Plant response to water—new tools for vineyard irrigators

Brian Loveys and Ping Lu
CSIRO Plant Industry, Horticulture Unit, Glen Osmond South Australia

Introduction
Irrigation practices always have the potential to be environmentally damaging through depletion of ground and surface water reserves, rising water tables, salinisation of soils, increasing soil sodicity and the leaching of nutrients and agricultural chemicals into watercourses. Problems such as these may threaten the long-term sustainability of many irrigation areas. Improving the efficiency of water use, thereby reducing abstraction and runoff, can minimise some of the problems associated with irrigation. However, as water inputs are reduced, there is an increased risk of inducing undesirable water deficits in the crop. It is therefore important that we understand fully crop responses to water deficits and continue to investigate the most appropriate tools for monitoring plant performance.

During the past ten years the Australian wine grape industry has experienced a period of massive expansion fuelled by demand for high quality, reasonably priced wines in world markets. Since 1987 the area planted to grapevines has increased from 60,000 ha to the current area of 146,000 ha. This expansion has occurred in a climate of decreasing availability of water for irrigation, an increase in its cost and a heightened awareness of environmental issues among growers, the public and governments. There is therefore considerable pressure on the wine grape industry to increase the efficiency of water use. An increased awareness of the benefits of soil moisture monitoring and its adoption for irrigation scheduling is contributing to better efficiency of water use, but soil moisture is really only a surrogate for what we really need to be assessing, which is the performance of the vine itself. This is becoming more important as strategic irrigation technologies such as partial rootzone drying (PRD) and regulated deficit irrigation (RDI) are increasingly adopted. PRD deliberately creates discontinuities in soil moisture, making scheduling based on soil water measurements more difficult. The margin for error in matching water input to plant requirement becomes smaller as the buffer provided by the high water inputs of the past is removed. Furthermore, as the link between water deficit and grape quality is exploited to produce wine grapes to specified quality, there will be an enhanced need to monitor plant performance in relation to water input.

In order to benefit most effectively from any plant-based measure of vine performance one of the first steps is to clearly define crop water use under a range of environmental conditions. There are a number of tools available to quantitatively determine vine water use. This paper considers the use of various sap flow sensors to determine transpiration through specific examples and also considers the application and possible limitations of two other methods of assessing plant response to irrigation and environment.

Sap flow sensing and grapevine transpiration
Commercial heat pulse sap flow sensors (Greenspan Technology, Warwick, Queensland) and Granier sensors (Granier, 1987) were used in these studies. For the experiment with heat pulse sensors sapwood radius and volume fractions of water and wood were calculated according to Yunusa et al. (2000). In the study with Granier sensors total sap flow of each vine was calculated as the product of sap flux density and cross-sectional sapwood area at the point of measurement. The whole-cross sectional area excluding the bark was considered as sapwood.

Figure 1 shows the relationship between sap flow, measured with heat pulse sensors, and transpiration of the same vine, measured with a digital electronic balance. Balance and sensors were logged at 15 m intervals throughout the experiment. There was close agreement between the sap flow and transpiration data, showing that this is a viable technique for the measurement of grapevine transpiration. Yunusa et al. (2000) similarly found a reasonable relationship between transpiration measured with heat pulse sensors and transpiration measured gravimetrically. In the same study Yunusa et al. also used sap sensors to measure transpiration of mature, field-grown, Sultana vines and found that sap flow was remarkably unresponsive to current evaporative demand. For example, on a day when a maximum vapour pressure deficit (VPD) of 1.5 kPa was compared with a much hotter day when maximum VPD was 5 kPa, maximum transpiration varied little, suggesting that the vines exerted significant control on transpiration rates at high levels of evaporative demand. Similar experiments were carried out by Lu (Lu et al., unpublished) with identical results. Lu used Granier sap flow sensors to assess transpiration of mature Sultana vines in the field and made comparisons on two close but separate days (January 19th and 25th) when maximum VPD was 3.6 and 1.8 kPa respectively. Despite this large difference in evaporative demand transpiration was virtually identical (Figure 2) as a result of changes in canopy conductance that was highly negatively correlated with VPD. These results suggest that water used by the vines amounted to 0.6 to 0.8 mm/day. It is also noteworthy that the diurnal transpiration changes recorded by Yunusa et al. (2000) show that there is considerable water use by the vines at night when VPD was high. For example, when VPD remained at 2–3 kPa during the hours of darkness transpiration was about 15% of the average day value. Eastham and Gray (1998) have also noted this phenomenon.

These data show that both heat pulse and Granier sap flow sensors are capable of accurately estimating whole vine transpiration. Braun and Schmid (1999) have also shown that the Granier system is a reliable means of assessing grapevine transpiration. The data highlight the remarkably tight control that grapevines are able to exert on transpiration as on hot dry days with high VPD transpiration changed little when compared with days of low evaporative demand. The mechanism responsible for this tight stomatal control has not been fully described, but it is noteworthy that diurnal changes in foliar abscisic acid (ABA) are much greater on days of high VPD when compared with days of low VPD (Loveys 1984). It
has also been found that the relationship between transpiration and VPD becomes uncoupled when part of the root system is exposed to dry soil (Davies et al. 2001), providing some explanation of the effectiveness of partial rootzone drying (PRD) in increasing water use efficiency (Loveys et al. 2000, Dry et al. 2000).

These sap flow experiments may have answered the question of how much water vines use, and they may help in the design of more efficient irrigation delivery systems which aim to match a plant’s water requirement with delivery rate, but the use of sap flow sensors as irrigation scheduling tools still requires a better understanding of the relationship between transpiration and acceptable stress levels.

Water potential as an aid to irrigation scheduling

It has long been recognised that there is a link between water availability and physiological performance of plants and this is well illustrated in grapevine where vegetative vigour and cropping level are influenced by available water. However, no unique relationship has ever been established between the thermodynamic state of water and specific aspects of physiological performance (Sinclair and Ludlow, 1985). Nevertheless, the relatively unsophisticated equipment required for the measurement of plant water potential and its ease of use may make this an attractive option for the assessment of vine response to irrigation input. There is a good correlation between soil moisture and some measures of plant water potential (Williams and Araujo, 2002). Pre-dawn water potential is thought to reflect the availability of water, as leaf water potential is then in equilibrium with soil water (Correia et al., 1995; Schultz, 1996), or perhaps just to the wettest portion of the soil (A meglio et al., 1999). Minimum values of leaf water potential ($\Psi_l$) occur around midday and can reflect the stress level of the vine. Stem water potential is sometimes thought to be a better measure of plant water status as this measure is less affected by short term fluctuations induced by stomatal behaviour and environmental changes (Chone et al., 2000; M C utchen and Shackle, 1992). Stem water potential is measured in much the same way as $\Psi_l$ except the leaf is covered and darkened to prevent transpiration for a short period before measurement. However, there are a number of considerations that may need to be taken into account before adopting water potential as a means to indicate the degree of stress being experienced by the vine. For example, midday $\Psi_l$ can vary considerably according to the genotype of the vine being measured. Figure 3 shows diurnal changes in $\Psi_l$ for Riesling and Sylvaner vines growing in adjacent rows and receiving the same irrigation. Pre-dawn water potentials were identical, suggesting that soil water conditions were similar, but as the day progressed $\Psi_l$ fell to lower values on the mild day due to much greater stomatal opening. As in the previous example, care would need to be
Canopy temperature as an indicator of transpiration

It has been recognised for many years that canopy temperature changes relative to ambient air temperature as a result of the evaporation of water from the leaf sub-stomatal cavities. One of the most convenient ways of measuring canopy temperature is by infrared thermometry. This non-contact technique has the potential to integrate the temperature of large areas of canopy or even whole vineyards in the case of aerial surveys. There are many examples of the use of infrared thermometry to assess canopy temperature in grapes and other horticultural crops (Fanizza et al., 1989; Canu et al., 1989; Orlandini et al., 1991; Germana, 1986; Sepaskhah and Kashefipour, 1994; Tormann, 1986; Jones 1999) but the technique has not been widely adopted in Australia as a means of assessing transpiration and water stress and therefore as an aid in irrigation scheduling. Since grapevines show strong stomatal control over transpiration, canopy-air temperature differences will show strong diurnal trends which could lead to difficulties in the interpretation of spot measurements and it may be advantageous to record continuously these variables. Figure 5 shows a typical graph of changes in the difference between canopy and air temperature for Sultana vines. As stomata open in the morning the canopy becomes cooler than ambient but later in the day stomatal closure and a reduction in transpiration results in the leaves warming relative to the air. Recent developments in thermal imaging technology and software to handle these data suggests that it may be timely to reassess this methodology as a means of determining canopy performance relative to ambient conditions and soil water availability. It is one of the few methods available that is non-invasive and has the ability to integrate the signals from large areas of vineyard. Figure 6 illustrates how thermal imaging technology can be used to assess leaf temperature. The false colour image shows a Eucalyptus pauciflora seedling. The two images were captured within a few minutes of each other as an external heat source changed ambient temperature. Leaf temperature could be assessed independently of background temperature changes through the image analysis software. This would be very useful in the determination of grapevine canopy temperature where the inclusion in images of objects that may be varying in temperature independently of the leaves such as patches of soil or trellis posts, for example, may skew the indicated temperature.

Conclusions

New research is providing us with insights into the amount of water used by grapevines and how they are able to control their water use according to prevailing conditions. Total actual

Figure 3. Diurnal changes in leaf water potential of Riesling and Sylvaner vines.

Figure 4. Diurnal changes in leaf water potential (A), VPD (B) and stomatal conductance (C) of field-grown Riesling vines on two January days of contrasting environmental conditions.

Figure 5. Diurnal changes in ambient air temperature measured with an automatic weather station located 50 m of the experimental site (A). Difference between canopy temperature, measured with an infrared thermometer (Everest model 11°C) and air temperature.
Figure 6. False colour images of a Eucalyptus pauciflora seedling. Images were captured with a ThermaCam SC2000 by Flir Systems. Spectral range 7.5–13µm and thermal sensitivity <0.1°C. Images were analysed using ThermaCam Researcher software. The temperatures indicated (mean±SE) were calculated by making 19 individual measurements from the single leaf immediately above the figures.

vapour water use may be less than previously thought. For example, the use of sap flow sensors in mature sultana vines growing in an environment with high evaporative demand suggests that the amount of water actually passing through the vines in a season is less than 2 ML/ha. Furthermore, the endogenous mechanisms that control water use are able to stabilise whole vine transpiration over a wide range of evaporative demands. These data suggest that irrigation scheduling based on environmental variables alone, such as pan evaporation, may overestimate vine water requirements, although other evaporative losses associated with the delivery system will be directly linked to environmental conditions. The correlation between evaporative demand and vine transpiration can to some extent be manipulated by irrigation practices that deliberately expose the vines to a degree of water stress.

There are many devices available to assess various aspects of plant physiological function, but to be useful as tools for irrigation scheduling they must be relatively inexpensive and easy to operate and for these reasons we have considered here just two, sap flow sensors and thermal-imaging technology. While it is quite easy to obtain data from these instruments the power of the techniques lies in the interpretation of the numbers. As our knowledge of genotype/environment interactions increases and computer acquisition and interpretation of data is refined it is likely that the direct measurement of plant performance will become a viable alternative to current methods of irrigation scheduling and that this will bring an improvement in the efficiency of water use.