 d
	0.2	-0.05	-0.13 a	-0.42 c	-0.68 c
	0.6	-0.04	-0.13 a	-0.39 c	-0.68 c
	1.0	-0.03	-0.13 a	-0.31 b	-0.59 b
	1.4	-0.03	-0.10 a	-0.26 a	-0.51 a
11 May					
	0.0	—	-0.12 c	-0.49 d	-0.68 d
	0.2	-0.05	-0.12 c	-0.41 c	-0.63 c
	0.6	-0.04	-0.12 c	-0.34 b	-0.59 b
	1.0	-0.03	-0.10 b	-0.32 b	-0.54 a
	1.4	-0.03	-0.08 a	-0.25 a	-0.51 a
9 June					
	0.0	—	-0.14 b	-0.62 c	-0.95 d
	0.2	-0.06	-0.14 b	-0.47 b	-0.89 c
	0.6	-0.04	-0.12 b	-0.43 b	-0.74 b
	1.0	-0.03	-0.12 b	-0.36 a	-0.65 a
	1.4	-0.03	-0.09 a	-0.32 a	-0.61 a
16 June					
	0.0	—	-0.12 c	-0.69 c	-1.05 d
	0.2	-0.07	-0.12 c	-0.55 b	-0.98 c
	0.6	-0.04	-0.08 b	-0.49 b	-0.86 b
	1.0	-0.03	-0.07 b	-0.42 a	-0.78 a
	1.4	-0.02	-0.05 a	-0.35 a	-0.76 a
7 July					
	0.0	—	-0.18 c	-0.85 e	-1.10 e
	0.2	-0.08	-0.15 b	-0.74 d	-0.96 d
	0.6	-0.05	-0.07 a	-0.48 c	-0.77 c
	1.0	-0.03	-0.06 a	-0.32 b	-0.63 b
	1.4	-0.02	-0.06 a	-0.25 a	-0.55 a
16 Aug					
	0.0	—	-0.50 d	—[c]	-1.29 d
	0.2	-0.12	-0.22 c	—	-1.03 c
	0.6	-0.06	-0.18 b	—	-0.69 b
	1.0	-0.03	-0.08 a	—	-0.57 a
	1.4	-0.03	-0.07 a	—	-0.54 a

[a]The last irrigation of the day previous to the five measurement dates listed above starting on 11 May occurred at 1800, 1600, 1900, 1900, and 1900 hr, respectively.
[b]Means followed by a different letter within a column for a particular date are significantly different at $p < 0.05$.
[c]Stem Ψ was not measured on 16 Aug.

Ψ_l and Ψ_{PD} at Ψ_l values less than -1.0 MPa for the nonirrigated treatment. Using all irrigation treatments on the dates Ψ_{stem} was measured in 1993, there was a significant linear relationship between Ψ_l and Ψ_{stem} (Figure 5).

The relationship between both measures of midday Ψ for the 1.0 and 1.4 irrigation treatments and VPD at the time of measurements on all dates was determined. The relationship between Ψ_l and VPD was best described by a linear function, Ψ_l = -0.434 - 0.099 * VPD, (R^2 = 0.51; p < 0.001), while that for Ψ_{stem} was Ψ_{stem} = -0.23 - 0.058 * VPD, (R^2 = 0.28).

All three measures of vine water status were significantly related with SWC (Figure 6) and soil Ψ_π (Table 5). The best regressions between SWC or soil Ψ_π were midday measurements of Ψ_l and Ψ_{stem}. In most cases, Ψ_{PD} was lower than the calculated mean soil Ψ_π across the irri-

Table 4 Leaf net CO_2 assimilation rate (A) and stomatal conductance (g_s) of Thompson Seedless grapevines measured at midday on selected dates during the 1993 growing season. Other information as found in Table 3.

Calendar date	Irrigation treatment	A (μmol CO_2 m^{-2} s^{-1})	g_s (mmol H_2O m^{-2} s^{-1})
11 June			
	0.0	13.6 c	413 c
	0.2	13.9 c	429 c
	0.6	14.6 c	497 b
	1.0	16.4 b	648 a
	1.4	17.8 a	623 a
7 July			
	0.0	9.8 d	208 d
	0.2	12.6 c	360 c
	0.6	13.9 bc	579 b
	1.0	15.7 a	692 a
	1.4	15.5 ab	652 ab
16 Aug			
	0.0	6.2 c	184 d
	0.2	9.9 b	345 c
	0.6	14.5 a	680 b
	1.0	13.7 a	637 b
	1.4	14.3 a	842 a

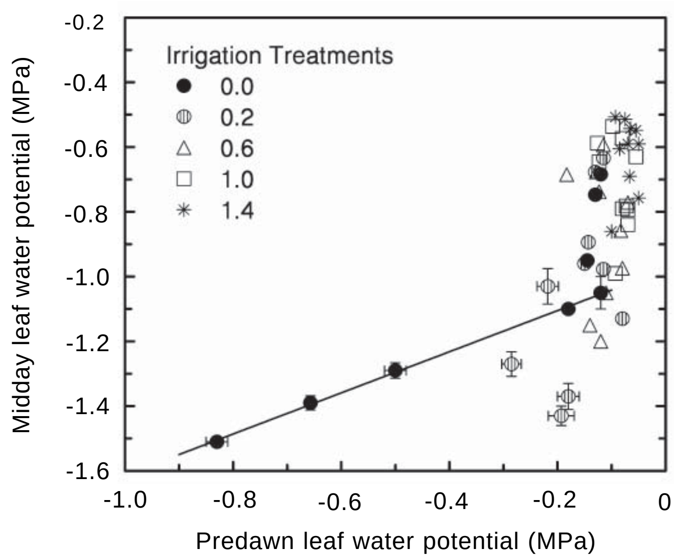

Figure 4 Thompson Seedless midday Ψ_l as a function of Ψ_{PD} for four irrigation treatments measured in 1991 and five treatments measured in 1992 and 1993. Each data point is the mean of a single leaf measured on five different vines. A linear regression was run through the five lowest data points of the 0 irrigation treatment (y = -0.978 + 0.635x). Standard error bars are given (where larger than the symbol) for the 0 irrigation treatment data points located along the linear regression line and several data points of the 0.2 irrigation treatment.

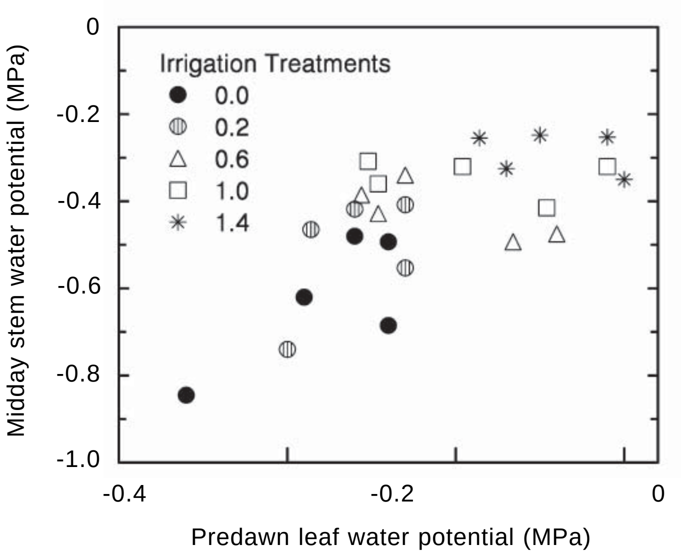

Figure 3 Thompson Seedless midday Ψ_{stem} as a function of Ψ_{PD} for the five irrigation treatments measured in 1993. Each data point is the mean of a single leaf measured on five different vines.

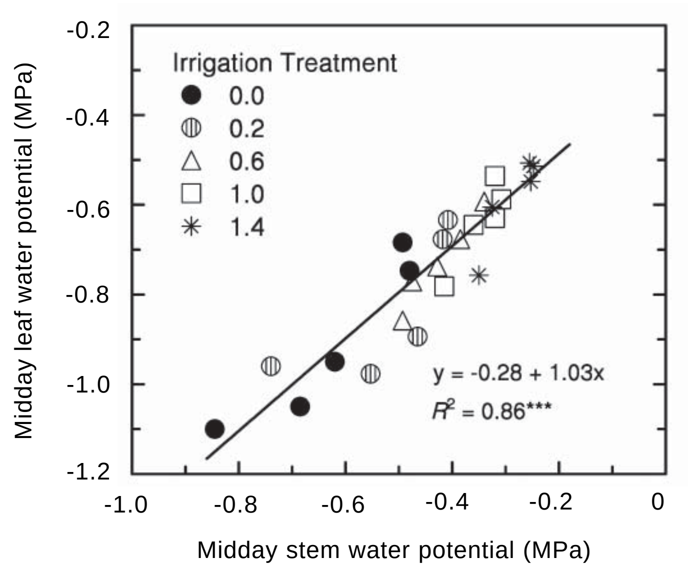

Figure 5 The relationship between Thompson Seedless midday Ψ_l and Ψ_{stem} measured in 1993. Other information is as given in Figure 4. (*** indicates significance at p < 0.001.)

gation treatments. Lastly, the irrigation treatments' seasonal means of Ψ_{stem} and Ψ_l from 1993 as a function of irrigation treatment resulted in significant differences among several of the treatments (Figure 7). As applied water amounts increased so did all values of vine water status. It appeared that all approached an asymptote at the 1.0 irrigation treatment.

Discussion

It was assumed that vines in the surrounding vineyard irrigated with the same amounts of water as those in the lysimeter (1.0 irrigation treatment) would not be stressed and that vine water use would be similar to the two vines growing in the lysimeter (Table 1). Water potential (Ψ_{PD}, Ψ_{stem}, and Ψ_l) readings taken at the end of the 1991 and 1992 growing seasons and throughout the 1993 growing season indicated that the 1.0 irrigation treatment was not stressed based upon previously published values of Ψ measured on Thompson Seedless grapevines (Grimes and Williams 1990). In addition, the fact that SWC remained constant once irrigations commenced indicated that water application were sufficient to meet vine water requirements.

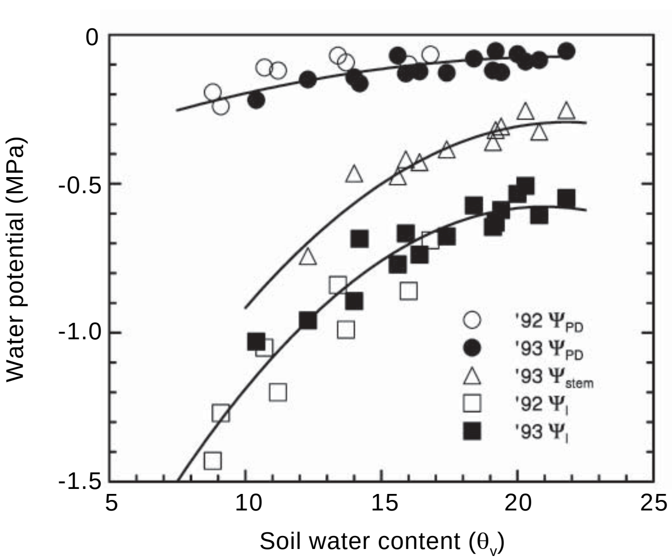

Figure 6 The relationship between three methods of measuring vine water status and SWC. The Ψ_{PD} and Ψ_l data were collected in 1991, 1992, and 1993 and the Ψ_{stem} data only in 1993. The Ψ values as a function of SWC were fitted to the following quadratic equations: $\Psi_{PD} = -0.36 + 0.025x - 0.000555x^2$, $R^2 = 0.52$***; $\Psi_{stem} = -2.42 + 0.195x - 0.00447x^2$, $R^2 = 0.90$***; $\Psi_l = -2.79 + 0.21x - 0.0050x^2$, $R^2 = 0.94$***, where x = SWC (*** indicates significance at $p < 0.001$).

Table 5 Relationships among predawn leaf (Ψ_{PD}), midday leaf (Ψ_l), and midday stem (Ψ_{stem}) water potentials for the irrigated treatments and mean soil matric potential (x in the equations below) (n = 36).

Ψ measurement	Regression[a]
Ψ_{PD}	y = -0.059 + 0.94x ($R^2 = 0.56$***)
Ψ_l	y = -0.476 + 5.72x ($R^2 = 0.88$***)
Ψ_{stem}	y = -0.126 + 6.85x ($R^2 = 0.83$***)

[a]*** indicates significance at $p < 0.001$.

Plant-based measurements must be consistent and sensitive to plant water status if they are used as a tool in irrigation management (Hsiao 1990, McCutchan and Shackel 1992, Selles and Berger 1990, Shackel et al. 1997, Strièeviæ and Èaki 1997). In this study significant differences among treatments for both Ψ_{stem} and Ψ_l occurred when differences were 0.05 MPa or greater. That is similar to what McCutchan and Shackel (1992) found for Ψ_{stem} of prune, but they were unable to detect significant differences at the same value (0.05 MPa) for Ψ_l. Chone et al. (2001) were able to measure significant differences in grape Ψ_{stem} when differences were 0.06 MPa but only detected differences in Ψ_l among treatments at differences of 0.16 MPa. In another study on grape (Williams and Araujo 2002), there were instances where differences in Ψ_{stem} and Ψ_l of 0.12 and 0.15 MPa, respectively, between treatments were not significantly different. The ability to detect significant differences in Ψ among treatments for a particular study could be due to its experimental design, absolute differences in soil water availability among treatments, environmental conditions at the time of measurement, or plant species. Another significant source of error may be that of the operator (Goldhamer and Fereres 2001) or the techniques used in measuring Ψ_l of grape (that is, not covering the leaf in a plastic bag just before cutting the petiole and placing the bagged leaf into the pressure chamber; Williams and Araujo 2002).

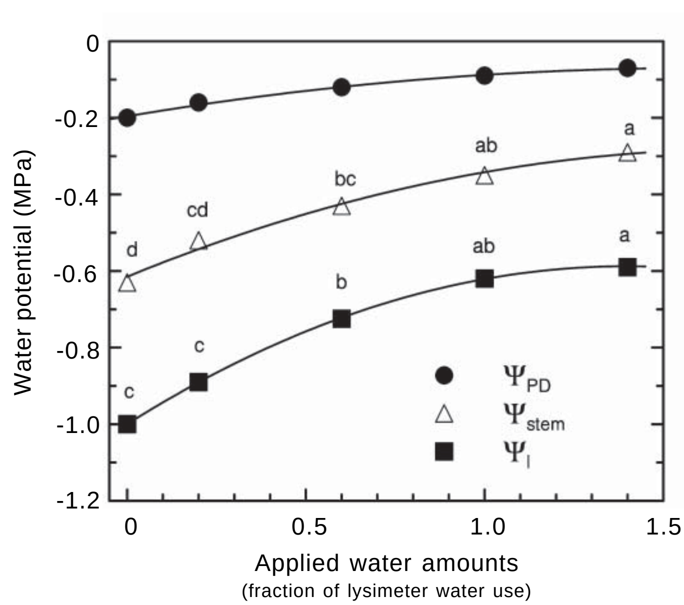

Figure 7 Seasonal mean Thompson Seedless Ψ values measured in 1993 as a function of irrigation treatment. Data points for a particular method of determining vine water status accompanied by a different letter are significantly different at $p < 0.05$. There were no significant differences in seasonal mean Ψ_{PD} among irrigation treatments. The five data points of all three methods to measure vine water status were fitted to quadratic equations.

Plant-based measurements of water status should reflect the amount of water available in the soil profile (Higgs and Jones 1990, Jones 1990). In this study all three measurements of vine Ψ were significantly related with SWC and soil Ψ_π, although R^2 values of Ψ_{stem} and Ψ_l were greater than that of Ψ_{PD} in both cases. The curvilinear relationships of Ψ_{stem} and Ψ_l to SWC in this study are similar to those reported on other plant species (Hensen et al. 1989, Jensen et al. 1989, Qian and Fry 1997, Saliendra and Meinzer 1989). McCutchan and Shackel (1992) found a curvilinear relationship between SWC and the difference in prune Ψ_{stem} between the dry and irrigated treatments. Garnier and Berger (1987) reported a linear relationship between Ψ_l of peach and SWC; however, it appears a curvilinear function could also have fit the data. Stem and leaf Ψs at 50% depletion of plant available water for this particular soil type (≈13% by volume) would be -0.64 and -0.9 MPa, respectively, based upon the curves generated in Figure 6. As SWC approached field capacity, midday Ψ_{stem} and Ψ_l leveled off at values of -0.3 and -0.55 MPa, respectively. The response of the seasonal mean Ψ_{stem} and Ψ_l also leveled off as applied water amounts approached full ET_c (Figure 7). While the data in Figure 7 were fitted to a quadratic function, a linear function would almost have fit the data equally well ($R^2 > 0.9$). Lampinen et al. (1995) also found that midday Ψ_{stem} of prune was linearly related to applied water amounts.

Plant-based measurements for the determination of water status during daylight hours, such as Ψ_{stem} and Ψ_l, are affected by variations in the environment and evaporative demand (Jones 1990). Leaf Ψ of grapevines is affected by solar radiation, relative humidity, VPD, and temperature (Smart and Barrs 1973, van Zyl 1987). Stem Ψ of non-water-stressed prune trees was most highly correlated with that of VPD when compared to other environmental factors (McCutchan and Shackel 1992). The environmental data presented in Table 1 demonstrates that there were differences in temperature and VPD during the time midday Ψ measurements were taken but only small variations in solar radiation. Therefore, radiation can be eliminated as a source of variation for both midday measurements of vine Ψ in this study. Since there is a strong linear relationship between ambient temperature and VPD in semiarid environments (Grimes et al. 1987), the relationship between both measures of midday Ψ for the 1.0 and 1.4 irrigation treatments and VPD were determined. The results indicated that Ψ_l of vines in the fully irrigated treatments decreased from a value of -0.53 MPa at a VPD of 1.0 kPa to -0.83 MPa at a value of 4.0 kPa. These values of Ψ_l (or Ψ_{stem}) may serve as an upper limit for non-water-stressed grapevines, similar to that proposed for prune by McCutchan and Shackel (1992) with Ψ_{stem}. Some of the decrease in Ψ_l as a function of VPD found in this grape study may have been due to the fact that SWC was less in 1991 and 1992, when VPDs were higher, compared to 1993 (Table 1).

While the relationship between VPD and Ψ_{stem} in this study was not significant (probably because of the limited number of measurements), it is interesting that the slope (b = 0.058) was very similar to that recorded for Colombard grapevines (b = 0.052) in Australia (Stevens et al. 1995). Both of these slopes are less than half that (b = 0.12) found by McCutchan and Shackel (1992) for prune, perhaps reflecting differences among species regarding the effects of VPD on g_s and subsequent effects on water relations.

Measurements of midday Ψ_{stem} and Ψ_l in this study were equally good in detecting differences among irrigation treatments throughout the growing season. That is not surprising, as midday Ψ_{stem} and Ψ_l of grapevines were linearly related with one another in this study using measurements taken from early in the growing season until July. Stem Ψ and Ψ_l were also linearly related when the measurements were taken late in the season (Williams and Araujo 2002) or on a diurnal basis (Stevens et al. 1995) using other grape cultivars. Direct comparisons between Ψ_{stem} and Ψ_l on other plant species are limited. Naor et al. (1995) only found a weak relationship between Ψ_{stem} and Ψ_l of apple. However, if one examines the seasonal midday Ψ_{stem} and Ψ_l data of Selles and Berger (1990) on peach and the data of McCutchan and Shackel (1992) on prune, both Ψ measurements would probably be highly correlated with one another.

Under the conditions of this study, the data indicate that midday Ψ_{stem} or Ψ_l would be a better indicator of vine water status than Ψ_{PD}. It is often assumed that Ψ_{PD} is a measure of the availability of water in the soil profile (Correia et al. 1995, Schultz 1996, Strièeviæ and Èati 1997, Winkel and Rambal 1993) and is related to gas exchange measured later in the day (Correia et al. 1995, Reich and Hinckley 1989, Running 1976). Several studies, though, have demonstrated that Ψ_{PD} is not in equilibrium with soil moisture (Cuelemans et al. 1988, Garnier and Berger 1987) or it is in equilibrium with the wettest portion of the soil profile (Ameglio et al. 1999, Tardieu and Katerji 1991). Others have also found significant differences in Ψ_l and/or Ψ_{stem} measured later in the day but no significant differences in Ψ_{PD} (Chone et al. 2001, Williams and Araujo 2002), as was found here. In this study, values of Ψ_{PD} were always slightly more negative than the mean soil Ψ_π or the Ψ_π of the wettest portion of the soil profile above 1.7 m in depth. Regardless of being more negative, it would appear that the values of Ψ_{PD} in this study were more closely aligned with the mean soil Ψ_π and not the Ψ_π of the wettest portion of the soil profile. Results from this study also demonstrate that the measurement of SWC to a depth of 3 m and out to the center between rows was necessary to determine accurately the amount of water in the soil profile available to the vines. This may have important implications for accurately modeling the soil water balance of vineyards (Lebon et al. 2003).

There may be several reasons as to why Ψ_{PD} was consistently lower than that of mean soil Ψ_π in this study. Of the 36 Ψ_{PD} values measured for the irrigated treatments, 34 were greater than -0.2 MPa, 31 were greater than -0.15

MPa, and 20 were greater than -0.1 MPa. The ability to measure such low values with the pressure chamber used in this study may have precluded an accurate determination of their values. Alternatively, operator technique could have consistently pressurized the chamber slightly beyond the true balance pressure. Lastly, the driest portions of the soil profile may have had more of an effect on the Ψ_{PD} values of vines than that of the wettest portions, which has previously been reported for cotton (Jordan and Richie 1971).

The strong relationships among midday Ψ_l and Ψ_{stem} and SWC and soil Ψ_π found here indicate that both were better than Ψ_{PD} in assessing soil water availability under the conditions of this study. It has been pointed out that the flux of water from the soil to plant is at a daily maximum at midday and the equilibrium between soil Ψ and vine Ψ depends on the rate at which water moves from the bulk soil to the roots (Stevens et al. 1995). Therefore, the equilibrium between soil Ψ and vine Ψ at midday would differ from that at predawn where there is a low flux of water and that midday measures of Ψ_l and Ψ_{stem} would more accurately reflect these differences.

Conclusions

This study was unique in that the control irrigation treatment was the amount of water used by vines growing in a weighing lysimeter and that the other treatments of applied water were various fractions, greater and less than that of the control. In addition, the high frequency of irrigation ensured that the control vines received the amount of water that was being used in some instances on an hourly or bi-hourly basis during periods of high evaporative demand. Therefore, it can be assumed that the 1.0 treatment would not have been stressed for water at anytime during the day even though water use was similar to or greater than reference ET on many occasions.

It appears that Ψ_{PD}, Ψ_{stem}, and Ψ_l values greater than -0.12, -0.6, and -1.0 MPa, respectively, would indicate that Thompson Seedless grapevines would not be stressed for water and are transpiring at close to full ET_c in this study. The nonstressed values for Ψ_{stem} and Ψ_l would account for the effects of a VPD of at least 4 kPa at the time measurements were taken.

The measurements of midday Ψ_{stem} and Ψ_l of Thompson Seedless grapevines were equally good in detecting significant differences among the treatments early in the season apparently before significant stress had occurred. Both midday Ψ_{stem} and Ψ_l had previously been shown to detect such differences late in the growing season on two different grape cultivars. In addition, both measures of midday Ψ were similarly affected by SWC, soil Ψ_π, and applied water amounts in this study. Thus, either method of measuring water potential could be recommended for assessing vine water status in nonirrigated or irrigated vineyards or deficit-irrigated vineyards, regardless of the irrigation frequency.

Literature Cited

Ameglio, T., P. Archer, M. Cohen, C. Valacogne, F.A. Daudet, S. Dayau, and P. Cruiziat. 1999. Significance and limits in the use of predawn leaf water potential for tree irrigation. Plant Soil 207:155-167.

Araujo, F., L.E. Williams, D.W. Grimes, and M.A. Matthews. 1995. A comparative study of young 'Thompson Seedless' grapevines under drip and furrow irrigation. I. Root and soil water distributions. Sci. Hortic. 60:235-249.

Chone, X., C. Van Leeuwen, D. Dubourdieu, and J.P. Gaudillere. 2001. Stem water potential is a sensitive indicator for grapevine water status. Ann. Bot. 87:477-483.

Correia, M.J., J.S. Pereira, M.M. Chaves, M.L. Rodrigues, and C.A. Pacheco. 1995. ABA xylem concentrations determine maximum daily leaf conductance of field-grown *Vitis vinifera* L. plants. Plant Cell Environ. 18:511-521.

Cuelemans, R., I. Impens, M.C. Laker, F.M.G. Van Assche, and R. Mottram. 1988. Net CO_2 exchange rate as a sensitive indicator of plant water status in corn (*Zea mays* L.). Can. J. Plant Sci. 68:597-606.

Garnier, E., and A. Berger. 1985. Testing water potential in peach trees as an indicator of water stress. J. Hortic. Sci. 60:47-56.

Garnier, E., and A. Berger. 1987. The influence of drought on stomatal conductance and water potential of peach trees growing in the field. Sci. Hortic. 32:249-263.

Goldhamer, D.A., and E. Fereres. 2001. Simplified tree water status measurements can aid almond irrigation. Calif. Agric. 55:32-37.

Grimes, D.W., and L.E. Williams. 1990. Irrigation effects on plant water relations and productivity of 'Thompson Seedless' grapevines. Crop Sci. 30:255-260.

Grimes, D.W., H. Yamada, and S.W. Hughes. 1987. Climate-normalized cotton leaf water potentials for irrigation scheduling. Agric. Water Man. 12:293-304.

Hensen, I.E., C.R. Jensen, and N.C. Turner. 1989. Leaf gas exchange and water relations of lupins and wheat. I. Shoot responses to soil water deficits. Aust. J. Plant Physiol. 16:401-413.

Higgs, K.H., and H.G. Jones. 1990. Response of apple rootstocks to irrigation in south-east England. J. Hortic. Sci. 65:129-141.

Hsiao, T.C. 1990. Measurements of plant water status. *In* Irrigation of Agricultural Crops. B.A. Stewart and D.R. Nielsen (Eds.), pp. 243-280. Agronomy monograph # 30. ASA-CSSA-SSSA, Madison, WI.

Jensen, C.R., I.E. Henson, and N.C. Turner. 1989. Leaf gas exchange and water relations of lupins and wheat. II. Root and shoot water relations of lupin during drought-induced stomatal closure. Aust. J. Plant Physiol. 16:415-428.

Jones, H.G. 1990. Physiological aspects of the control of water status in horticultural crops. HortScience 25:19-26.

Jordan, W.P., and J.T. Ritchie. 1971. Influence of soil water stress on evaporation, root absorption and internal water status in cotton. Plant Physiol. 48:783-788.

Koide, R.T., R.H. Robichaux, S.R. Morse, and C.M. Smith. 1989. Plant water status, hydraulic resistance and capacitance. *In* Plant Physiological Ecology: Field Methods and Instrumentation. R.W. Pearcy et al. (Eds.), pp. 161-183. Chapman and Hall, New York.

Lampinen, B.D., K.A. Shackel, S.M. Southwick, B. Olson, J.T. Yeager, and D. Goldhamer. 1995. Sensitivity of yield and fruit quality of French prune to water deprivation at different fruit growth stages. J. Am. Soc. Hortic. Sci. 120:139-147.

Lebon, E., V. Dumas, P. Pieri, and H.R. Schultz. 2003. Modelling the seasonal dynamics of the soil water balance of vineyards. Funct. Plant Biol. 30:699-710.

McCutchan, H., and K.A. Shackel. 1992. Stem-water potential as a sensitive indicator of water stress in prune trees (*Prunus domestica* L. cv. French). J. Am. Soc. Hortic. Sci. 117:607-611.

Naor, A. 1998. Relations between leaf and stem water potentials and stomatal conductance in three field-grown woody species. J. Hortic. Sci. Biotech. 73:431-436.

Naor, A., I. Klein, and I. Doron. 1995. Stem water potential and apple size. J. Am. Soc. Hortic. Sci. 120:577-582.

Naor, A., and R.L. Wample. 1994. Gas exchange and water relations of field-grown ‘Concord’ (*Vitis labruscana* Bailey) grapevines. Am. J. Enol. Vitic. 45:333-337.

Qian, Y., and J.D. Fry. 1997. Water relations and drought tolerance of four turfgrasses. J. Am. Soc. Hortic. Sci. 122:129-133.

Reich, P.B., and T.M. Hinckley. 1989. Influence of pre-dawn water potential and soil-to-leaf hydraulic conductance on maximum daily leaf diffusive conductance in two oak species. Funct. Ecol. 3: 719-726.

Running, S.W. 1976. Environmental control of leaf water conductance in conifers. Can. J. For. Res. 6:104-112.

Saliendra, N.Z., and F.C. Meinzer. 1989. Relationship between root/soil hydraulic properties and stomatal behavior in sugarcane. Aust. J. Plant Physiol. 16:241-250.

Schultz, H.R. 1996. Water relations and photosynthetic responses of two grapevine cultivars of different geographical origin during water stress. Acta Hortic. 427:251-266.

Selles, G., and A. Berger. 1990. Physiological indicators of plant water status as criteria for irrigation scheduling. Acta Hortic. 278:87-100.

Shackel, K.A., et al. 1997. Plant water status as an index of irrigation need in deciduous fruit trees. HortTechnology 7:23-29.

Smart, R.E., and H.D. Barrs. 1973. The effect of environment and irrigation interval on leaf water potential of four horticultural species. Agric. Meteorol. 12:337-346.

Stevens, R.M., G. Harvey, and D. Aspinall. 1995. Grapevine growth of shoots and fruit linearly correlate with water stress indices based on root-weighted soil matric potential. Aust. J. Wine Grape Res. 1:58-66.

Strièeviæ, R., and E. Èati. 1997. Relationships between available soil water and indicators of plant water status of sweet sorghum to be applied in irrigation scheduling. Irr. Sci. 18:17-21.

Tardieu, F., and N. Katerji. 1991. Plant response to the soil water reserve: Consequences of the root system environment. Irr. Sci. 12:145-152.

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.

Williams, L.E., and F. Araujo. 2002. Correlations among predawn leaf, midday leaf, and midday stem water potential and their correlations with other measures of soil and plant water status in *Vitis vinifera* L. J. Am.Soc. Hortic. Sci. 127:448-454.

Williams, L.E., N.K. Dokoozlian, and R.L. Wample. 1994. Grape. *In* Handbook of Environmental Physiology of Fruit Crops. Vol. 1. Temperate Crops. B. Shaffer and P.C. Anderson (Eds.), pp. 83-133. CRC Press, Orlando, FL.

Williams, L.E., and M.A. Matthews. 1990. Grapevines. *In* Irrigation of Agricultural Crops. B.A. Stewart and D.R. Nielsen (Eds.), pp. 1019-1055. Agronomy monograph 30. ASA-CSSA-SSSA, Madison, WI.

Williams, L.E., C.J. Phene, D.W. Grimes, and T.J. Trout. 2003a. Water use of young Thompson Seedless grapevines in California. Irr. Sci. 22:1-9.

Williams, L.E., C.J. Phene, D.W. Grimes, and T.J. Trout. 2003b. Water use of mature Thompson Seedless grapevines in California. Irr. Sci. 22:11-18.

Winkel, T., and S. Rambal. 1993. Influence of water stress on grapevines growing in the field: From leaf to whole-plant response. Aust. J. Plant Physiol. 20:143-157.