Methods for Measuring Grapevine Water Status

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ABSTRACT

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Plant water status is an indicator of plant health. Grape growers can use this information to build an irrigation strategy to control water stress in grapevines, which in turn affects fruit composition. Plant water status can be derived by examining the plant physiology, the microenvironment where the plant is growing, or both the plant and microenvironment can be examined to obtain the most comprehensive information.

This paper examines the porometer and pressure bomb, two conventional instruments which provide measures of plant transpiration and plant water potential, respectively. Porometry is a non-invasive method that measures resistance of air flow through the leaf of a plant, which depends upon the degree of resistance imposed by the stomata. The pressure bomb involves an invasive procedure that provides a measure of water tension in the xylem vessels of the plant.

Sap flow is a newer method used to obtain water status measurements in grapevines. A number of methods have been developed, all of which are based on applying a source of heat and then measuring temperature differences within the sap of the plant. Research on sap flow dates back to the 1930's, however research and technological advances have made it possible to measure sap flow in a wide range of plants with relative ease, accuracy, and for a moderate cost.

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1. INTRODUCTION

1.1 Introductory Comments

Plant water status is a good indicator of plant health and how well adapted the plant is to its environment. Plant water status can provide information on potential crop yield or for an irrigation strategy. The water potential of a plant governs transport across cell membranes. Water potential can be used to evaluate the water status of a plant and provide a relative index of water stress. Technological advancements have increased the relative ease and number of variations to measure water potential.

One of the earliest methods used to measure water flow was based on the injection of an indicator substance into the plant's water stream (Sakuratani 1981). These indicator substances included dyes, salts, or radio-isotopes. However, this method could not be applied to intact plants because the indicator substances needed to be applied to cut plants.

Williams (2001) demonstrated that pre-dawn leaf, midday leaf, and midday stem water potentials for *Vitis vinifera* cultivars and different *Vitis* species to be highly correlated with one another and with other measures of vine water status. Based on these findings, midday leaf water potential is an appropriate and convenient means of estimating vine water status.

Smart (2001) suggests the use of the non-invasive method of measuring leaf angle to assess water status. This is based on the principle that leaves under water stress will droop to reduce sunlight exposure and further stress. The angle measured is between the petiole and the base of the leaf. This angle is correlated to leaf stress. Although this method may be sensitive in detecting extreme water stress it is likely more difficult to detect mild water stress.

A relatively newer method used to measure grapevine water status is a sensitive gauge called a dendrometer. It is based on the concept that water stressed vines will show less trunk shrinkage than well-watered vines. This instrument monitors trunk diameter at the micron range and can be connected to a data logger which records the minute-by-minute changes.

The first part of this paper will describe two conventional methods for measuring water status in grapevines: porometry and pressure bomb. This will be followed by an analysis of the newer method of sap flow to measure water status, and a comparison of sap flow to the conventional methods. The second part of this paper will review five papers important to the advancement of sap flow technology in grapevines.

Although most of the gauges and equipment can be used or modified to measure water status in a range of plants, where possible, this paper has focused on studies that have applied water monitoring techniques to grapevines.

1.2 Background Information

Water potential is a measure of the free energy associated with water per unit volume (J/m3) (Taize and Zeiger 2002). Pure water has a water potential of zero. The addition of solutes, such as sugars, minerals, ions, and amino acids, added to water will lower water potential making it more negative. Water potential becomes increasingly negative when the water lost by a leaf through transpiration is greater than the flow into the leaf from the vascular tissue. This results from an increase in the solute concentration. Water in the soil and in plants moves from regions of higher water potential to lower water potential.

Water potentials can be measured in the leaf or the stem. Measurement of the leaf or stem water potential integrates the amount of water the vine's roots have access to throughout the soil's profile. These measurements can be made at multiple sites within the vineyard with ease. Chone et al. (2000) found that the stem water potential was a comprehensive indicator of early water deficit in plants, while the leaf water potential was not. Midday stem water potential for grapevines under field conditions was the first indicator of water deficit and for non-irrigated vines the midday stem water potential was highly correlated to the stem water potential. Midday leaf water potential was found to be a less significant indicator of water constraints.

Stem water potential measurements are obtained by stopping transpiration from a leaf before measuring the leaf water potential by placing the leaf into a plastic bag, inside an aluminum sack, one hour before measurement. French researchers claim stem water potentials gives better results than leaf water potential measurements, however, the two measurements have been shown to be well correlated (Williams 2001).

The water potential of a plant will be the greatest at pre-dawn, and immediately fall as the stomata in the leaf open in response to light (Smart 2001, Williams 2001). As the leaves start to transpire, the tension in the water transported through the xylem vessels increases. This tension increases to about midday when transpiration is at its maximum. From this point water tension decreases to sunset. This correlates to the daily decrease and then increase in water potential, respectively. This is the pattern regardless of water availability. However, if the plant is experiencing water stress, the pre-dawn and midday water tension will be higher, i.e. more negative water potential. Therefore, water potential can be used as an indicator of plant water status.

Transpiration is closely tied to the weather with hot, sunny, windy, low humidity conditions causing the highest transpiration. Increasing morning temperature and sunshine, and decreasing humidity cause an increase in transpiration, and thus a decrease in water potential.

If the soil is dry, one of the vine's first responses to this stress is to close its stomata around midday if the stress becomes too severe. Research over the years by Smart (2001) in Australia has shown this to happen around -13 bars (atmospheres) pressure. Once the leaf water potential reaches -13 bars, the stomata begin to close and the plant water potential decreases. Reynolds and McCarthy believe water stress occurs around -10 bars from their research (A.G. Reynolds 2003, personal communication). This corresponds with Williams (2001) who has found from his research that the midday water potential of irrigated vines are generally not less than -10 bars.

Williams (2001) generally does not initiate irrigation until the water potential is less than –10 bars (equivalent to a stem water potential value of –7.5 bars) and he comments that many growers and vineyard consultants do not begin irrigation until -10 bars is reached in white wine cultivars and –12 bars is reached in red wine cultivars. Furthermore, the date these values are reached is dependent upon root growth, soil texture, soil moisture content, vine canopy size, row spacing, trellis type, and evaporative demand.

2. CONVENTIONAL METHODS USED TO MEASURE GRAPEVINE WATER STATUS

2.1 History/Theory

Grapevine water use can be acquired at three levels: leaf, plant, and community (Lascano et al. 1992). A plant first starts showing signs of water stress at the leaf or plant level, so the best method to measure water status is often at the level where the quickest response to water constraints will be noticed. Water status measurements from potted plants are difficult to interpret when making comparisons to field plants because of the differences in their above-ground and below-ground environment, therefore, it is important that research be done out in the field.

At the leaf level, porometry measurements have been used and transpiration rates of .02 to .29 mm/h have been reported (Smart 1974). These measurements are limited by a calculation involving extrapolation of a single leaf measurement at the plant and community level, which requires information about the position of each leaf within the canopy.

At the plant level, measurements of water use have been obtained from potted plants or lysimeters. A lysimeter is an underground scale that measures water percolating down the soil via gravity. They are not widely used because of the high installation cost. Moreover, lysimeters do not provide a practical method to measure evapotranspiration (ET) due to the extensive root system in grapevines, and they are limited by only gathering water that is under saturated gravitational flow.

At the community level, grapevine water use is normally estimated empirically by relating the potential evapotranspiration to the pan evaporation and to a crop coefficient. This method is limited by the crop coefficient, which is both crop-specific and site-specific. The method is further limited in that it gives estimates of water requirement, but not water use. The water balance method also measures water at the community level by using seasonal values of rainfall and irrigation amounts along with the measurements of water use obtained by the neutron attenuation method (Lascano et al. 1992). However, this method is limited by the problem of tube placement, that is, deciding where to place the tubes and how many to use to adequately measure water use in a vineyard. This method also lacks the ability to measure daily values of water use.

2.2 Porometer

Early porometers were slow, cumbersome, and required considerable operator skill for timely measurements. One of the latest models, the CSIRO/Thermoline porometer, is faster, smaller, and is operated by one person (Rebetzke et al. 2000). It resembles a stapler that clamps a portion of a leaf within a gas-tight cuvette. A fixed quantity of air is released when the trigger is pressed and the time for the air pressure to fall between the two pre-calibrated values is recorded automatically.

2.2.1 Porometer Methodology

Plant transpiration is controlled by the opening and closing of stomata, which is dependent upon the ambient temperature, air pressure, humidity, and wind speed. The stomata are sensitive to light, relative humidity, carbon dioxide, water stress, pathogens and pollutants (on line: http://www.delta-t.co.uk).

The magnitude of photosynthesis and transpiration depends to a large degree on the resistance of gas exchange between the air and the interior of the leaf. The ease which water vapour and gases escape from plant leaves through the stomata is referred to as stomatal conductance or water flux. This is inversely related to stomatal resistance, which measures the limitation posed by the stomatal pores, through which water vapour and gases are able to diffuse in and out of the leaf.

Porometry is the study of gas diffusion through pores, specifically leaf stomata. A porometer measures this resistance and the time it takes to force pressurized air through the leaf. If this resistance is low, it means more of the stomata are open and therefore photosynthesis and transpiration rates are potentially higher. Measurements of leaf area and leaf temperature are used with the porometer measurement of water vapour diffusion to calculate leaf surface conductance as an indicator of water loss and CO_2 uptake for photosynthesis.

2.2.2 Porometer Research

Steady-state diffusion porometers are widely accepted for in situ measurements of leaf stomatal conductance. Steady state porometers are comparatively complex, require a vigorously stirred leaf chamber, and repeated recalibration. Dynamic diffusion porometers are simple, but require frequent although easy recalibration.

Viscous-flow porometers are best suited for measuring comparative measurements of leaf conductance versus absolute measurements and their use is mainly restricted to amphistomatous leaves (Rebetzke et al. 2000), which have stomata on both the upper and lower leaf surfaces. The rate of air movement through a leaf is predominately determined by the resistance at the surface of the leaf.

Rebetzke et al. (2000) found that in their assessment of the new improved viscous-flow porometer, to measure leaf conductance in wheat, the instrument provided a sturdy and rapid means to measure leaf conductance. The researchers noted that it took an average of 12 seconds to take three leaf measurements per plot, and most of the time was spent moving between the sample plants. Theoretically measurement of three leaves per plot for a 250-plot study could be measured in 1 hour versus ~8 hours using a steady-state diffusion porometer.

Smart (2001) has an affinity to the diffusion porometer for measuring water status and feels it provides a very sensitive guide to water stress, although the instrument is expensive.

2.3 Pressure Bomb (aka pressure chamber)

The pressure bomb or pressure chamber is a device for applying pressure to a leaf or small shoot. The bulk of the leaf is placed in the pressurized chamber with the stem exposed to the outside of the chamber through a seal.

2.3.1 Pressure Bomb Methodology

Water in plant tissue is under negative pressure, i.e. suction. This is caused by the transpiration (evaporation) of water from the leaves and by the pull on the water column in xylem tissues being transmitted to the roots. When a leaf is severed from a vine, the water recedes back away from the cut end. If the leaf is placed in the pressure chamber, with the cut surface protruding from the chamber, the slow application of pressure will force the water column back to the cut end. At the first appearance of water, the pressure required to force water from the severed stem, is equal to the negative pressure the plant tissue was under at the time the leaf was severed. This is the underlying principle upon which the pressure bomb is based.

If a low pressure (e.g. -3 bar) is sufficient to force water to the cut surface of the sample, the plant is under relatively low moisture stress (high water potential) and likely has sufficient water for growth. Conversely, if high pressure (e.g. -20 bar) is necessary to force water to the cut surface the moisture stress is relatively high (low water potential). The significance of moisture stress varies with species. The permanent wilting point in grapevines is -18 bar (On-line: http://www.pmsinstrument.com/importan.htm). The permanent wilting point is the point where the water potential of the soil is so low that plants cannot regain turgor pressure even if all water lost through transpiration ceases. At this point, the water potential of the soil is less than or equal to the solute potential of the plant (Taize and Zeiger 2002).

2.3.2 Pressure Bomb Research

Pressure bomb measurements are dependent upon the following conditions: ambient vapour pressure deficit, which increases as relative humidity decreases; temperature and light, because both contribute to evaporative demand; time of day the measurement is made; and the amount of water in the soil profile. As an example, Williams (2001) found midday leaf water potentials measured with a pressure bomb were one bar higher when the ambient temperature was 29.5 °C versus 36.5 °C.

There are different opinions on the best time to take the pressure bomb measurement. Williams (2001) suggests midday because this is when the grapevine uses the greatest amount of water on a daily basis, while Smart (2001) prefers early afternoon. Differences in weather conditions can vary the readings too, as Williams found readings differed by one bar in California versus Smart who found larger differences in Australia. Cloud cover can also have a large effect on pressure bomb readings.

To take an accurate pressure bomb measurement, Williams (2001) suggests enclosing the leaf in a plastic bag to minimize transpiration before severing it from the plant. Within 10 seconds of severing the leaf, the water potential measurement should be taken. Williams has found a difference in the reading of between 2 to 3 bars between bagging and not bagging the severed leaf, with the latter being more negative. On the other hand, stem water potentials are taken by enclosing a leaf in a plastic bag surrounded by aluminum foil, at least 90 minutes before making the reading. This allows the leaf to stop transpiring and come into equilibrium with the water potential of the stem. Some researchers feel that stem water potential is a better measurement because comparatively it minimizes to a degree the effects of the environment on an exposed leaf.

Smart (2001) feels that the two shortfalls of the pressure bomb as an instrument to schedule irrigation are: 1) the readings are too sensitive to the current weather and are inherently dynamic, thus subject to sampling error; and, 2) vines at tensions less than -13 bar are actually experiencing more stress than their readings indicate.

3. SAP FLOW – A NOVEL METHOD USED TO MEASURE GRAPEVINE WATER STATUS

The standard protocol for assessing the accuracy of water flow instruments, such as sap-flow gauges, is to compare the measurement to gravimetric (balance) measurements of water loss from potted plants. The sap flow index of a plant is a measure of the flow of the fluid contents of the xylem, the sieve elements of the phloem, and the cell vacuole. Sap flow gauges are one of the relatively newer methods used to monitor water status in grapevines.

The measurements of sap flow in plants dates back to 1932, when Huber used the method to measure xylem sap velocities (on-line: http://advmnc.com/greenspan/sapflow.html), but its application to grapevines has been more recent dating back just over 10 years. Variations in the instruments used to measure sap flow and the methods used to calculate sap flow have evolved over this time as well.

This section looks at the methods of heat pulse, Granier, and heat balance, which have been used to measure sap flow in the research of grapevine water status.

3.1 Heat Pulse

Huber (1932) laid the foundation for the heat pulse velocity technique for sap flux measurement (Sakuratani 1981, Steinberg et al. 1989). Huber’s technique was based on the application of a pulse of heat detected by a thermocouple set at a point upstream from the heat source. Determining the thermal conduction independent of the water flow was complicated when the flow was slow, so Huber and Schmidt modified the technique with the compensation method.

The heat pulse method measures sap flow in the stem of a trunk. Its use as an indicator of water status has been widely accepted due to its simplicity and accuracy as compared to other methods. The major disadvantage of this method is that the measured pulse velocity is different from the stream velocity of water in a trunk or stem of plants (Sakuratani 1981). Furthermore, the calculation of actual values of water flow in a stem of trunk is complicated by the determination of the cross sectional area of the conducting water system.

3.1.2 Heat Pulse Methodology

Sap velocity involves estimating the time required for a heat pulse injected into the xylem to travel a finite distance downstream (Steinberg et al. 1989; Lascano 1992). The major limitation of this approach is in that it only measures sap velocity. Calculation of sap flux (mass x time) from the sap velocity requires knowledge of the active conducting area of the xylem, a figure that is difficult if not impossible to obtain, as well as not being constant over time. The method requires a variable conversion factor, which can be obtained by recording the rate of water loss by the weight loss method.

The heat pulse method is semi-continuous in that only the measurements taken in the first few minutes of a 15-30 minute interval are used to calculate sap flow velocity (Braun and Schmid 1999a). The balance of the interval is necessary to dissipate the heat and bring the instrument back to a state of equilibrium before the next measurement can start. Braun and Schmid (1999a) argue that the non-continuous measurement of data makes it difficult to infer correlations with a rapidly changing environment, e.g. climate or light.

3.1.2 Heat Pulse Research

Three papers that reported research on sap flow with grapevines using the heat pulse methodology are examined under section 5.2 to 5.4 of this paper.

3.2 Granier System

The Granier system (Granier, 1987; Braun and Schmid, 1988, 1989) involves the use of two probes that are inserted into the stem of the plant, making it a slightly invasive method. One of these probes is heated and the temperature difference between the probes is measured to obtain the sap flow rate. In contrast, a heat band is use to supply the heat source in the heat balance method (section 3.3). The band is nestled up against the stem of the trunk, being totally non-invasive in the measurement process. The heat dispersion using the Granier method is considered on two dimensions versus that of the heat balance which takes all three dimensions of the heat dispersion into the sap flow calculation.

The Granier system differs from the heat pulse method (section 3.1) in that the supply of heat is constant versus a pulse of heat as in the heat pulse method. The Granier method measures temperature difference between the probes whereas the heat pulse method measures the rate at which the pulse of heat travels upstream from the heat source.

3.2.1 Granier Methodology

Use of the Granier method involves the radial insertion of two cylindrical probes 2 cm into the sap wood. Each probe with a diameter of 2 mm and a length of 20 mm is inserted a vertical distance of 10 to 15 cm apart from one another into the stem (Granier 1987; Braun and Schmid 1998). The upper probe is heated at a constant power and the temperature difference between the two probes is measured. Each probe contains a thermocouple in the middle and these probes are connected together in opposition.

Braun and Schmid modified the equipment slightly for grapevines by shortening the length of the probes to 15 mm, since the stem diameter of the average 10 to 15-year old grapevines used in the study were 35 to 40 mm, which is much smaller than the trees for which Granier had originally designed the method.

The Granier method for calculating sap flow uses the following 4 equations (Granier 1987):

1. $K = 0.0206\, u^{0.8124}$

   where
   u = mean sap flux density along a radius (m/s)

In an earlier study, Granier calculated the mean sap flux density (u) along a radius by calibration using different species.

2. $$K = \frac{\Delta T_M - \Delta T}{\Delta T}$$

   where
   ΔT_M and ΔT are the temperature differences between the two probes, for no flow ($u = 0$), and positive flow ($u > 0$), respectively; and

   where
   T_M = temperature of the heated probe obtained when $u = 0$
   T = temperature of the heated probe when $u > 0$

3. $u = 119 \times 10^{-6}\ K^{1.231}$ solved from equation 1

   where
   u = mean sap flux density along a radius (m/s)

4. $F = u\ S_A$

   where
   F = total sap flow (m3/s)
   S_A = cross-sectional area of the sapwood at the heating probe (m^2)

To accurately compute sap flow using the Granier method, the ΔT_M must be determined separately for each sensor. This value is influenced by the thermal characteristics of the wood surrounding the heated probe, e.g. wet wood has a lower ΔT_M versus dry wood.

According to Granier's method, sap flow is a function of the mean sap flux density and the sapwood cross-sectional area at the heating probe. Sap flux density, which is the flow per unit of sapwood cross-sectional area, varies according to the tree crown class. This is substantiated by the measurement from Granier's study (1987) which showed the smallest Douglas fir tree had a sap flux density half that of the dominant tree.

The Granier formula converts measurements to sap flux densities. The Granier formula was developed for sap flux densities between 0 to 130 x 10^{-6} m/s, as found on Douglas fir trees with sap flux densities ranging from 0 to 35 x 10^{-6} m/s (Granier 1987); however, grapevines exhibit larger sap flux densities up to ~200 x 10^{-6} m/s (Braun and Schmid 1998)

3.2.1 Granier Research

Granier's 1987 study used the Granier method to measure transpiration differences between trees and to estimate transpiration of a whole stand, using a 24-year old Douglas-fir stand in France. Granier developed this new method to measure xylem sap flow which was shown in previous research to be an accurate and inexpensive method to estimate whole-tree transpiration. Granier found the cumulative water consumption values for the whole season gave similar results for the sap flow technique as compared with the neutron probes measurements, however over shorter periods the values were very different. The difference was attributed to errors in estimation by the water balance method during periods of heavy rain.

Estimated transpiration of the whole Douglas-fir stand using the Granier method was compared with water balance measurements taken with a neutron probe and potential evapotranspiration (PET) estimated by the Penman formula. The results showed that exchangeable water volume within a stand increase with both stand density and age. Granier concluded that errors in the estimation of the whole stand using the sap flow method depend upon how representative the selected test trees are of the stand. Granier found that five trees appeared to be a sufficient representative sample since the sap flow density, except for suppressed trees, was relatively constant among the trees.

Braun and Schmid (1998) substantiated their use of the whole cross sectional area of the grapevine stem to convert measured velocity into mass flow after a xylem dye test revealed that the heartwood - the thermal mass of non-conducting tissue in the stem - even in 20 year-old grapevines had not yet developed and the older vessels were still transporting water (Nadezhdina et al. 2002).

Braun and Schmid (1998, 1999b) assessed the validity of the Granier measurements two ways. The first method involved cutting grapevine stem sections, connecting them to a pressurized water tank, and then measuring the flow rate with the sensors. These sensor measurements were compared to the water flowing out of the cut stem, which was collected and weighed before the flow rate was determined at pressure steps from 10 KPa up to 150 KPa. Corresponding sap flux densities ranged between 12.6×10^{-6} m/s and 225.6×10^{-6} m/s. This range showed very good agreement between the measured and calculated Granier values without any significant error. However, increasing pressures above this range was associated with increasing error. At sap flux densities of 225×10^{-6} m/s the error was ~5.2%, and it increased to 7.2% at ~400×10^{-6}m/s. At higher sap flux densities the deviation between the measured sap flux density and the calculated value increased to unacceptable levels. This deviation was attributed to the thermal mass of the sensor and the limiting heat transfer from the sensor to the surrounding tissue, showing that increasing pressure drastically increased error.

The purpose of the second approach was to validate the long and short term accuracy of the Granier measurements. This was done by comparing Granier measurements taken on 10 minute intervals to weight loss measurements of potted grapevines in a greenhouse. Weight loss measurements were taken manually in the first experiment on an hourly basis daily for 89 days and in the second experiment the weight loss measurements were taken electronically every 10 minutes. The vines in the study were 14 year old *Vitis vinifera* vines with a leaf area between 2 to 4 m^2, which was much lower than the field vines of 6 m^2. Good agreement was found between the measurements, with the highest relative error occurring at low flow rates, but always within ± 10%. This error was attributed to the thermal mass of the sensor itself – the time necessary to transfer the heat from the xylem vessels to the sensors. Over the long term the error for the measurement period was less than 1.5%, indicating that the errors partially cancelled out over time and after a long period no deterioration of the accuracy was apparent. However, accuracy did decrease over the shorter 10 minute intervals, with the Granier values lagging the balance values on all days. Environmental changes that occurred for short periods were not fully reflected in the Granier measurements, thus reducing its application for physiological plant analysis.

3.2.4 Granier - Conclusion

The study by Granier (1987) shows the importance of taking measurements from the average plant, whether it is a tree in a stand or a vine in a vineyard. The larger trees not only had a greater sapwood cross sectional area, but likely corresponded with a greater amount of surface area for transpiration and hence the higher sap flow rates. As for grapevines, higher leaf cover as a single difference is associated with a higher rate of transpiration.

Braun et al. (1998) affirm that use of the original calibration by Granier could be used on the morphologically different stem of grapevines since sap flow stayed below the critical 200 x 10^{-6} m/s. The Granier-system appears to give very good results for long-term water use studies, however it is limited in its ability to get accurate instantaneous readings and therefore makes it best suited for long-term measurements of total water use (Braun and Schmid 1998, 1999).

3.3 Heat Balance

In 1960, Vieweg and Ziegler first proposed the use of the continuous application of heat to directly measure mass flow of sap (Steinberg et al. 1989). Presently two forms of the stem heat balance (SHB) approach to measure sap flux directly are reported.

Under the first form, a constant temperature difference is maintained between the sensors at and above the heated segment by varying the power of the heater. The advantages of this are: the gauge requires no calibration; the response to changes in the sap flow is almost instantaneous; and, the accuracy of the method has been shown in the field (Steinberg et al. 1989). However, the electrodes and temperature sensors must be inserted in the trunk, which limits application to trunks of appreciable diameter, and it requires sophisticated electronic equipment to maintain the steady temperature gradients.

Under the second form a constant heating power is applied, allowing the temperature difference between sensors above and below the heater to vary. Several advantages with this method are:

1. the sensors are located on the outer surface of the stem, since they were originally designed for use with herbaceous plant with smaller diameters (8-20 mm);
2. other than a zero-set procedure, it is an absolute measuring technique that does not need calibration;
3. commonly available data-loggers can record and process the signals from several gauges at one time; and,
4. it is simpler and less expensive than the constant temperature method.

Although the method can be applied to larger diameter stems, the lag between the sap flow and gauge response is expected to increase because of the extra time needed to establish steady-state conditions.

Variations on the heat balance method entail the insertion of a heat source or sensing probes into the trunk stem, or a non-invasive approach with the alignment of a heating plate or sensing instrument against the stem.

The steady-state heat-flow method, originally developed by Vieweg and Ziegler, involved the placement of a thermocouple on either side of a continuous heat source inserted into the stem (Sakuratani 1981). The temperature difference between the thermocouples and the surrounding air is measured to obtain absolute values of water flow rate, but this method required calibration procedures that were not successful under field conditions. In 1979 research, Sakuratani also attempted to evaluate a version of the steady-state heat-flow method by measuring temperature differences between the stem surface and the air, and between two points along the stem. Although this was more sensitive than the heat pulse method, it was found to be inconvenient and inaccurate under field conditions. This method required the accurate determination of both the heat transferred from the stem surface to the air and the thermal conductivity of plant stems.

In the mid-1960's and 1970's the heat flux plate technology measuring heat flux density between the water flow in the xylem and the cambium of a tree trunk was used to evaluate water flow rate in the trunk (Sakuratani 1981). This method requires stems larger than those of ordinary crops to enable the heat flux plate to be inserted into the bark.

Heat balance technique of sap flow measurement has been used successfully to quantify plant water use on a wide range of plants and for a wide range of purposes. The technique has been use in studies of whole plant physiology to quantify field-scale energy, water balances, and to evaluate elevated atmospheric CO_2 on transpiration (Peressotti and Ham 1996).

3.3.1 Heat Balance Methodology

The heat balance method of measuring sap flow involves encircling a plant stem with a flexible heater band to apply a known amount of energy to the stem, and then accounting for the dissipation of that energy within the system (Lascano et al. 1992; Braun and Schmid 1998,1999a; Tarara and Ferguson 2001). A schematic diagram depicting the heat balance methodology can be found in Appendix 6.2.

Under steady state conditions the heat input is balanced by the heat fluxes out of the stem. There are four components to the heat output: 1) conduction up the stem, 2) conduction down the stem, 3) radial conduction through the foam sheath, and 4) convection in the sap flow through the stem. Both the heat losses measured through the conduction of the wood (1 and 2) and radial losses through the insulation (3) are subtracted from the energy input to arrive at the heat energy put into the water passing through the heated zone (4). This heat energy in the water is directly proportional to the water flow, as 4.18 kJ of energy is necessary to increase the temperature of 1 kg of water by 1°K (Braun and Schmid 1999a). The mass flow through the xylem is measure directly. The stem steady-state heat balance method is direct and requires no calibration or knowledge of the cross-sectional area of the xylem vessels (Lascano et al. 1992).

The main assumptions under the heat balance method include the following: 1) the heated stem segment is at steady state; 2) there are negligible radiant and latent heat losses; and 3) there is radial homogeneity in the stem. At high flow rates, the heat balance method can fail because the temperature measured above and below the heater may not represent a uniform temperature across the stem (Tarara and Ferguson 2001).

The heat-balance method to measure sap flow is desirable because it is non-invasive and does not require knowledge of the cross-sectional area of the xylem vessels nor empirical transformations of the data, which are limitations of other sap flow methods such as the heat pulse method (Tarara and Ferguson 2001).

3.3.2 Single-heater Gauge

One heat source is applied to the stem by a single-heater gauge as compared to the dual-heater gauge which has two heating units.

3.3.2.1 Heat Balance Single-heater Methodology

To calculate the sap flow rate using a single-heater gauge the following equations are used (Peressotti and Ham 1996):

1. $$F = \frac{(Q_h - Q_r - Q_{v,u} - Q_{v,d})}{c\,(T_{out} - T_{in})}$$

   where
   F = sap flow rate in kg/s
   Q_h = heat applied to the single segment (W)
   Q_r = radial heat flow (W)
   $Q_{v,u}$ = axial conduction up the stem (W)
   $Q_{v,d}$ = axial conduction down the stem (W)
   c = the specific heat of the sap (J/kg^3 °C)
   T_{out} = temperature out of the segment (°C)
   T_{in} = temperature into the segment (°C)

2. $Qr = K_{sh} \times E$

where
E = voltage output from a thermopile wrapped around the edge of the segment (mV)
K_{sh} = sheath conductance (W/mV)

Steinberg et al. (1989) note that the sheath conductance K_{sh} can be measured in three ways:

1. using the lowest K_{sh} values, which are at pre-dawn, and assuming zero sap flow;
2. using the lowest K_{sh} values obtained when the entire tree canopy was enclosed in plastic and placed in the dark for several days, and assuming zero sap flow; and,
3. taking the measured values on the test tree trunk after it has been severed above and below the gauge to establish zero flow.

Steinberg et al. (1989) obtained the sheath conductance (K_{sh}) by each of the three methods mentioned and found that conditions could not be duplicated exactly and slightly different K_{sh} values were obtained using each method. In practice, it is not practical to enclose the leaf canopy in an airtight cover, nor is it practical to destroy each test tree by severing it at the stem. Therefore, the minimum pre-dawn values are the recommended approach to obtaining K_{sh}. This value did not vary greatly from the other two estimates for zero flow. Steinberg et al. notes that the values introduce little error by assuming there is zero flow at predawn, when K_{sh} is at its lowest.

3.3.2.2 Heat Balance Single Heater Research

Sakuratani's 1981 paper describes the method and apparatus developed for measuring the water flow rate in intact plant stems using the heat balance method. Water flux in potted soya bean and sunflower plant stems using the apparatus were compared to transpiration measured directly by a balance. The soya bean plants were 10 weeks old with a stem diameter of ~1.0 cm. The sunflower plants were 4 weeks old with stems of 0.4 to 0.5 cm in diameter. The water flow measured by the new apparatus showed good agreement to the transpiration rates measured by the balance at rates higher than 20 g/h. However, below 20 g/h Sakuratani's new method was found to systematically deviate by 1.2 to 2.2 times from the transpiration rates determined using the balance.

Sakuratani concluded that if the transpiration rate is low, it is necessary to accurately measure the thermal conduction upstream ($Q_{v,u}$), downstream ($Q_{v,d}$), and the energy lost by convection (Q_r) from the surface of the heated stem into the surrounding air. However, if the transpiration rate is high, as in the daytime on clear sunny days, then the heat balance method can accurately determine water flow in the stem of intact plants.

Steinberg et al. (1989) tested the accuracy of sap flow measurements on a potted tree in a greenhouse with a single-heater gauge to take measurements using the steady state heat balance method over several 3 to 5-day periods. The tree had a trunk diameter of 45.2 mm and leaf area of 6.1 m^2. The gauge measurements were found to be within 4% of the weight loss measured by the balance. Steinberg et al. note that this is a significant improvement over the results reported by Vaker and Van Bavel, and Sakuratani (1981) who reported errors of 10%. The sap flow and transpiration in wood plants can vary significantly because of the different morphology. The trunks and branches of trees can function as huge water storage systems and could cause a lag between changes in transpiration and sap flow. This could be part of the reason for the error differences.

The results from Steinberg et al. (1989) study showed that changes in sap flow lagged changes in transpiration and was more apparent for short-term measurements. Sap flow lagged transpiration in the morning, but exceeded transpiration in the afternoon and night. Steinberg et al. (1989) suggest that gauge data be integrated over one 24-hour period, preferably pre-dawn to pre-dawn, in order to alleviate these differences. Possible causes for this lag were attributed to the heat capacitance of the trunk.

To evaluate the response of the tree and gauge system Steinberg et al. (1989) calculated a time constant based on the measured time that was required to register 63.2% of the total response to a step change in transpiration. They found the time constant was 20 minutes at a sap flow of 80 g/h at 12:45p and 76 minutes under zero sap flow conditions. This response time is not critical in the common application of the gauge, however, Steinberg et al. contend that rapid changes in sap flow will not be detected, or will be reduced by the water capacitance of the tree above the gauge location and the heat capacitance of the insulated part of the trunk. Hence, this method is not useful for measuring transpiration rates over short periods.

The temperature rise did not appear to cause physiological injury in the 3 to 5 days the test was performed, but could be a problem over longer periods or higher temperatures. Steinberg et al. (1989) conclude that other than the insertion of thermocouples 2mm into the trunk, the dual-heater gauge is non-invasive, remaining on the outer surface of the trunk. In the case of small diameter stems and trunk, the insertion of the thermocouples may not be possible or necessary. The gauge is simple and suitable for use in the field if protected from moisture and rain.

Shackel et al. (1992) used the heat balance method to estimate sap flow through the 60- to 75-mm diameter stems of 3-year-old peach trees under field conditions for 36 days. Shackel et al. used a commercially available gauge (SGB50, Dynamax, Houston) and a datalogger (CR10, Campbell Scientific, Logan, Utah) to take measurements at 15-second intervals and store average values for 10-minute periods.

The heat balance measurements were compared to lysimetric measurements for accuracy. The measurements differed significantly in both direction and magnitude. These differences were attributed to the environmental temperature differential, which led to differentials within the plant stem surface below and above the gauge heater. This difference, which is critical in calculating the sap flow, is not formally considered within the theoretical model of the gauge function.

Using the heat balance model to calculate the sap flow rate, small temperature differentials between the stem surface temperature above and below the gauge heater often gave errors with two orders of magnitude. Also, temperature differentials exceeding –1 °C were recorded in the absence of heating power to the gauge, indicating that ambient conditions can impose temperature changes and affect the accuracy of this model.

Shackel et al. (1992) further commented that the model is limited to the consideration of temperature differentials that results from heat energy applied to the stem itself. However, large diurnal differences are common in the soil and air under field conditions and the plants are part of the environment so the surrounding temperatures will influence their internal and external temperatures.

Single-heater gauges can be operated at a variable or compensating power mode by applying controlled heat at a user-defined temperature, which eliminates the problem of overheating the stem as in the steady state system where the heat is constant. However, a gauge factor needs to be computed (Peressotti et al., 1996). A number of variation on the heating systems of the heat balance model have been tested, but it is necessary to calibrate for zero-flow or make constraining assumptions about the heat balance (Peressotti and Ham 1996).

Peressotti and Ham (1996) identified two problems associated with the application of a constant amount of heat to the stem of a plant with a single resistance heater. These are: 1) the steady amount of heat applied tends to overheat the stem during periods of low flow, especially at night; and 2) the traditional gauge requires an estimate of the radial heat flux (Q_r) away from the heated segment. The Q_r is typically calculated from measurements of the radial temperature gradients within the instrument and from knowledge of the sheath or gauge's thermal conductance, K_{sh}. K_{sh} is dependent upon how much of the gauge is attached to the stem, and it therefore must be determined empirically for each gauge-stem combination. The calibration to calculate K_{sh} can be done using the night time data, where zero-flow is assumed. However, Peressotti and Ham (1996) point out that research done by Ham and Senock showed K_{sh} values vary with time and can lead to significant errors under low flow rates. It was suggested that environmentally induced temperature gradients within the gauge may lead to substantial errors in flow measurements under field conditions.

Braun and Schmid (1998, 1999a) examined the stem morphology of grapevines in relation to water flow and evaluated the use of the variable-power single-heat balance method on older, mature grapevines with stem diameters of 35 to 45 mm. The grapevines used in this study were vinifera vines that were dug out of the field the prior year and transferred to pots where they were monitored in a greenhouse. These grapevines had a leaf area between 2 and 3 m^2, as compared to ~ 6m^2 leaf area of the vines in the field at this time. The thermocouples were positioned behind the bark in direct contact with the xylem, but not inserted into it, which was found in research on apple trees to give good estimates of the temperature increase of the xylem sap (dTsap). The potted vines were placed on a balance connected to a computer that recorded measurements every 10 minutes.

The results showed minimal time delays between measured values from the gauge and the actual water loss from the scale measurement. This agrees with prior research with the heat balance gauge, where other researchers found a time lag to occur only where a significant portion of the stem had already developed into non-conducting heartwood (Braun and Schmid 1998). Plants with significant heartwood have a stored heat component that can cause time shifts with sap flow. This results a delay in the calculated sap flow and a delay in the regular decrease of sap flow in the evening. However, this is not a problem in grapevines as shown by Braun et al. (1998, 1999a), where dye colouring of the xylem vessels revealed a radial decrease in staining from the outside in, but still with some staining in the oldest rings. This indicates that the largest portion of water is transported in the younger outer rings. There was no visible heartwood in the 21-year-old grapevines examined.

At low flow rates there was no detectable difference between the measured and calculated sap flow. However, there was a tendency for this method to overestimate the flow by an average of 20% and up to 50% at high flow rates. The overestimation was attributed to the heat balance equipment not being able to heat the xylem fluid in all the rings evenly. The result was an overestimation in the water flow readings, since the heat energy is directly proportional to the water flow.

Braun and Schmid (1999a) experimented with heater band heights and found that a change in the height of the heater band from the recommended 1.5 times the diameter of the stem, to twice the diameter increased the error of the heat balance data by up to two times that of the scale measurement. Measurements of the temperature differentials at the four different heights showed sap flow differences of ± 20%. The orientation of the heater band may measure a side with a large shoot to give readings that were not representative of the mean flow. However, the researchers believe that this is not sufficient to explain neither the ± 20% difference nor the 100% over estimation.

Differences observed between the measurements of the outside and inside of the stem revealed that the heater was not able to heat the rings uniformly, which was noticeable when the sap started flowing in the morning. In addition, temperature differences of the xylem fluid between the younger outer and older inner rings were as much as 1°C. Temperature differences between the inside and outside of the stem varied over the 24 hours, with the inner being higher when sap flow was higher during the day time and lower during the low flow rates of the evening and predawn. This higher inner temperature during the day indicates that the heat transferred to the xylem vessels in the inner ring is flowing at a lower rate than the outer ring. Thermal heterogeneity of sap flow was identified as a source of error in the observed over estimation of flow that was significant at higher flow rates. Braun and Schmid (1998, 1999a) conclude that the flow velocity at low flow rates was similar for the inner and outer year rings. However, with increasing flow it appeared that the younger outer rings contribute more to the total flow and it was not possible to accurately measure the temperature differentials for the heat balance calculation to calculate sap flow. They contend that this would not be an issue under controlled environmental conditions, such as a laboratory or greenhouse, where steady state conditions are obtained before a measurement.

From the result of the heat balance study, Braun and Schmid (1999a) were not able to determine the depth into the stem at which a true mean sap flow rate could be measured. However, they did show that this was based on flow rate and the degree of thermal heterogeneity encountered, which leaves out the possibility of applying a correction factor.

Braun and Schmid (1999a) contend that the results from Fichtner and Schulze's 1990 study, which showed very good agreement between the balance and sap flow measurements in cut sections of tropical vine stems up to 20 mm in diameter and the very high flow (2.5 kg/h), was not limited by the heat balance system. However, the system was in a sheltered area that did not exactly mimic the natural field conditions of a vineyard. This is important when considering the radial loss as discussed above, which Braun and Schmid claim to be the reason for significant error in their measurements. Radial loss is not an issue in laboratory situations or when using cut stems where steady state conditions are obtained before a measurement. Braun and Schmid (1999a) conclude that the heat balance system may be acceptable with commercially grown grapevines that have very thin stems and low leaf areas.

3.3.2.3 Heat Balance Single Heater Conclusion

The single heater heat balance method was shown to provide good sap flow results for grapevines with low leaf cover. The heat balance method is a direct measure of mass flow that has a good response to changes in flow. However, it overestimates flow rates, especially at high flow rates. Variations in the heater height can give different flow measurements. A minimum heater height is necessary to obtain accurate readings as well as a heater band with a proper fit so that sufficient thermal equilibrium between the xylem fluid and the temperature sensors is obtained.

3.3.3 Heat Balance Dual-heater Gauge

Two sources heat are applied to the stem, which eliminates the need to calculate the sheath conductance value (K_{sh}).

3.3.3.1 Heat Balance Dual-heater Gauge Methodology

Calculating flow for a dual-heater gauge requires the following equations (Sakuratani 1981; Steinberg et al. 1989; Peressotti and Ham 1996):

1. The energy balance of a heated stem segment:

   $$Q_h = Q_r + Q_{v,u} + Q_{v,d} + Q_f + S$$

   where
   Q_h = heat applied to the single segment (W)
   Q_r = radial heat flow (W)
   $Q_{v,u}$ = axial conduction up the stem (W)
   $Q_{v,d}$ = axial conduction down the stem (W)
   Q_f = heat flux due to mass transport of sap (W)
   S = the change in heat storage (W)

The heat energy applied Q_h is equal to the heat lost due to conduction, convection, and mass flow. The conduction heat is the energy transferred upstream $Q_{v,u}$ and downstream $Q_{v,d}$ by thermal conduction along the stem. Q_r is the energy lost by convection from the surface of the heated stem into the surrounding air and Q_f is the energy lost by mass flow.

2. The energy balance for each individual heated segment heated can be written as:

   a) $Q_{h1} = Q_{r1} + Q_{v,u1} + Q_{v,d1} + Q_{f1} + S_1$

   b) $Q_{h2} = Q_{r2} + Q_{v,u2} + Q_{v,d2} + Q_{f2} + S_2$

   where subscript 1 and 2 represent the upper and lower stem segments, respectively.

3. The energy flux in terms of a difference equation is obtained by subtracting 2b from 2a to get:

   a) $Q_{h1} - Q_{h2} = Q_{r1} + Q_{v,u1} + Q_{v,d1} + Q_{f1} + S_1 - Q_{r2} - Q_{v,u2} - Q_{v,d2} - Q_{f2} - S_2$

   Three assumptions made to simplify the equation to:

   b) $Q_{h1} - Q_{h2} = Q_{v,d2} + Q_{r2} - (Q_{v,u1} + Q_{f1})$

   - Assumption 1: the radial heat flow away form the segments is equal ($Q_{r1} = Q_{r2}$)

- Assumption 2: the heat conducted downward from the upper heater is equal to the heat conducted upward from the lower heater ($Q_{v,d1} = Q_{v,u2}$)

- Assumption 3: the change in heat storage within the stem segments is negligible and equal ($S_1 = S_2 = 0$)

4. The amount of convective heat transport in the sap stream for each stem segment is defined as:

   a) $Qf1 = cF\,(T_{out} - T_{mid})$

   b) $Qf2 = cF(T_{mid} - T_{in})$

   where
   c = specific heat of the sap (J/kg^3 K)
   F = sap flow (kg/s)
   T_{in} = temperature of the sap upstream in the segment (°C)
   T_{out} = temperature of the sap downstream in the segment (°C)
   T_{mid} = temperature of the sap at between the two heated segments (°C)

5. The axial terms $Q_{v,u1}$ and $Q_{v,u2}$ can be quantified with Fourier's law as:

   a) $Q_{v,u1} = \underline{K_{st}\,A\,(T_{out} - T_{h1})}$

   b) $Q_{v,u2} = \underline{K_{st}\,A\,(T_{in} - T_{h2})}$

   where
   T_{h1} = temperature of the stem segment on the same radial plane as the upper heater (°C)
   T_{h2} = temperature of the stem segment on the same radial plane as the upper heater (°C)
   K_{st} = stem thermal conductivity (W/m K)
   A = stem cross-sectional area (m^2)
   Δ z = longitudinal distance (m) between the edge of the heater and the position where T_{out} or T_{in} are measured

6. The final equation obtained by substituting equations in 4 and 5 into the residual heat flux equation 3, the sap flow is obtained:

$$F = \frac{Q_{h1} - Q_{h2} + [Kst\,A\,(T_{in} - T_{out}) / \Delta z]}{c\,(2\,T_{mid} - T_{in} - T_{out})}$$

- Assumption 4: the heaters are maintained at the same temperature ($T_{h1} = T_{h2}$) to ensure that $Q_{r1} = Q_{r2}$ (assumption 1)

3.3.3.2 Heat Balance Dual-heater Gauge Research

Peressotti and Ham (1996) set out to develop a new type of sap gauge that did not require calibration, did not overheat the stem, and could be used in a wide range of applications without being constrained by assumptions or the operating environment. Their research tested the dual-heater gauge on corn plants grown in pots. The plants were grown under controlled conditions in a greenhouse and put on a 5-day watering regime during the measurement period.

Findings from this study showed that sap flow measurements by both the dual and single-heater gauge gave comparable results with that of the weight loss estimates of transpiration, and the dual-heater gauge giving the more accurate readings. Gauges measured flow rates from 0 to 140 g/h and daily water use from 137 to 1064 g/d.

The single-heater gauge gave the most accurate measurements when the soil water was not a limiting factor, but overestimated flow by 34.5% when water stress conditions were at their highest. The relatively large error was attributed to a change in the water storage in the plant or a poor contact between the gauge and the stem due to the expansion and contraction during the stress cycle.

The sap flow measurements taken by the dual-heater gauge at night were always slightly higher than the weight loss measurements. This was attributed to hydration of the plants during the night and power measurements biases at the low voltages. The single-heater gauge was not connected at night so overheating the stem would be avoided.

Daily accuracy of the dual-heater gauge remained within ±10% over the 5-day test period. The dual-heater had a faster response time compared to the single-heater system. This was tested by severing the stem above both gauges when the sap flow was 100 g/h, and then computing the flow every 1 s. Since the dual-heater gauge does not have a gauge factor, theoretically it can provide a measurement of flow as soon as the system reaches thermal equilibrium with the stem, giving it a use as a hand-held instrument in the field. The current 15 minutes necessary to bring the instrument back to equilibrium for accurate readings would need to be shortened if it were developed specifically for this purpose.

Stem temperatures were always higher in the single-heater gauge and reached a maximum value of 13.8°C above the temperature of the unheated stem.

3.3.3.2 Heat Balance Dual-heater Gauge Conclusion

Advantages of the dual-heater gauge over the single-heater gauge identified from the results of Peressotti and Ham's (1996) study were the following:

1. the dual-heater gauge does not require the assumption of zero flow at night in order to estimate the sheath conductance (K_{sh});
2. post-processing of the dual-gauge data is not necessary and sap flow measurements are possible within 15 minutes after attachment to the stem;

3. the dual-heater gauge does not overheat the stem during periods of low flow; and

4. from a logistics perspective, it is easier to build the dual-heater gauge because a radial thermopile is not needed and all the components are positioned on a single layer, making it possible to mass-produce. However, the dual gauge does require more complicated hardware, which may be an issue with more advances in microelectronics.

4. COMPARISON OF CONVENTIONAL AND NOVEL METHODS TO MEASURE GRAPEVINE WATER STATUS

The pressure bomb method is invasive, that is, every reading requires that some part of the plant be severed, thus making it impractical to take continuous measurements throughout the day like that of non-invasive methods. In contrast, a sap flow gauge can be connected to a data logger and measurements can be taken automatically at frequently intervals around the clock.

Smart (2001) suggests taking pressure bomb readings for at least three fully exposed leaves. These few readings provide information for a narrow period, and therefore provide limited information. It is less likely that these readings will provide a good representation of the average diurnal water usage of the plant or eliminate the effect of outliers. For one, the time of the day to get the best reading as discussed above differs. Additionally, the effects of the inherent dynamic environmental conditions at the other times of the day are not considered in the pressure bomb readings. In contrast, use of the sap flow gauge allows a relatively continuous measurement of water flow providing a larger sample size of data, so theoretically a more accurate average water usage by the plant can be obtained. A larger data set reduces sampling errors, such as the effect of outliers.

The porometer measurements can be taken rapidly but it is a manual process, unlike that of the sap flow gauge. It is not feasible to take as many measurements as a sap flow gauge so the information obtained is over a limited time frame.

Test samples using the porometer, pressure bomb, and sap flow gauges all need to be taken from a leaf or stem that is representative of the total population.

5. RESEARCH ANALYSIS

5.1 Measurement of water flow in young grapevines using the stem heat balance method (Lascano, R.J., R.L. Baumhardt, and W.N. Lipe 1992)

This study by Lascano et al. (1992) assessed the applicability of the stem heat balance method to measure water use in grapevines using commercially available stem flow gauges. The steady state heat balance method developed by Sakuratani in 1981 had been applied to a number of crops including: tomatoes, sunflower, soybeans, rice, trees, and ornamental shrubs. Lascano et al. noted that there was no information available on water use of individual grapevines in an undisturbed field environment. This study marked the first application of this methodology to grapevines in a field setting.

The study was conducted in a commercial vineyard in New Deal, Texas, which had fine sandy loam soil. Stem flow gauges (Dynamax) were used to measure water flow on the five three-year old Chardonnay grapevines with a bilateral cordon training system. The vines were spaced 3.05 m between the rows and 1.22 m between the vines.

Lascano et al. first tested the accuracy of each of the 5 sap flow gauges that were used in the study by comparing the gauge measurements with scale measurement values. Sap flow and scale measurements for one to three days were taken between days 163 to 194 from three-year-old potted Cabernet Sauvignon plants.

The measurements were obtained by fitting a sap flow gauge to the plant and then watering the pot so that the mass in the evening before measurements started at 30 kg. To simulate field conditions, the pots were placed in the vineyard between two Chardonnay vines. Scale measurements were taken at hourly intervals between sunrise and sunset. The sheath conductance value (K_{sh}) for each of the five sap flow gauges used in the experiment was obtained at this point of the study by taking the lowest predawn levels and assuming zero sap flow, as recommended by Steinberg et al. (1989). The sheath conductance value (K_{sh}) is used to calculate the radial outward flux, one of the components in the heat balance equations to compute sap flow (refer to section 3.3.2.1 of this paper).

Water loss measured by the sap flow gauges was less than that measured with the scale, however by midday these differences disappeared. This lag in the morning was attributed to the water capacitance of woody plants, i.e. the water stored in the trunk and leaves. This lag was noticeable when the stem flow gauge did not sense environmental changes, such as the increased cloud cover leading to the leaf stomata responding with a decline in the rate of water loss. The errors that resulted in the measurements over the short-term decreased in the cumulative values to 5 to 10%.

At the end of the test, daily sap flow measurements by the gauges were found to be within 5% of those measured by the balance. Lascano et al. (1992) concluded that based on these results, the stem flow method accurately measured daily water loss values of potted grapevines and was suitable for measuring seasonal water use by grapevines in the field.

The sap flow gauges were mounted on five three-year-old Chardonnay plants at a height of .4 m above the ground. Measurements were taken from May 17 to August 25, 1990 (100 days). Hourly sap flux values (kg/s) were calculated from the signals generated every 15 seconds from the gauges. A weekly maintenance check was made to the sap flow gauges to ensure that a clean and close contact was maintained between the heater and stem. Each gauge and corresponding weather shield was wrapped with aluminum foil over packaging bubble-wrap for additional insulation.

Evapotranspiration data was gathered weekly during the growing season from six neutron-access tubes measuring volumetric water content at a depth of 2.8 m. Measured evapotranspiration (ET) is the water lost to soil evaporation (E) and to crop transpiration (T). The E can be estimated assuming T is the sap flow, and then subtracting this from ET. At the end of the test period, the ratio of E/ET was found to be .77, which means that the soil evaporation was the major contributor to evapotranspiration. Lascano et al. suggests drip or trickle irrigation replace the current flood-irrigation system to increase water efficiency and drastically minimize the high water losses due to soil evaporation (E).

Weather data was gathered every 15 seconds and averaged for every hour. The measurements recorded were: air temperature, relative humidity, short-wave irradiance, and wind speed. Total rainfall over the measurement period was 195 mm and was measured with a tipping-bucket type gauge. The data gathered by sensors placed 2.0 m above ground level were used to calculate daily values of potential evapotranspiration (PET) as an evaporation index.

Daily water flow rates over the experiment period for a vine ranged between 2.4 kg/d to 6.7 kg/d. The total mean cumulative sap flow per unit area over the 100 day measurement period for the three-year old Chardonnay vines was found to be 461 ± 44 kg/plant or 124.0 ± 11.8 mm/land area. Lascano et al. found that the grapevine water use was low in this study, as compared to the total water loss from the field, other field crops in the same region, and to the calculated evapotranspiration of 870 mm.

Lascano et al. conclude that the stem heat balance method is capable of accurately measuring the daily water use of grapevines in the field.

This was a very comprehensive study undertaken involving an extensive number of measurements taken on a frequent and timely basis. It appears that the study was well planned and executed. The paper is well organized considering all the information compiled and reported.

Given all the weather data compiled by Lascano et al. during their study it would have been useful if they could have related more of this information back to the plant physiology and microclimate in the vineyard. Transpiration is a function of all weather data recorded so it would have been useful to see how this correlated with the measured sap flow rates i.e. sap flow versus calculated transpiration.

Notations of water additions either by irrigation or rainfall on the mean daily sap flow graphs would be useful in interpreting the effects of the increasing and decreasing sap flows. Also, Lascano et al. noted that the warm and dry weather with only 5 mm of rain prompted the vineyard manager to irrigate on day 148 and day 160, and did not give a reason for the irrigation treatment on day 175. It would have been useful to have water potential information to show whether the plant was experiencing stress or whatever information may have been used to make the decision to irrigate.

There was good agreement between calculated sap flow measurements and weight loss measurements during the evaluation of the sap flow gauges on the Cabernet Sauvignon vines. Braun et al. (1999a), who undertook grapevine studies using sap flow methodology, attributed the good agreement in the gauge evaluation results to the younger grapevine and hence thinner stems, as well as the lower than normal leaf cover of .3 m^2. Both of these factors would result lower flow and less transpiration. Braun et al. attribute the time lag reported by Lascano et al. (1992) to the positioning of the thermocouples. The thermocouples were places on the outside of the bark and the bark acted as an additional insulator buffering temperature changes sensed by the sap flow gauge. Positioning at the point of maximum sap flow provides maximum sensitivity to water stress conditions and changes in the micro-climate.

The cumulative flow information and interpretation of this information was very useful since the researchers could find no other published information to compare their findings. It is difficult to compare published information since the experimental conditions and environmental conditions will greatly impact the transpiration rates.

5.2 A preliminary evaluation of the suitability of sap flow sensors for use in scheduling vineyard irrigation (Eastham, J. and S.A. Gray 1998)

Eastham and Gray looked at the potential use of sap flow measurement for scheduling irrigation in vineyards. Sap flow was measured from February 20 to March 26, 1995, a period of 35-days, on 5 different *Vitis vinifera* grapevines using the heat pulse method. Irrigation was withheld from the control vines to investigate whether sap flow sensors could be used to detect the effect of water deficits on transpiration rates.

The criteria on which the sensors were assessed were the following:

1. their suitability for use on a range of grape varieties;
2. the ability of the sensor to measure difference in transpiration rates under varying demands for water due to different canopy sizes and the changing evaporative demand from weather conditions; and
3. the ability of the sensors to detect changes in transpiration rate in response to the development of water deficits in the root zone.

The study was carried out on campus at the University of Adelaide, South Australia. All vines were drip irrigated before the study treatment. The control vines consisted of one Sultana and two Cabernet Sauvignon vines, all located in a row where irrigation water was withheld although they received an accumulated rainfall of 7.0 mm over the test period. The vines had a cumulative mean canopy area of 12.7 m^2, which was assumed to remain constant over the test period. Measurements from these vines were compared to the treatment plot containing selected Muscat Gordo Blanco, Carina, and Marroo Seedless vines with a cumulative mean canopy area of 7.7 m^2. In addition to the 7.0 mm rainfall, these vines received 38 mm of irrigation during the test period.

The transpiration rate of the selected vines was measured using 'Greenspan® sapflow sensors'. The sensors use the heat-pulse method and in prior research a calibrating experiment had shown sap flow to be consistently underestimated in kiwifruit vines and apple trees. This underestimation was attributed to the thermal heterogeneity of the woody matrix caused by large vessels and substantial interstitial area in kiwifruit, which is similar in grapevines.

The sap flow measurements showed:

1) the mean daily transpiration rate of the non-irrigated vines, which ranged from 0.8 mm/day to 2.5 mm/day, was greater than the 0.5 to 1.7 mm/day of the irrigated vines. However, the normalized transpiration rate of the non-irrigated vines, ranging from ~.06 to ~.2 mm/m^2 day, the difference which was statistically significant in comparison to the ~.07 to .26 mm/ m^2 day of the irrigated vines. The normalized transpiration rate is the transpiration per unit leaf area. The lower transpiration in the non-irrigated vines was the result of a greater progressive depletion in soil water. The results found cumulative transpiration increased linearly with increased leaf area;

2) over time, transpiration for non-irrigated vines became less than that from the irrigated vines; and

3) daily maxima in sap flow were generally slightly greater for irrigated compared to non-irrigated vines, which was in part due to the greater leaf area of the Marroo Seedless as compared with the Cabernet Sauvignon. However, non-irrigated vines showed a noticeable increase in sap flow at night over the treatment period as compared the irrigated vines.

The data indicates that sap flow sensors were able to detect differences in the timing and the amount of water used by irrigated and non-irrigated vines, which shows that sap flow sensors do have potential application in irrigation scheduling. The differences were attributed to both the differing canopy sizes, similarly found by Lascano et al. (1992), and the changing evaporative demand due to diurnal and daily changes in evaporative demand.

Water loss through transpiration is positively correlated with leaf area. Different sized vine canopy was accounted in the transpiration calculation by dividing the transpiration rate by the leaf area to result a transpiration rate in mm/m^2 day. The non-irrigated vines had a canopy area of 10.0, 11.8 and 16.4 m^2 for the two Cabernet Sauvignon vines and the Sultana vine, respectively. The irrigated vines had a canopy area of 3.4, 6.2 and 13.4 for the Muscat, Carina, Marroo vines, respectively. The canopy area of each vine was assumed to remain constant throughout the study period of February 20 to March 26, 1995, since the canopy should be fully developed by the mid-February. An estimation of the canopy area at the end of the test period would have allowed or discounted differences in canopy as a possible source of error in the normalized calculated transpiration rates.

The canopy range was much larger for the irrigated versus the non-irrigated (10 m^2 versus 6.4 m^2, respectively). Each varietal is unique in terms of how vigorous the growth is under different growing conditions. It would have been better, although I don't know how realistic under field conditions, if the varietals selected in each of the treatments were the same and had approximately the same canopy area. This would eliminate the variable of varietal and canopy in the interpretation of the results. Although, Williams (2001) demonstrated in unpublished work that pre-dawn leaf, midday leaf, and midday stem water potentials for *Vitis vinifera* cultivars and different *Vitis* species to be highly correlated with one another and with other measures of vine water status.

5.3 Use of Sap-flow sensors to schedule vineyard irrigation. I. Effects of post-veraison water deficits on water relations, vine growth, and yield of Shiraz grapevine (Ginestar, G., J. Eastman, S. Gray, and P. Iland 1998a)

Rapid cell division is occurring in fruit during the period bloom to veraison and water stress during this period can reduce berry size and yields. During this period water deficit research has shown that water deficits affect yield more than water deficits after veraison (Ginestar et al., 1998a). In addition, if a grapevine is nearer its critical leaf area to fruit weight ratio because of a high crop load, then berry development may be more sensitive to water stress as compared to a vine with a greater leaf area to fruit weight ratio.

Variations in reported yield due to different irrigation treatments is likely because of the plants response is different under differing environmental conditions. The sensitivity of grape yield and composition to both pre- and post-veraison water stress, indicate there is a need for careful scheduling of irrigation to make the most effective use of water.

The study by Ginestar et al. (1998a) evaluated the feasibility of using transpiration data from sap-flow sensors as a basis for scheduling irrigation to achieve different levels of plant water stress and to influence grape yield and composition.

Ginestar et al. (1998a) monitored the sap-flow of grapevines in the field using the heat pulse method. The grapevines were subjected to varying degrees of plant water stress stimulated by different irrigation treatments. The results showed that intensity and duration of the applied stress was linearly related to post-veraison water use. Ginestar et al. suggests that data from sap-flow sensors may have a use as a basis for irrigation application by providing quantitative information on the degree of water stress experienced by a vine and allowing manipulation of canopy size, plant water status, and yield. Sap flow sensors rely on measured plant responses and may prove more useful for irrigation scheduling that those that are based on individual measurements of factors that affect water use, such as canopy size, climatic conditions, and soil water availability. Strategies that use sap flow information from sensors could be developed, but would depend on the interaction between the grapevine variety, soil type, viticultural practices, and irrigation system design.

Ginestar et al. (1998a) measured sap-flow in five year-old Shiraz vines planted on their own roots in the Barossa Valley, South Australia. The experiment was set up in a randomized block with three replicates per treatment. Each replicate consisted of a single row of 40 vines with six buffer vines at the edge of each block. Vines were grown on a two-wire vertical trellis, with alternate vines trained to upper and lower wires positioned at a height of 1.4 m and .9 m respectively. The spurs and foliage were trained upwards on the upper wire and downwards on the lower wire. Vines were spaced 1.5 m within rows that were 3 m apart. Vines were spur-pruned by hand to approximately 30 spurs, with 2 nodes per spur on the uppers vines and 3 nodes per spur on the lower vines. The vines were drip irrigates with 3.5 L/hr drippers spaced at 1m intervals.

Climate at the site was Mediterranean, with annual precipitation of 516 mm of which 388 falls in the spring and summer (August to May). The topsoil at the site was sandy loam with clay-loam subsoil. Winter cover crops were established between the vine rows and were incorporated into the soil by cultivation just before budbreak.

All blocks received the same irrigation program before veraison. The 3 post-veraison irrigation treatments were:

1. wet treatment – irrigated at weekly intervals at 14 mm, with the total irrigation amounting to 95.6 mm, close to the 100 mm maximum allowed in the region.
2. medium treatment – irrigated the same as the wet treatment with 50% of the water applied, i.e. 7 mm
3. dry treatment – no post-veraison irrigation

No irrigation was applied two weeks before harvest due to irrigation problems.

Greenspan® sapflow sensors were installed one week after veraison (Feb 8th) to measure the transpiration rate on two adjacent vines per replicate, one on the upper wire and the other on the lower wire. Measurements of flux were taken at 30-minute intervals around the clock starting at 0600 hr until harvest.

The water status of the vine was determined by measuring the leaf water potential with a pressure bomb before dawn (0500-0630) and at solar noon (1300-1400) at two-week intervals from veraison to harvest. Three leaves from each the upper and lower wire canopy were tested. Canopy measurements of both the leaf area and shoot length were taken after harvest, at veraison, and one month after veraison.

Throughout the post-veraison period, no significant difference in transpiration between the wet and medium treatments resulted, while 15 days after veraison, however transpiration in the dry treated vines was significantly lower and remained the lowest throughout post-veraison.

Table 5.1 summarizes Ginestar et al. (1998a) findings. The results reveal that additional water applied in the Wet treatment did not increase the vines transpiration rate above that of the Medium treatment suggesting that the water supply used in the medium treatment adequately matched the plant's water demand. Compared with other treatments, the vines in the Dry treatment were already more stressed by day 10.

Despite the similar water use of the Wet and Medium treatment, the predawn leaf water potentials indicated more stress in the Medium treated vines than the Wet treated vines and the lower midday leaf water potentials for the Dry and Medium treatment were similar. This was attributed to the lower soil water availability in the root zone for the Medium treatment. With the exceptions of the Wet treatment predawn measurements and the initial predawn measurement for the Medium and Dry treated vines, the positioning of the vines did not make a difference to the midday or predawn leaf water potentials.

The number of lateral shoots was significantly lower in the Dry treatment at harvest which Ginestar et al.(1998a) relate to the water stress, as development of laterals from the main shoot have been shown to occur mainly after veraison. No difference was expected in the mean leaf area as seen, since the irrigation treatments were the same to veraison. However, a reduction of 65% in the leaf area of the Dry treatment was a result of water stress. Ginestar et al. (1998a) note that LWP's of -1.3 MPa is generally required before leaf drop occurs. No significant difference between the treatments was noted at the final measurement of LWP, which the researchers ascribe to the same irrigation treatment (i.e. none) to all vines for the last two weeks of the study.

The study conducted by Ginestar et al. (1998a) demonstrates the usefulness of the sap flow measurements using the heat pulse method and its application for an irrigation program. From the water flow data we can correlate the results to: 1) vine water use – more water did not translate to a higher usage; 2) water relations – variations in irrigation treatment had the greatest significance on midday transpiration rates and withholding water after veraison and post veraison did lead to significant deficits in plant water status; 3) leaf area – no irrigation significantly reduced the leaf area by 65%; and, 4) yield – is significantly reduced under water stressed conditions and was related to severity and duration.

Table 5.1 Effect of post-veraison water deficits on vine growth, water relations, and yield of Shiraz grapevines

Measurement	Treatment		
	Wet	**Medium**	**Dry**
Vine water use:			
Daily Sap flow per vine (L/day)	1.2 to 5.8	1.6 to 6.6	.6 to 3.0
Mean sap flow/vine (L/day)	3.8	4.2	1.8
Mean cumulative sap flow per vine from veraison to harvest (mm)	60.6 ± 2.2	65.4 ± 2.6	27.0 ± 2.4
Water relations:			
Predawn LWP[note 2] (MPa)	-0.40 to -0.75	~-0.5 to -1.0	~-0.55 to -1.23
Midday LWP (MPa)	-1.2 to –1.5	-1.4 to –1.6	-1.5 to 1.7
Midday LWP Upper Trellis vs. Lower Trellis	no significant difference	no significant difference	no significant difference
Predawn LWP Upper Trellis vs. Lower Trellis	upper less	upper less initially; no significant difference after	upper less initially; no significant difference after
Intensity of water stress ($p > 0.05$)	significant	significant	significant
Duration of water stress (MPa day)	14	23	43
Leaf area:			
mean leaf area (m^2) at veraison [note 1]	5.3d	5.8d	4.9d
mean leaf area (m^2) at harvest	4.7d	3.5d	1.7e
mean total number of main shoots at harvest	70d	68de	59e
mean total lateral shoot number at harvest	212d	174d	92e
mean total lateral shoot > 5 cm number at harvest	54d	48de	36e
mean canopy density at veraison (leaf area/canopy volume = m^2/m^3) of upper and lower Trellis	2.4f	2.4f	2.1f
mean canopy density at harvest (leaf area/canopy volume = m^2/m^3) of upper and lower Trellis	2.1f	1.5g	0.8h
Yield:			
relative yield (%)	+19	+4	0
Crop load:			
mean leaf area to fruit weight ratio at veraison	8.8f	11.1e	8.0f
mean leaf area to fruit weight ratio at harvest	6.9e	6.0e	3.1f

note 1: Least significant difference (LSD) used to test significance of difference between treatment means. Different letter indicates significance.
note 2: LWP = leaf water potential

This study was well planned and executed. The application of the research results is realistic because the study was performed under field conditions. It is important to the advancement of research in the wine industry since Shiraz vines were used, which are an important grape varietal for the Australian export market. Quantitative measurements of key plant physiological parameters resulting from irrigation treatments were recorded and interpreted using ANOVA (analysis of variance) for significance. Statistical analysis increases the relevance of the data interpretation.

Ginestar et al. (1998a) measured the leaf area at veraison and harvest. While there was no significant difference between the irrigated treatments, the leaf area of 4.9 m^2 at veraison for the Dry treatment did differ significantly from the measurement at harvest of 1.7 m^2. Thus, the previous study by Eastham and

Gray (1998) making the assumption that the canopy area did not change over the study may be a source of error.

Rather than using calendar dates, the researchers gave the measurements in terms of veraison, post-veraison, harvest, and post harvest. This is useful since these stages of growth and maturity vary under different climatic conditions.

5.4 Use of Sap-flow sensors to schedule vineyard irrigation. II. Effects of post-veraison water deficits on water deficits on composition of Shiraz grapes (Ginestar, G., J. Eastman, S. Gray, and P. Iland 1998b)

This paper is the second part to Ginestar et al. study discussed in section 5.3 of this paper, which evaluated the feasibility of using transpiration data from sap-flow sensors as a basis for scheduling irrigation to achieve varying degrees of water stress grapevines to influence grape yield and composition.

Table 5.2 summarizes the findings on berry growth and fruit composition of 5-year old Shiraz grapevines (outlined in section 5.3) subjected to a Wet, Medium, and Dry irrigation treatment. The different irrigation applications commenced at veraison when 14 mm/week and 7 mm/week were applied to the Wet and Medium treatments respectively. No irrigation was applied to any treatment after March 23 (grapes harvested April 11th).

Ginestar et al. (1998b) conclude that post-veraison irrigation scheduling can be used to control grape yield and berry composition, thereby influencing economic yield. Their study showed juice pH, berry colour, and berry weight to be quantitatively related to water stress in vines during the post-veraison period. Conversely, soluble solids, pH, and titratable acidity, were not significantly affected by post-veraison water stress. Vine water measurements from sap-flow sensors can be used as a basis for applying either excessive, sufficient, or deficit amounts of irrigation to influence the degree of water stress to influence berry weight and fruit composition.

Part II of Ginestar et al.'s (1998b) comprehensive study was well planned and executed. The paper is well written in that it includes tables, graphs, and a written description of the study results in terms of fruit composition.

Table 5.2 Effect of post-veraison water deficits on the composition of Shiraz grapes

	Treatment			
	Wet	**Medium**	**Dry**	**Note**
Fruit Exposure (%)	27	47	68	fruit exposure is directly correlated with leaf cover
Leaf Cover (%)	11	39	65	
Berry Weight:				
- one week after veraison	no significant difference			
- second week after veraison	significantly higher	significantly lower	significantly lower	
- maximum weight reached	day 45	day 45	day 52	
- harvest: day 63 (g)	.89e	.84e	.66f	
Fruit Composition - Total Soluble Solids:				
- one week after veraison (°Brix)	13	13	13	
- harvest (°Brix)	23.4e	23.0e	22.9e	
Juice pH:				
- one week after veraison	2.7	2.7	2.7	
- harvest	3.50e	3.54e	3.66e	- dry treatment had greater bunch exposure which may have increased berry temperature causing greater respiration of malic acid; - greater translocation of potassium to the berries with stressed leaves, which increased the extent of the exchange of potassium for protons within the cells of the berries resulting an increase in pH.
Juice Titratable Acidity:	no difference			
Anthocyanins & Phenolics:				
- post-veraison (mg/berry)	no difference			
- harvest (mg/berry)	1.58e	1.53e	1.29f	
anthocyanins concentration at harvest (mg/g of berry mass)	1.78f	1.83ef	1.96e	- concentration higher in Dry due to the smaller berries; - lower concentration in Wet and Medium treatment may be due to greater cluster shading
Total Phenolics in the berry macerate at harvest (abs/g)	1.49f	1.47f	1.63e	- function of the decrease in berry weight with increase in water stress

The next step would be to characterize the wines according to the different irrigations treatments and determine whether there a significant difference exists between the wines made from the three irrigation treatments from a sensory perspective. This could be done by using various sensory analysis including: triangle tests and preference tests to determine whether there is a significant difference between the wines; descriptive analysis and cob-web diagrams to depict the test results; and, ANOVA to determine statistical significance in the results.

In the fruit compositions part of the results section, Ginestar et al. comment that the concentration of soluble solids was approximately 2° Brix in all treatments at harvest. This appears to be a mistake as the °Brix at harvest is ~23 for all treatments.

5.5 Device for Simulating High Rates of Sap Flow in Grapevines (Tarara, J.M. and J.C. Ferguson, 2001)

In this paper, Tarara and Ferguson assessed the accuracy of standard heat-balance sap-flow gauges using a constructed sap-flow simulator device. They were specifically interested in assessing the suitability of heat balance gauges in grapevines under high sap flow conditions. Their research also facilitated the development of new gauge designs for use in mature grapevines.

Grapevines have a low plant density relative to other crops, but on a per vine basis the rate of transpiration in well-watered canopies can be upwards of 60 L/day, as in the case of Thompson Seedless in California (Tarara and Ferguson 2001).

Many of the water status experiments are performed using potted plants. However, testing may be limited because a pot may not be large enough to hold the specimen or reasonably duplicate the sap-flow rate of a mature field-grown plant, as in the case of grapevines. Therefore, it is essential that field trials be done to test the accuracy of the equipment.

Heat balance sap flow gauges were constructed in-house based on a U-shaped design. These gauges were first tested under greenhouse conditions on 10-year-old potted Concord vines, that had been dormant when excavated from a vineyard. The vines had an average trunk diameter of 45 mm with an estimated vine leaf area of 2 to 3 m^2 during the test period. These pots were sealed to prevent soil evaporation.

The heat balance sap flow measurements were found to underestimate transpiration by 16% on a cumulative 24-hour basis as compared to transpiration rates calculated gravimetrically. Maximum sap flow rates exceeded 550 g/hr, with most daily maxima around 450 g/hr.

Subsequently, 20 heat balance sap flow gauges were operated simultaneously in an irrigated vineyard of 10-year-old Vitis *labrusca* cv. Concord vines. Measurements were taken for 94 days during the summer of 1999. Midsummer vines with full canopies averaging 14 to 18 m^2, had transpiration rates averaging 10 L/day per vine with maximum sap flow rates exceeding 3,000 g/hr. Daily maxima averaged 1,350 g/h across all vines.

Based on this data, vine water use was estimated for a 120-day period to be 183 mm per acre. This is low compared to sap flow value of 417 mm per acre obtained by lysimetry from well-watered drip-irrigated vines in the same area.

The results from the potted grapevine and the field grapevine test opened up questions on the validity of the sap flow gauges for rapidly transpiring vines.

The sap flow stimulator device constructed to evaluate the sap flow gauges consisted of components to control water delivery to a severe trunk section and components to monitor the flow rate. Radial thermal homogeneity in the stem is critical to the success of the heat-balance method and flow pattern influences temperature distribution (Tarara and Ferguson 2001). Systematic errors of 90 to 300% were found in whole trees when the assumption was made that sap flow is uniform through the sapwood depth (Nadezhdina et al. 2002). Initial trials with input pressures of 0.3 MPa (~ 40 psi) achieved flow rates up to 3,000 g/h. Each trunk was used in the simulator device for about one week.

Braun and Schmid (1999a) found in their research that the water flow rate differed between the younger outer xylem vessels showing greater flow rates than the inner older xylem vessels. This difference in flow between the rings should be imitated in the simulator. Fichtner and Schulze's 1990 research and Braun and Schmid (1998a) showed there to be relatively low resistance to flow in vine vessels and if water is pushed through with pressure it will tend to move evenly through all vessels. So it could be argued that the sap-flow simulator is not a true simulation of a grapevine vessel so the validity of the sap flow stimulator to evaluated sap flow gauges is questionable.

Tarara and Ferguson addressed this concern that - a trunk on the simulator device is under pressure versus a transpiring vine *in situ* is under tension. The concern is that the simulator device would force water through the severed stem that might have been unused under field conditions. Three severed grapevine stems were compared: a freshly severed specimen left in the vineyard in a container of dyed water, a freshly severed specimen that was put on the simulator under pressure with a dye injection, and a freshly severed specimen place under vacuum with a vacuum aspirator to simulate the effect of water tension. Examination of the conductive xylem vessels showed similar toroidal flow pattern in all three severed grapevine stems. This demonstrated that the flow pattern through the simulator device in the severed trunk did mimic a trunk connected to a full canopy in the field.

When the simulator device was used to test the sap flow gauges, the results showed that the standard designs performed well up to about 500 g/h. Above 500 g/h, apparent thermal heterogeneity across the stem caused the gauges to underestimate sap flow by as much as 66%, which explains some of the suspicious estimates of vine water use in the field. Thermal heterogeneity in the radial aspect increases the likelihood that thermocouples at the stem surface do not measure a representative tissue temperature and this leads to an underestimated sap flow. Researchers have addressed this issue by inserting the thermocouples into the stem to a depth where the measurement is expected to represent an average radial temperature. Tarara and Ferguson were looking for a non-invasive design so their model places the thermocouple junctions at positions along the stem surface where thermal homogeneity exists at high flow rates.

The original design was modified and sap flow rates from the gauge agreed with those computed from mass balance to within 10% at low to medium flow rates of 1,500 g/h. The divergence point was at ~2,000 g/h, and at 5,000 g/h the gauge underestimated transpiration by up to 50%.

A key strength of the heat-balance method is in estimating cumulative daily water use rather than in estimating a precise flow rate at a given time since the errors that do occur in this method, such as violation of the steady state, self-compensate over a 24-hour interval. However, the error(s) under high flow rates are a concern as they make a larger contribution to the cumulative water use total, as compared to low flow rate errors.

Tarara and Ferguson recommend that that longest trunk segment feasible be used to minimize the potential difficulties from preferential flow patterns in the radial aspect. Average vessel lengths of .6m to 3 m have been reported (Tarara and Ferguson 2001)

Tarara and Ferguson conclude that the sap-flow simulator is useful in assessing sap-flow in unfamiliar woody species or on large plants where modifications to existing gauge designs may be required because of stem morphology or high flow rates. The method is destructive, but allows repeated testing in situations where potted specimens may be unavailable or impractical to maintain. The simulator is simple in design, inexpensive, and allows the testing of gauge performance under a variety of controlled flow rates.

The test to address the concern over whether the simulator device mimicked the water tension in the xylem vessels showed toroidal flow patterns that differed from Braun and Schmid's 1998 experiment where they showed that in even 20-year old grapevines there was no detectable heartwood. Tarara and Ferguson reported 77, 79, and 82% of the cross-sectional area comprised the conducting elements in: the freshly severed, the injected dye, and the vacuum aspirator applications of dye water, respectively. It appears that there is noticeable heartwood in these cut stem sections from 11 year old Concord grapevines, with a diameter ranging between 34 to 38 mm or the sap flow simulator device does not mimic water tension in the xylem vessels of grapevines.

6. Summary and Further Research

6.1 Summary

There are many conventional and innovative ways to determine plant water status. Decisions on what method to adopt will depend upon many factors including: the size of the budget; environmental conditions; field conditions; crop growing; or whether an invasive or non-invasive method is appropriate.

Each device and method has its own strengths and weaknesses which should be considered when making decisions from single instrument measurements. The quantitative information relating to water status that a grower can obtain about the plant, soil, and environment will enable the grower to make reasoned irrigation decisions.

The research findings covered in this report are summarized in Appendix 1.

6.2 Further Research

It was evident from research on the use of sap flow gauges to measure water status in grapevines that there was a lack of research under field conditions; rather, most of the research was under controlled conditions. When research was done out in the field, varied sources of errors were prevalent, as compared to the results found under controlled conditions.

The dendrometer is a sensing device that has been used to measure water status in trees dating back to the 1960's. However, its use on grapevines is relatively new. As it seems for all gauges measuring water status, there are identifiable strengths and weaknesses. This is no exception for the dendrometer, which is reported to be less responsive in its measurement of water flow than leaf measurement devices measuring turgor pressure (BC 1997).

My research proposal involves the use of a data logger that receives information from sensing devices placed on grapevines in the field. This includes the dendrometer and sap flow gauges as well sensing devices to measure leaf temperature, solar irradiance, air temperature, air humidity, and soil moisture. The data logger receives information from these sensing devices that are strategically positioned to gather information on the physiology of the plant and the environmental conditions. This information is sent to a PC, which in turn interprets this information and makes programmed irrigation decisions. For example, irrigation is applied as instructed by the computer at a level that will expose the vines to mild stress during key growth periods with the objective of increasing fruit quality for increased wine quality.

Objectives

This research project will develop the methodology to use a phytomonitoring system in the cool climate viticulture area of the Okanagan to monitor vine water status in *Vitis vinifera* grapevines.

The grapes grown using the phytomonitoring system to control water status will be assessed for on their chemical attributes of °Brix, titratable acidity, and pH to asses grape quality. The grapes will be used to make wine and the wine will be assessed on colour, aroma, taste, and texture to determine if ultimately the use of the phytomonitoring system significantly affected wine quality.

Experimental Design

The experiment is to be conducted at an Okanagan vineyard in B.C. with a drip irrigation system. The test site is to be sectioned into three plots, with each test vine representing the average vines in the plot from one of the three chosen varietals: Chardonnay, Pinot Noir, and Cabernet Sauvignon. Chardonnay is a preferential choice for white cultivars because of its prevalence in wine growing regions of Canada as well as being a wine for which a premium price can be obtained. Pinot Noir is being selected because of the challenges in growing this varietal well in cool climate regions. Cabernet Sauvignon is being selected because of the challenges in growing this grape to maturity to obtain sufficient °Brix to make a balanced wine typical of the varietal character.

Description of New Technology

It is important to understand the characteristics of your vineyard soil and site to effectively manage water application. Phytomonitoring involves the use of computerized technology to observe real-time plant physiology conditions. It combines the use of sensors and data processing software to constantly monitor the conditions of the plant and its surrounding environment.

The standard sensor set recommended for grapevines by PhyTech Ltd. (Israel) is: 3 stem diameter sensors, 3 trunk diameter sensors, 1 sap flow rate sensor, 1 leaf temperature sensor, 1 solar irradiance sensor, 1 air temperature sensor, 1 air humidity sensor, and 1 soil moisture sensor. A description of the positioning of the sensors is given by PhyTech in their document titled 'Phytomonitoring Technique for Viticulture', which can be obtained from the company. Briefly, the positioning of the sensors is as follows. The stem diameter sensors are positioned at the lowest green internode of the shoot, which bares the leaf with the leaf and sap flow rate sensor. The leaf sensor is placed on a fully expanded leaf at mid-level in the canopy and the sap flow rate sensor is place at the petiole of this leaf. The trunk diameter sensor is attached to the upper and the thickest part of the trunk, after carefully removing any dead bark. The solar irradiance sensor is installed over the top of the canopy, the air temperature and humidity sensors are installed inside a radiation shield. The soil moisture sensor is place a depth of 35 to 50 cm below the soil surface.

Validating the Technology

The control plot is set to irrigate on the standard scheduling method used by the grower. The irrigation system in the experimental plot is based on the phytomonitoring system.

Chemical measurements are taken to compare and assess the grape quality. Wines are made from each the control and the experimental grapes. Preference tasting and descriptive analysis are conducted on each of the wines to determine whether there are significant preference and quality differences.

Appendix 6.1 Summary of grapevine water status research

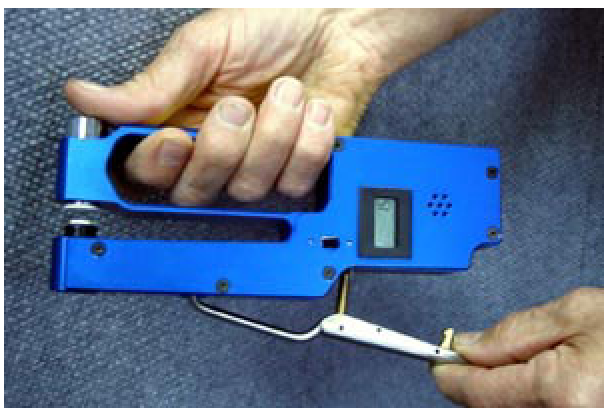
Year:Reference	Method	Conditions	Plant	Evaluation	Notes
1992: Eastham and Gray	Heat Pulse	♦ field	♦ a variety of *Vitis vinifera* vines	✓ sap flow sensors responded to irrigation	♦ potential for sensors to have application in irrigation scheduling
1998a & 1998b: Ginestar et al.	Heat Pulse	♦ field	♦ 5 year old Shiraz grapevines	✓ responsive to deficit irrigation treatments; ✓ provides quantitative plant response to water use, canopy size, climatic conditions, and soil water availability	♦ daily sap flow ranged from 1.2 to 5.8 L/day and 1.6 to 6.6 L/day for the wet and Medium irrigation treatment; ♦ post-veraison water deficit treatment sap flow ranged from .6 to 3.0 L/day; ♦ mean daily sap from veraison to harvest was 3.8, 4.2, and 1.8 L/day for the Wet, Medium, and Dry irrigation treatments
1987: Granier	Granier	♦ field	♦ 24 year old Douglas Fir stand in France	✓ whole season gave similar results for the sap flow technique as compared with the neutron probes measurements ✗ shorter periods the values were very different from the neutron probe measurements; errors attributed to estimation by the water balance method during periods of heavy rain	♦ maximum sap flux density ranged from zero up to 35 x 10^{-6} m/s
1998 & 1999: Braun and Schmid	Granier	♦ greenhouse – potted plants ♦ cut stems	♦ grapevines	✓ good over long term, error < 1.5% ✗ lacks in ability to respond instantaneously ✗ was not found to reflect short term environmental changes	♦ sap flux density ranges below 200 x 10^{-6} m/s ♦ sap flux density range tested using this method: ♦ 225 x 10^{-6} m/s associated with 5.2% error ♦ 400 x 10^{-6}m/s associated with 7.2 % error ♦ > 400 x 10^{-6}m/s associated with unacceptable error levels
1981: Sakuratani	Heat Balance - single heater	♦ potted plants	♦ soybean ♦ sunflower	✓ transpiration rates > 20 g/h good agreement; ✗ < 20 g/h transpiration rate deviates systematically from balance measurements	♦ if the transpiration rate is low, it is necessary to accurately measure the thermal conduction upstream ($Q_{v,u}$), downstream ($Q_{v,d}$), and the energy lost by convection (Q_r), from the surface of the heated stem into the surrounding air
1989: Steinberg et al.	Heat Balance – single heater	♦ greenhouse – potted plants	♦ tree	✓ gauge measurements within 4% of balance measurements; errors attributed to water storage in trunk and branches of tree ✗ low responsiveness reduces suitability for transpiration measurements over short periods	♦ tree diameter 45.2 mm; leaf area 6.1 m^2 ♦ sap flow lagged transpiration in morning, but exceed transpiration in the afternoon and night; lag attributed to heat capacitance of the trunk; ♦ gauge response results: 20 minutes at sap flow of 80 g/h (12:45p); 76 minutes under zero sap flow conditions
1992: Shackel et al.	Heat Balance	♦ field	♦ peach trees having stems with a diameter of 60 to 70 mm.	✗ negative ✗ method resulted lots of errors when compared to lysimetric measurements ✗ errors attributed to temperature differential in stems due to environmental conditions, that are not considered in the heat balance model	♦ differed from other studies in that the 1) environmental conditions were not controlled, and 2) the stems of the plant tested were larger and would be expected to take a longer time to reach thermal equilibrium by passive heat conduction in comparison to the smaller stems and gauges used in other studies.

Appendix 6.1 Summary of grapevine water status research

Year:Reference	Method	Conditions	Plant	Evaluation	Notes
1992: Lascano et al.	Heat Balance	♦ greenhouse – potted plants ♦ field	♦ 3-year old Cabernet Sauvignon ♦ Chardonnay vines	✓ accuracy within 5% of balance measurements	♦ accurately measures daily water use of grapevines in the field
1996: Peressotti and Ham	Heat Balance – dual heater	♦ greenhouse – potted plants	♦ corn	✓ more accurate measurements than single-heater gauge, but always slightly higher than balance measurements; × single-heater gauge overestimated flow by 34.5% under maximum water stress conditions; error attributed to poor contact between gauge and stem;	♦ flow rates measured 0 to 140 g/h and 137 to 1,064 g/day ♦ dual-heater gauge error within ± 10%
1998: Braun and Schmid	Heat Balance	♦ greenhouse – potted plants	♦ mature Riesling grapevines	✓ low flow rates no detectable difference; × high flow rates 20 to 50% error	♦ 35 to 45 mm diameter stems ♦ variation in height of heater band showed sap flow differences of ± 20%
2001: Tarara and Ferguson	Heat Balance	♦ greenhouse – potted plants ♦ field	♦ 10-year old Concord grapevines	× underestimated sap flow at high flow rates	♦ sap flow up to 500 g/h performance acceptable ♦ sap flow > 500 g/h showed underestimates by up to 66%; attributed to thermal heterogeneity at the stem surface and within the stem where the water is flowing

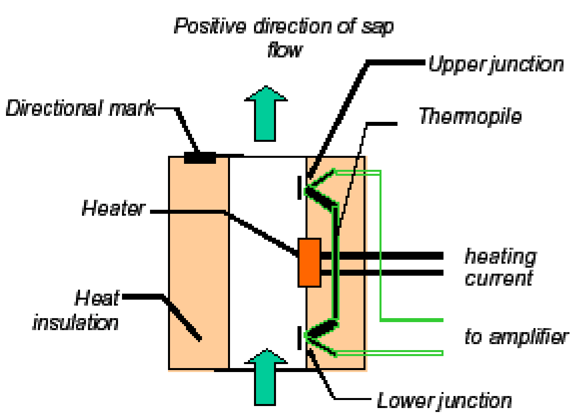
Gypsum Block

Theta Probe



Thermoline Porometer
http://www.thermoline.com.au/products/porom.htm

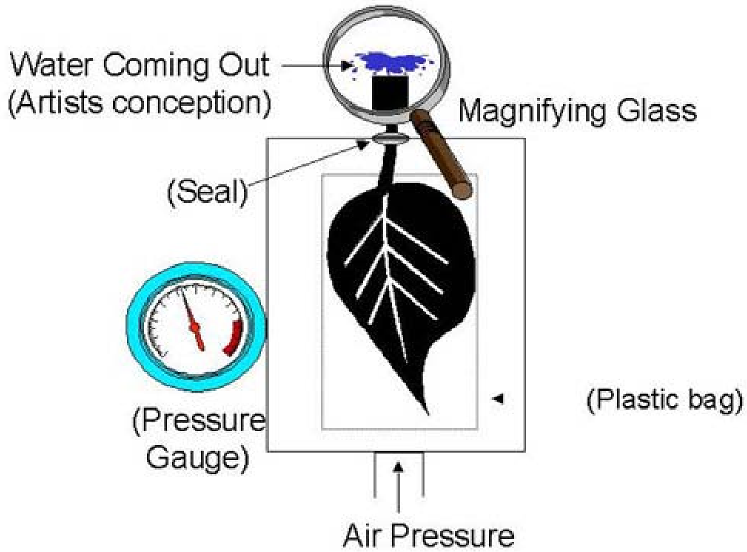
Measurements from soil sensors connected to this low cost data logger can be logged every 2 hours



Methodology of a Heat Balance Sap Flow Gauge

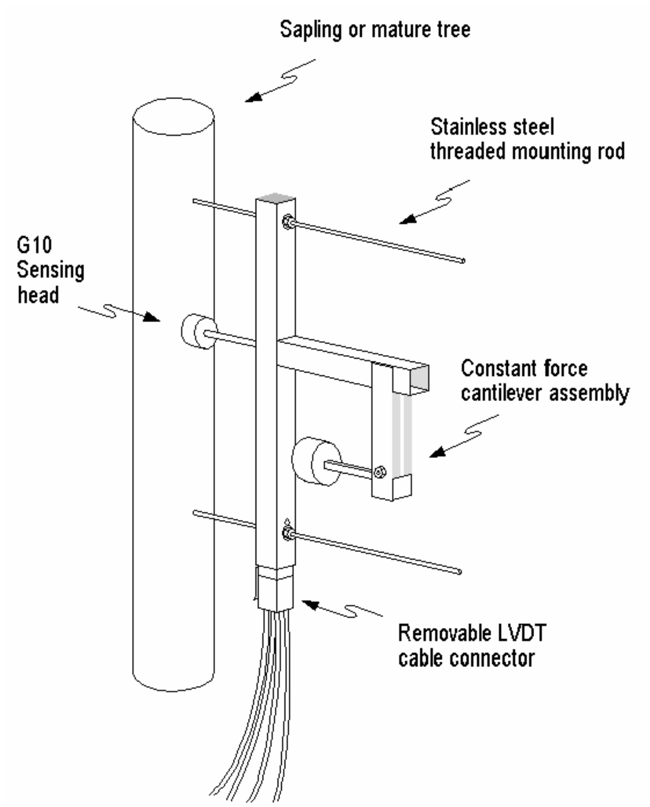
Stem sap flow gauge

on-line: http://www.agrisupportonline.com/phy/downloads/webfiles/SF-4%20Leaflet.pdf



Schematic diagram of how a pressure bomb works
on-line: http://fruitsandnuts.ucdavis.edu/crops/bomb-fig1.shtml

The petiole is closely observed as pressure is applied until the sap just appears
on-line:http://www.practicalwinery.com/novdec01p42.htm



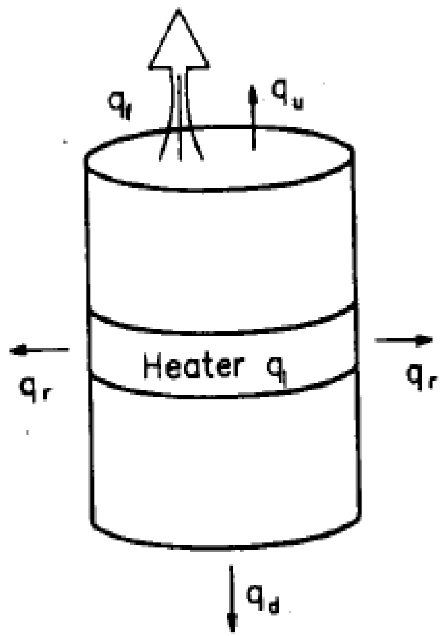
Schematic diagram of a Point Dendrometer used to measure the reaction of the plant to environmental changes

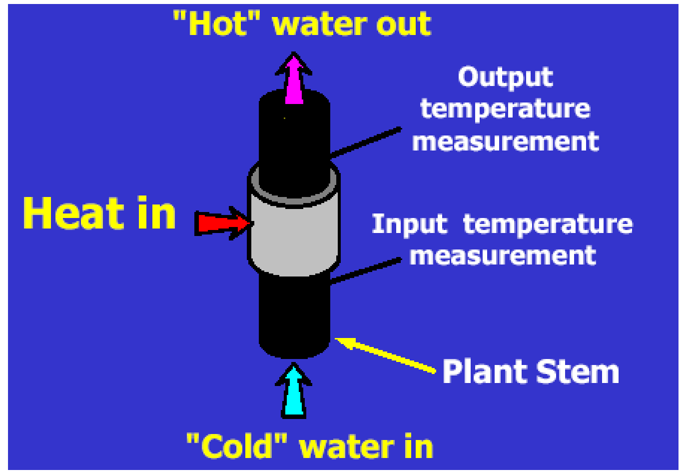
ditch for lysimeter

Penn State – Agricultural Soil Science website

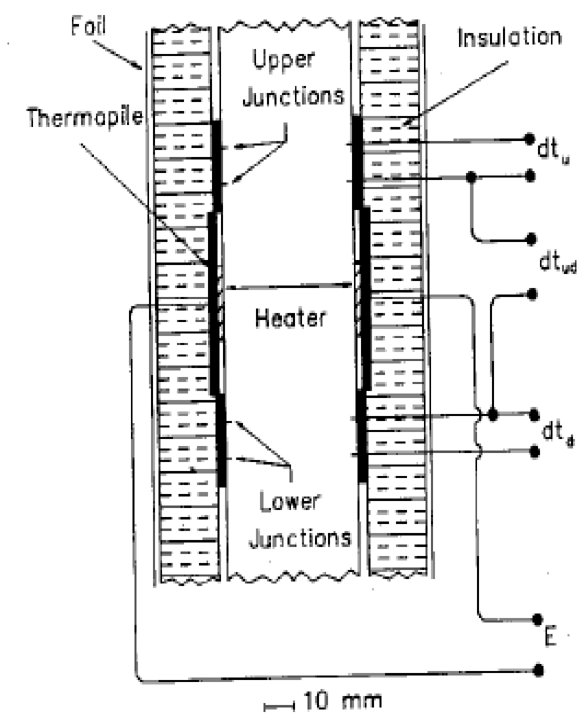
lysimeter tubing & pipes

spreading limestone

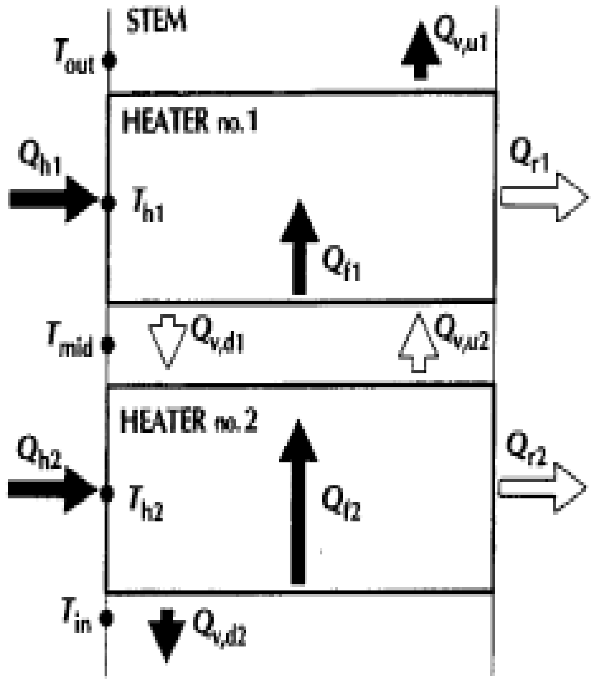




Schematic diagrams of a single-heater sap flow gauge



Schematic diagram of the assembly of a single-heater sap flow gauge and the variables used to calculate sap flow



Dual-heater sap flow gauge
Peressotti and Ham, 1996

Granier Sap Flow Gauge

Heat Balance Sap Flow Gauge

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