Measurement of Water Flow in Young Grapevines Using the Stem Heat Balance Method

R. J. LASCANO[1]*, R. L. BAUMHARDT[2], and W. N. LIPE[3]

There are numerous published discussions on the water use and water requirements of grapes (*Vitis vinifera*, L.), but data on the actual water use of individual plants in an undisturbed field environment are not available. We assessed the applicability of the stem heat balance method, using commercially available gauges, to determine the daily and seasonal water use of three-year-old Chardonnay plants in New Deal, TX. We first evaluated the gauges in the field by simultaneously measuring the hourly and daily water use of a potted three-year-old Cabernet Sauvignon plant gravimetrically and with a stem flow gauge. Second, we measured, over a period of 100 days between anthesis and harvest, starting on 17 May 1990, the daily sap flow of five Chardonnay plants in a vineyard that was irrigated by flooding. Our results show that the stem flow gauges were accurate within 5% to 10% of the daily value of transpiration as measured gravimetrically. The mean cumulative sap flow of the plants in the field over the entire measurement period was 461 ± 44 kg/plant or 124 ± 12 mm on an area basis. When the total sap flow for each plant was normalized by its leaf area, the variability among plants was greatly reduced. The mean cumulative evapotranspiration (ET) over the 100-day period was measured as 528 ± 13 mm, implying that soil evaporation was 77% of ET. We conclude: *(1)* that the stem heat balance method is capable of accurately measuring the daily water use of grape plants in the field; *(2)* that for our experimental conditions, the water use by the grape plants was low compared to the total water loss from the field, to the water use of other field crops in the same area, and to the calculated potential ET of 870 mm.

KEY WORDS: water use, transpiration, stem flow gauge, evapotranspiration, *Vitis vinifera*

Water use in a vineyard (*Vitis vinifera* L.) is a function of the energy and water balance of each plant and of the exposed soil surface. The measurement of either balance is difficult due to the wide row spacing which produces large diurnal variations in exposure of plants and soil to solar radiation. Furthermore, direct measurement of water use in vineyards by traditional methods, *e.g.*, water balance methods, is awkward due to problems also associated with wide row spacing. Nevertheless, grape water use studies have been conducted at three levels: leaf, plant, and community (24).

At the leaf level, grapevine transpiration has been estimated mostly from porometry measurements. The reported values, for a wide range of conditions, ranged one order of magnitude, from 0.02 to 0.29 mm/h (3,17,19,23). The usefulness of these results is limited because extrapolation of single leaf measurements to the plant and community levels requires information about the position of each leaf within the canopy, *i.e.*, canopy architecture, and of each plant within the vineyard.

At the whole plant level, measurements of water use have been obtained from either potted plants or from field lysimeters (3,8,9,12). Results from potted plants, when compared to field plants, are difficult to interpret because of drastic differences in their above- and below-ground environment. In contrast, lysimeters can provide accurate estimates of evapotranspiration (ET), provided conditions inside the lysimeter are similar to those of surrounding plants. However, in the case of grapes, the use of lysimeters is not a practical method to measure ET due to the extensiveness of root systems of commercially grown varieties. Reported values of annual ET for a wide range of environmental conditions and varieties ranged between 150 to 800 mm, as reported by Smart and Coombe (24), Williams and Matthews (27), and Evans *et al.* (8).

At the community level, grape water use is normally estimated by empirically relating potential evapotranspiration (PET) to pan evaporation and to a so-called crop coefficient (4,8,18). The application of this procedure is equally limited because crop coefficients are both crop- and site-specific. Furthermore, these procedures give estimates of water requirement, but not of water use. Another way of estimating water use at the community level is by using water balance methods; see examples given by Williams and Matthews (27), using seasonal values of rainfall and irrigation amounts and by measuring water use with the neutron attenuation method. This procedure is limited by the problem of deciding where to place access tubes and how many tubes are needed to adequately measure water use of a vineyard. Also, the neutron method lacks the necessary resolution to measure daily values of water use.

While many studies have been made of the water use and water requirements of grapes, information about the water use of individual plants in an undisturbed field setting is not available. Direct measurement of water use from single plants without altering the environmental or physiological factors that affect transpiration is now possible using the stem steady-

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[1]Assistant Professor, [2]Research Associate, and [3]Professor, Texas Agricultural Experiment Station, Rt. 3, Box 219, Lubbock, TX 79401-9757.

*Author to whom correspondence should be addressed.

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state heat balance method developed by Sakuratani (20,21). This technique has been used to measure the water use of crops such as cotton (2,6,11), tomatoes (21), sunflower (2,10,20), soybeans (21), rice (22), and horticultural plants including trees (7,25,26) and ornamental shrubs (13). To our knowledge, this technique has not been applied to grape plants. Thus, the purpose of this work was to evaluate the applicability of the stem heat balance method to measure water use in grape plants and to measure over a 100-day period the water use of five three-year-old Chardonnay grapevines using commercially available stem flow gauges.

Theory

The theory and principles of operation of the stem steady-state heat balance method are given elsewhere (1,2,10,25). For additional information, the reader is also referred to the review of the measurement of sap flow in stems given by Dugas (5). Briefly, the method works by applying a known amount of heat to a small segment of the stem from a thin flexible heater that surrounds the stem and is itself encircled by foam insulation. In steady state, heat input from the heater is balanced by the heat fluxes out of the stem. The heat output consists of four components: conduction up the stem, conduction down the stem, radial conduction through the foam sheath, and convection in the sap flow through the stem. Thus, the energy balance of the heated stem is given by

$$P - (q_u + q_d + q_r + q_f + S) = 0.0 \qquad \text{[Eq. 1]}$$

where P is the power (heat flux) applied to the heater, q_u and q_d are the conductive heat fluxes above and below the heater, respectively, q_r is the radial heat outward from the stem, q_f is the convective heat flux carried by the sap, and S is a storage term. The magnitude of S is small compared to the other terms in Equation 1 and can be assumed to be zero (10). All terms in Equation 1 are expressed in units of power, W.

The power of the heater (P) is calculated from the input voltage (V) in volts and the resistance (R) in ohms of the heater (*i.e.*, $P = V^2/R$). Conductive fluxes above and below the heater (q_u and q_d) in W are calculated by applying Fourier's law:

$$q_{u,d} = K_{st} \cdot A \cdot dT_{u,d}/dx \qquad \text{[Eq. 2]}$$

where K_{st} is the thermal conductivity of the stem (W/m °C), A is the cross sectional area of the stem (m²), and $dT_{u,d}/dx$ are the temperature gradients (°C/m) above and below the heater. Temperature differences, $dT_{u,d}$, are measured with a pair of thermocouples separated by a distance dx (m), differentially wired, and mounted on cork above and below the heater. The radial outward flux (q_r) in W is found by

$$q_r = K_{sh} \cdot E \qquad \text{[Eq. 3]}$$

where K_{sh} is the sheath conductance (W/V) and E is the emf output (V) of thermopiles located on a thin wrapper encircling the heater. For a detailed description of thermocouple and thermopile locations on the stem gauge see Figure 2 in Steinberg *et al.* (25). The values used for K_{st} in Equation 2 and for K_{sh} in Equation 3 are discussed in the **Materials and Methods** section.

The remaining term in Equation 1 is the convective heat flux carried by the mass transport of the sap (q_f) in W calculated from the measured rise in temperature:

$$q_f = C_p \cdot F \cdot (T_u - T_d) \qquad \text{[Eq. 4]}$$

where C_p is the volumetric heat capacity of water (J/kg °C), F is the sap flow rate in the stem (kg/s), T_u and T_d are the mean temperatures of sap flowing out of and into the system, respectively (°C).

Substituting Equations 2 to 4 with Equation 1 and solving for the sap flux F in kg/s gives:

$$F = [P - (K_{st} \cdot A \cdot (dT_u + dT_d)/dx) - K_{sh} \cdot E] / [Cp \cdot (T_u - T_d)] \qquad \text{[Eq. 5]}$$

This method is direct and requires no calibration or knowledge of the cross-sectional area of the xylem vessels. The stem heat balance is different from the heat pulse method, which calculates sap flow rates (F) from measurements of sap velocity estimated from the time required for a heat pulse to travel away from a heated segment of the stem. The heat pulse method is empirical because it requires a calibration factor to convert sap velocity to sap flow rate, and the calibration factor can be specific to a plant species and to a gauge. For a detailed description of this method the reader is referred to Dugas (5).

Materials and Methods

Experimental site: The water use of grape plants was measured using the stem flow heat balance method in a commercial vineyard (Pheasant Ridge) located in New Deal, Texas (33° 45' latitude, 101° 50' longitude), which is located 25 km north of Lubbock, Texas. The soil at the winery is classified as an Amarillo, fine sandy loam, 1% to 3% percent slope, mixed, thermic Aridic Paleustalfs.

Test of individual gauges: For a period of 31 days, between days of the year (DOY) 163 and 194, each of the five gauges was evaluated in the field by simultaneously measuring the water loss from a potted three-year-old Cabernet Sauvignon plant with a scale and with a stem flow gauge. The procedure used was as follows. The plant was fitted with a gauge, and the pot was watered so that the total mass on the evening before measurements started was 30 kg. The potted plant was positioned in the field in a row between two Chardonnay plants. The next day, between sunrise and sunset, hourly values of water use as obtained from the scale were recorded, with a precision of ± 1 g. Soil evaporation from the pot was minimized by covering the soil surface with a 3-cm layer of vermiculite covered with a thin layer of Amarillo fine sandy loam soil. The output from each stem flow gauge was recorded and processed as described previously. It was not possible to obtain a continuous record of the weight loss from the scale due to communication limitation of the weighing scale. Each gauge was tested in the manner described for a period of one to three days. The purpose of this evaluation was to examine the applicability of the stem heat balance method to measure the water use in grapes and to obtain values for K_{sh}, the sheath conductance (see Eq. 3) for each of the five stem-flow gauges used to measure the water use of the Chardonnay plants.

Stem thermal conductivity (K_{st}) and sheath conductance (K_{sh}): The value used for K_{st} in Equation 2 was 0.422 W/(m °C) as suggested by Steinberg *et al.* (25). The value of K_{sh} used in Equation 3 was calculated from Equation 5 by solving for K_{sh} using F values measured gravimetrically during the evaluation of each gauge. Calculated values of K_{sh} using this method were similar to those obtained using the lowest pre-dawn values for K_{sh} and assuming zero sap flow, as recommended by Steinberg *et al.* (25).

Experimental plants: To measure the water use of grapes, five three-year-old Chardonnay plants, planted in 1987, were selected as the test plants. These plants were spaced 3.05 m between rows and 1.22 m between plants for a plant population density of 2 691 plants/ha. The five test plants were within a 50-m segment of one row. The type of trellis used was bilateral cordon.

Measurement of water use: Direct measurements of the water use of the five test plants was made with commercially available stem-flow gauges (Dynamax® Model SGB-16WS, 9888 Bissonnet, Suite 150, Houston, TX 77036). This model fits stems between 15 and 18 mm in diameter. The gauges, with their accessory weather shields, were mounted 0.4 m above the ground. Measurements started on 1990 DOY 137 (17 May), and continued for 100 days until 1990 DOY 237 (25 August). Signals generated by the gauges were recorded every 15 seconds using a data logger (Campbell Scientific, Inc., Model CR-7, Logan, UT 84321), with data stored on magnetic tape and used to calculate hourly values of F. On a weekly basis, data were down-loaded to a minicomputer and processed using a spreadsheet.

Each gauge was checked weekly by removing it from the stem and assuring that there was a clean and close contact between the heater and stem. In addition, we took the precaution of additional insulation by wrapping each gauge and its weather shield with aluminum foil over packaging bubble-wrap.

To calculate evapotranspiration (ET) over the growing season, volumetric water content profiles around the test plants were measured by neutron attenuation to a depth of 2.8 m. Six neutron-access tubes were installed halfway between plants. Readings were made weekly throughout most of the 100-day period and before and after irrigation events. Evapotranspiration was calculated from the repeated measurements of the soil water content profile, assuming zero drainage at 2.8-m depth and no runoff. The plot was flood-irrigated on DOY 148 with 200 mm, DOY 160 with 50 mm, and DOY 175 with 200 mm, for a total of 450 mm. In addition, 195 mm of rain fell over the measurement period.

Leaf area: The leaf area of each of the five test plants in the vineyard was measured non-destructively, weekly in May and in June and every other week in July and in August. The leaf area of the potted plant used to evaluate the stem flow gauges was measured four times. The procedure used was to measure, and record via a voice-activated cassette recorder, the maximum width (W) and maximum length (L) of each leaf on each of the five plants. These two measurements were converted to equivalent leaf area units by using "calibration" equations obtained three times over the 100-day period. These calibration equations related the leaf (W × L)/2.0 to its area as measured with an area meter (Delta-D-Devices, Type CB, Pullman, WA 99163). For each of the calibrations, the area of 75 leaves removed from nearby plants were measured. To estimate the value of the leaf area for each plant on each day, third-order polynomials were fitted to the measured values.

Weather data: An automated weather station, using the same data logger used with the stem gauges, was positioned near the test plants. The weather parameters measured every 15 seconds and averaged for every hour were: air temperature and relative humidity (Campbell Scientific, Inc., Model 207 probe), short-wave irradiance (LI-COR, Model LI200S, Lincoln, NE), and wind speed (R. M. Young, Model 05103, Traverse city, MI). Total rainfall was measured with a tipping-bucket type gauge (Texas Electronics, Model TE525, Dallas,

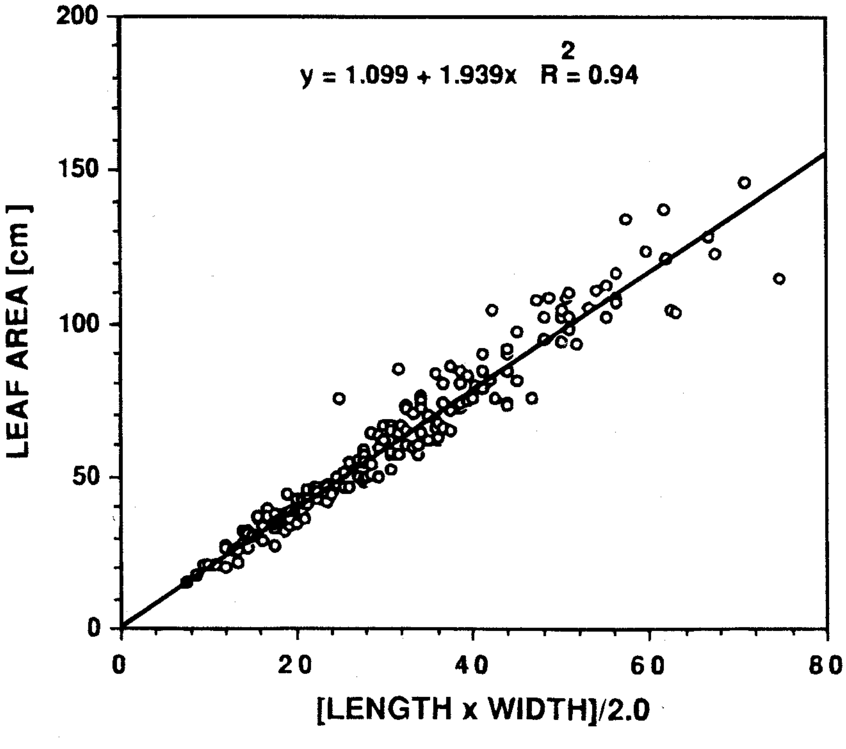

Fig. 1. Relationship between leaf area and the product of leaf length (L) times leaf width (W) divided by two. The data plotted correspond to 225 leaves and the regression equation shown was used to convert measured L and W to area.

TX). Sensors were placed 2.0 m above ground level. These data were used to calculate daily values of potential evapotranspiration (PET) as an index of evaporativity using a Penman-Monteith type equation (15).

Results and Discussion

Leaf area: Leaf area, as a function of the product of leaf length and width divided by 2, is shown in Figure 1. This relation was measured three times over the experimental period. We found no statistical difference in the intercepts and slopes of the calculated linear regressions; thus, all data were pooled, and one equation was used to convert measured leaf length and width to area. The linear regression equation used is given in Figure 1.

As an example of the estimated leaf area as a function of day of year (DOY), the leaf area for test plant No. 4 is shown in Figure 2A. The plotted line is a third-order polynomial fitted to the measured data and used to calculate daily values of leaf area. The fitted daily values of leaf area for all test plants are given in Figure 2B. Even though the five plants were in close proximity to each other, their leaf areas over time differed. The maximum leaf area was reached between DOY 191 and 215. Test plant No. 5 had the smallest leaf area with a maximum value of 3.3 m^2, and test plant No. 1 had the largest leaf area with a maximum value of 5.5 m^2. Throughout most of the season (DOY 135 - 190), the leaf area of test plant No. 4 was about 50% larger than that of the other plants and, thereafter, rapidly declined to 3.0 m^2 by DOY 235. Most of the leaf-area decline towards the end of the measurement period, at harvest-time, was due to leaf hopper (*Erythroneura* sp.) damage.

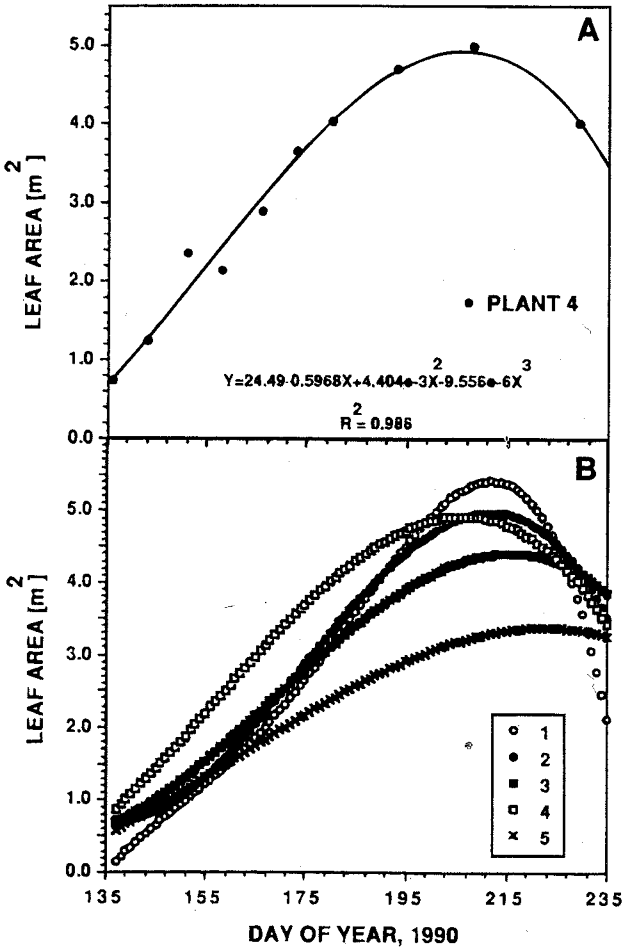

Fig. 2. Leaf area measured as a function of day of year, 1990 for test plant four (A). The symbol (●) are measurements and the continuous line is a third order polynomial equation fitted to the data over time. The equation used is shown. Fitted leaf area as a function of day of year, 1990, for the five test plants (B).

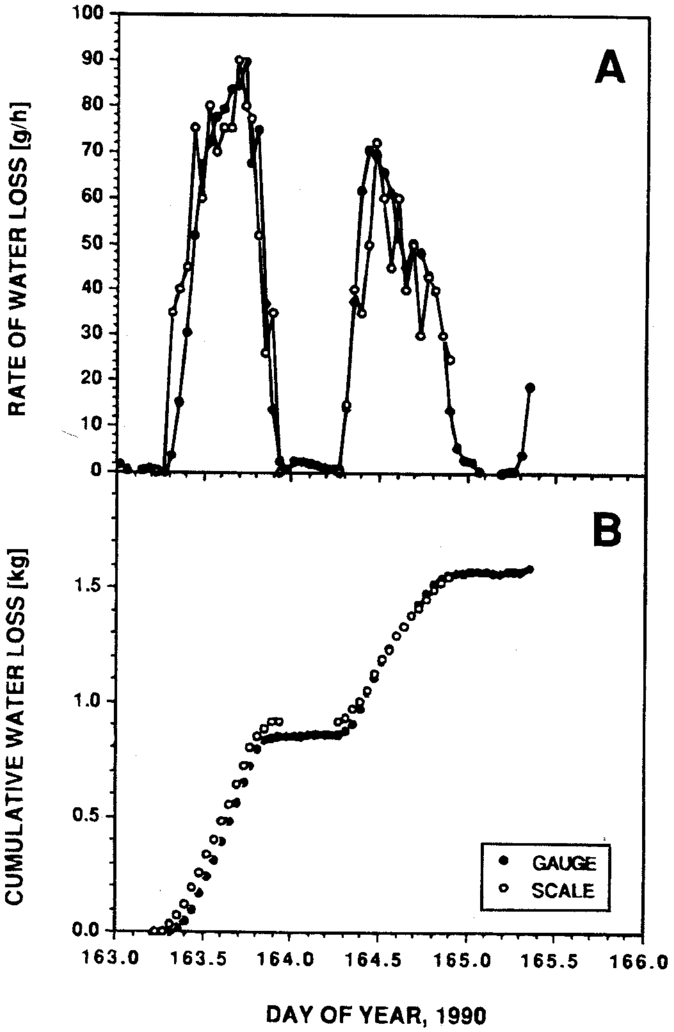

Fig. 3. Hourly (A) water loss and cumulative (B) water loss from a potted grape vine as a function of day of year, 1990. The symbol (●) corresponds to the stem flow gauge one and (○) to the weighing scale.

Phenological data were taken from an adjoining study by Lipe *et al.* (16). They reported the dates of first budbreak, 50% budbreak, and 100% budbreak for these grapevines were on DOY 81, 100, and 115, (1990), respectively. The delay between the first budbreak and 50% budbreak was due to a freeze on DOY 90. Anthesis was on DOY 140 and veraison was estimated to be on DOY 204 (1990). The numbers of buds per vine at pruning and bud break were 22 and 30, respectively. The vines had 20 canes per vine and 27 clusters per vine. The grapes were harvested during the third week of

August (DOY 233 - 240). The mean cluster mass was 91.0 g, yield was 6.45 t/ha, and the juice Brix was 20.6°.

Gauge evaluation: An example of hourly values of water loss from the three-year-old potted Cabernet Sauvignon plant measured with a stem flow gauge and with the scale are shown in Figure 3A. Corresponding cumulative water losses are shown in Figure 3B. At the time of measurement the potted plant had a leaf area of 0.3 m^2; that is, this plant was considerably smaller than the test plants (see Fig. 2B). The data plotted in Figures 3A and 3B correspond to the stem flow gauge used in test plant No. 1. Similar results were obtained with the other four gauges throughout the 31-day measurement period (data not shown). In the example shown in Figure 3A, in the early morning hours of the first day of measurement (DOY 163), the water loss measured with the gauge was less than that measured with the scale; however, by the middle of the day these differences disappeared. The lag measured in the morning can be attributed to the water capacitance of woody plants, *i.e.*, water stored in the trunk and leaves. Similar results were measured on a potted *Ficus benjamina* tree (24). On the second day of measurement, DOY 164, the lag occurred later in the morning and again diminished in the afternoon hours. Other discrepancies between the two measurements can be attributed to the time constant of the gauge due to the relatively large heat capacitance of the trunk section. For example, cloud cover during the day caused the leaf stomata to respond with a decline in the rate of water loss. However, this response was not sensed by the stem flow gauge. Thus, care must be used to interpret hourly values of sap flow measured with the stem gauge. Nevertheless, the integrated hourly values given in Figure 3B show that by the end of DOY 163 the cumulative values were within 10% of each other and within 5% at the end of DOY 164. Similar results were reported by others (2,13). Therefore, we concluded that stem flow method accurately measured the daily values of water loss from the potted plant and that this method was suitable to measure the seasonal water use by grapevines in the field.

Daily and cumulative sap flow: The mean daily sap flow measured with the five stem gauges in mass of water per vine (kg/d), per unit land area (mm/d), and per unit leaf area (mm/d) are shown in Figures 4A, 4B, and 4C, respectively. The results plotted in Figure 4A indicate that, between DOY 137 and 175, the mean rate of mass flow increased from 2.4 to 6.7 kg/d, thereafter remained relatively constant for 20 days declining to 3.2 kg/d on DOY 215, and then increased to almost 5 kg/d by DOY 237. It is not surprising that the maximum daily rates of water use occurred early in the growing season (mid-May to mid-June), due to the unseasonably warm, clear, and dry weather over this 30-day period and the associated exponential leaf growth over the same time period. For example, the mean maximum daily air temperature for this period was 34 °C, and daily maximum values exceeded 40°C on seven days. The mean daily irradiance was 28 MJ/m^2d, and the mean daily calculated PET was 11.3 ± 2 mm/d. This warm and dry weather, with only 5 mm of rain, prompted the vineyard

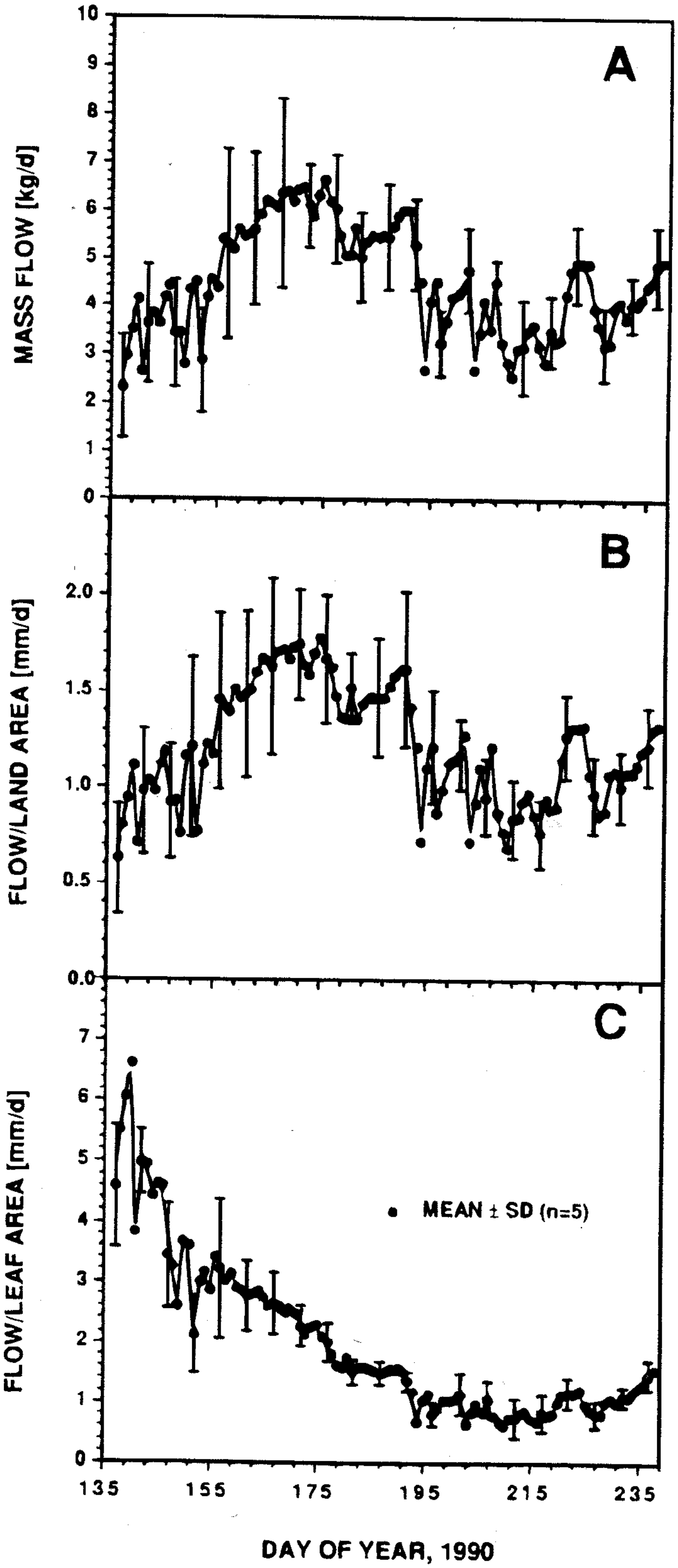

Fig. 4. Measured mean daily values of sap mass flow per plant (A), sap flow per unit land area (B), and sap flow per unit leaf area (C) as a function of day of year, 1990. The symbol (●) is the mean ± one standard deviation (SD). For ease of reading only the SD of every other five data points is plotted.

manager to irrigate the grapes with 200 mm of water on DOY 148 and again with 50 mm on DOY, 160. The mean cumulative sap mass flow over the measurement period was 460.8 ± 43.7 kg/plant or 1240.0 ± 117.6 m^3 of water/ha.

Daily values of sap flow per unit land area, *i.e.*, [(mass/plant) × (population density)/(water density)] are shown in Figure 4B. The mean cumulative sap flow per unit land area was 124.0 ± 11.8 mm/d. The pattern of daily water use shown in Figure 4B is the same as that on a mass flow basis (Fig. 4A), except that the units are now in mm/d. These results show that grapes have a low daily rate of water use (transpiration) compared to other agronomic crops (cotton and sorghum) grown in this area. These results are partly due to the low leaf area index (LAI) of the grapes throughout the growing season. For example, the LAI increased from 0.14 to a maximum value of 1.48 between DOY 137 and 215. However, for similar values of LAI a cotton crop in Lubbock, Texas, will typically have daily transpiration rates between 2 and 6 mm/d (14). In the case of grapevines, the maximum sap flow seldom exceeded 2 mm/d, indicating that grape plants can be considered as a "low water-use" crop when compared to cotton.

The mean daily sap flow per unit leaf area in mm/d is shown in Figure 4C; the mean cumulative value over the measurement period was 203.3 ± 19.6 mm. When the sap flow is calculated in this way and compared to either the sap flow on a mass (Fig. 4A) or a land area basis (Fig. 4B), two attributes are apparent: *(1)* The pattern of daily water use, which decreases from 6 mm/d on DOY 137 to a low of 1 mm/d at the end of the season; conversely, the sap flow on a mass or per unit land area is the opposite, particularly early during the growing season. *(2)* The variability, as indicated by the standard deviation of the mean, between plants is greatly reduced when the sap flow is normalized by the leaf area. The same was found with wax leaf *ligustrum* (13). These results indicate that the sap flow variability among plants is real and is not due to measurement error with the stem flow gauges.

Evapotranspiration versus sap flow: The mean cumulative evapotranspiration (ET) measured by the neutron method between DOY 137 and 237 is plotted in Figure 5. Also shown, for the same time period, is the cumulative calculated potential evapotranspiration (PET), cumulative rain plus irrigation, and cumulative mean sap flow per unit land area measured with the five stem flow gauges. The mean cumulative ET over the measurement period was 528.1 ± 13.2 mm; calculated cumulative PET was 869.7 mm; and cumulative rain plus irrigation was 645.0 mm.

The measured ET is the water lost to soil evaporation (E) and to crop transpiration (T); thus, E can be estimated by assuming that sap flow is equal to T and subtracting it from ET. At the end of the experimental period, the ratio of E to ET was 0.77. This ratio is very high, showing that soil evaporation was the main factor in the water loss by the system in spite of rather infrequent rainfall and/or irrigation. This is due in part to the considerable portion of the soil surface that, over the length of the measurement period, was never shaded by the plant canopy and to flood-irrigation, a very inefficient method to meet the water requirements of a vineyard. We contend that the efficiency of water use would drastically be improved, *i.e.*, reduction of losses due to E, by using a drip or trickle irrigation system. This value of E/ET is 2.6 times larger than that found for dryland cotton in Lubbock, Texas, with a maximum LAI of less than 2.0 (14).

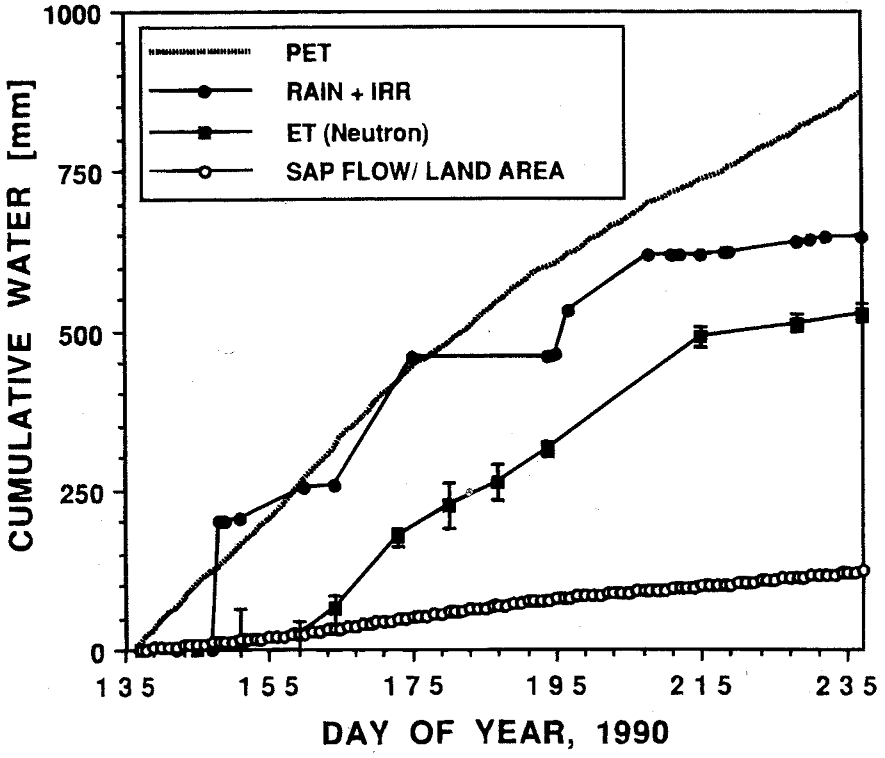

Fig. 5. Cumulative values of calculated potential evapotranspiration (PET), mean sap flow per unit land area, mean evapotranspiration (ET), and rain plus irrigation (IRR) as a function of day of year, 1990. The bars in (■) are the mean ± one standard deviation (n = 6).

Although there was an adequate supply of soil water and a high evaporative demand, the water use by the grapevines was small when compared to other agronomic crops in our region. The total mean cumulative sap flow per unit land area, over a 100 day period, for three-year-old Chardonnay plants was 124.0 ± 11.8 mm. We were unable to find similar data for transpiration values of grapevine in the published literature. However, our findings support the conclusion reached by Evans *et al.* (8). They measured, for a three year period and with lysimeters, the ET of mature vines in south central Washington State as 360 mm/year on average. As Evans *et al.* (8) indicated, their ET measurements of grapes are considerably lower than other published USA data and are similar to published South African and South Australian values. This ET value is comparable to our measurement of 124 mm of water use over a 100-day period by young grapevines in our experimental conditions. However, our measurement is considerably lower than the value given by Williams *et al.* (28) for a three-year-old Thompson Seedless grapevine in Fresno, California. They measured 575 mm of water use (ET) over a 200-day period using lysimetry. In neither case did Evans *et al.* (8) and Williams *et al.* (28) report the leaf area of their vines, making it difficult to compare the three values.

The results obtained with stem heat balance method suggest that this technique can be used to measure the water use of grapevines. This technique offers an alternative method to quantify water use, and thus, issues related to water relations of grapevines that previously were difficult to assess are now possible, *e.g.*, effect of irrigation on water use and yield, movement of water in individual canes and to clusters.

Conclusions

We evaluated the accuracy of commercially available stem flow gauges to measure the sap flow of grape plants and used them, over a 100-day period, to find the daily sap flow of five three-year-old Chardonnay plants in a vineyard. Our results show that the stem flow method is accurate and suitable to measure daily values of sap flow. Our measurements indicate that the daily sap flow values were within 5% to 10% of those measured gravimetrically. The grape plants in the vineyard transpired on the average 461 ± 44 kg/plant or 124 ± 12 mm over the 100-day observation period. From an independent measurement of ET, we were able to calculate that, of the total amount of water lost, 77% was soil evaporation for our experimental conditions. Our results confirm what others have found, that a grape crop has a low water requirement. They also suggest that flood or sprinkle irrigation is a wasteful method to meet the water requirements of the grapevine and that water application using drip or trickle irrigation could improve the efficiency of water use.

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