CUT 1001: AO6 – Use of irrigation for management of heat stress

This is an excerpt from the final report CUT 1001: **Optimising industry returns from existing soil and water research.**

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GWRDC project number: CUT 1001

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Date: 30th November, 2012

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Adoptable Outcome 6. Use of irrigation for management of heat stress

Authors: Lexie McClymont and Ian Goodwin

1. Background

Current recommendations regarding mitigation of heat stress of grapevines during high temperature events are to apply water before temperatures rise and continue irrigation as required throughout the heat event to ensure water is readily available for uptake (Giddings 2004, Webb et al. 2009, Edwards et al. 2011). Recent surveys investigating grower responses to severe heat events in 2009 and subsequent damage (Webb et al. 2009) have reinforced the success of this approach in mitigating heat stress. However, few studies have considered the limitations to this approach or the degree to which it may be successful in extreme events. Furthermore, the ability of some growers to irrigate prior to and during heat events is compromised by supply limitations and irrigation system capacities. Growers surveyed by Webb et al. (2009) identified a number of alternative/additional approaches to mitigating heat stress, including manipulation of canopy architecture or row orientation to increase fruit shading and the use of spray protectants, mulch, cover crops, shade cloth and evaporative cooling. Some of these management options could offer additional benefits such as frost protection (evaporative cooling systems) or are primarily adopted because of benefits such as improved soil health or reduced soil water evaporation (mulching) with heat mitigation being a possible secondary benefit. On the other hand, some practices (e.g. increasing canopy shading, cover cropping) could increase the risk of disease or soil water deficits. Thus the potential benefits and costs of various management practices need to be understood. An improved understanding of the effectiveness of irrigation in alleviating heat stress and the conditions under which its effectiveness may be compromised will assist growers in evaluating the benefits-costs of heat management options.

2. Heating and cooling of grapevines

Grapevine temperatures can be increased by convective or radiative heating. Convective heating occurs when air temperatures exceed plant temperatures and heat is transferred to the plant, this process can also work to cool plants. Radiative heating occurs when thermal energy from the sun is intercepted and absorbed by the plant. Radiative heating can be reduced by shading (decreasing direct radiation), by increasing the ability of a plant to reflect, rather than absorb, thermal energy or by decreasing indirect radiation (thermal energy reflected by soil or other surfaces).

Transpiration cools plants in much the same way that perspiration cools people. As water vapour exits plant surfaces via stomata, heat is transferred from the plant and the plant is ‘evaporatively’ cooled. Stomatal closure decreases the ability of plants to evaporatively cool. Thus, water deficits can increase the risk of heat damage by causing stomatal closure and potentially allowing plant temperatures to reach critical levels. Evaporation of ‘free’ water from a plant surface will also reduce plant temperatures. Evaporative cooling of apples by over-tree irrigation is used to prevent sunburn damage of fruit (Lolicato 2011).

The various mechanisms of heating and cooling grapevines mean that air temperature alone will not always be a good predictor of grapevine temperature. In addition to soil water conditions influencing transpiration rates, atmospheric conditions (e.g. wind, radiation) influence the effectiveness of evaporative cooling and convective heating or cooling (Figure 1). Similarly, the degree of radiative heating will be influenced by management practices or indirect interception of thermal energy.

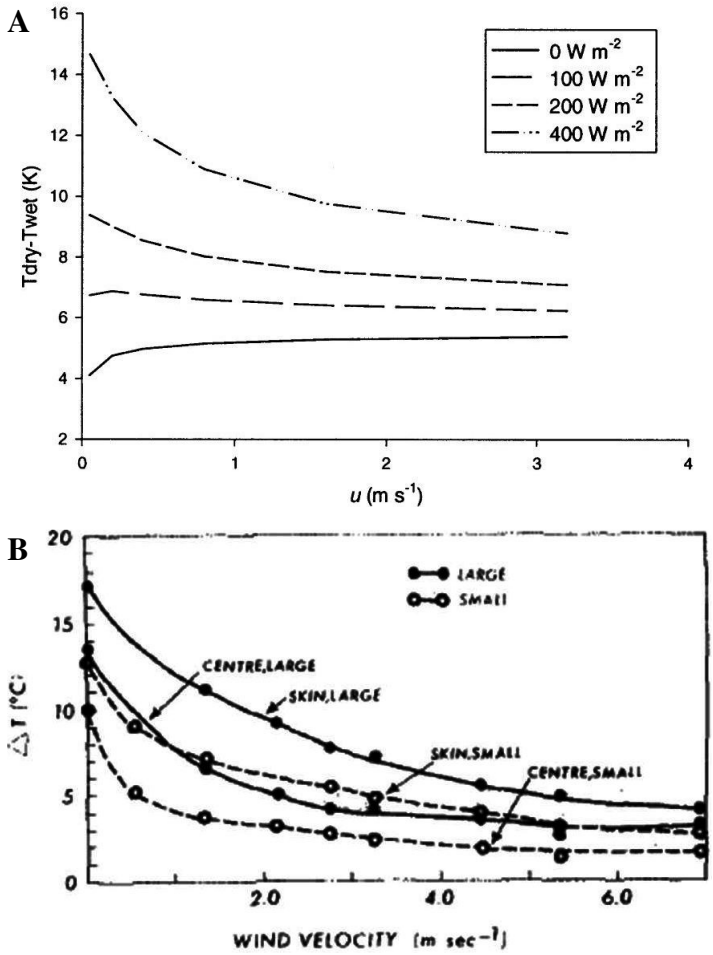


Figure 1. Influence of transpiration rates and atmospheric conditions on grapevine temperatures. **A** Variation in modelled leaf temperature differences between 'dry' (non-transpiring) and 'wet' leaves as a function of wind speed and net radiation (air temperature 20 °C, relative humidity 50 %). From Jones et al. (2002) by permission of Oxford University Press. **B** Effects of wind velocity and berry size on skin and internal berry temperature relative to air temperature. From Smart and Sinclair (1976) with permission from Elsevier.

3. Grapevine responses to high temperatures

Many studies have investigated the effects of temperature on grapevines and it is not within the scope of this document to review these studies in detail, instead readers are referred to Downey et al. (2006), Dry (2009a), Webb et al. (2009) and Thomson and Downey (in preparation). However, some general observations can be made. Severe heat events are associated with leaf damage and loss, berry sunburn and desiccation, and subsequent crop losses (Webb et al. 2009). Canopy function responses to high temperatures include stomatal closure (Sepúlveda and Kliewer 1986, Greer and Weston 2010) and reduced net photosynthesis (Kriedemann 1968, Greer and Weston 2010). These processes generally recover within a week of removal of heat stress (Matsui et al. 1991, Greer and Weston 2010, Edwards et al. 2011). Williams et al. (1994) suggested that the optimum leaf temperature for grapevine photosynthesis is 25 to 35 °C, depending on cultivar and growing conditions. Accumulation of sugar in berries has often been reported to slow or stall following heat events when daytime air temperatures were 40 °C or higher (Matsui et al. 1991, Webb et al. 2009, Greer and Weston 2010). On the other hand, Soar et al. (2009) reported that sugar accumulation was not affected when well-watered Shiraz vines were heated for brief periods, this was possibly because photosynthesis did not decrease. Temporary ceasation of sugar accumulation was associated with decreased photosynthesis that persisted for a number of days after Semillon vines were exposed to high temperatures (Greer and Weston 2010).

Alternatively, adverse effects of high temperatures on fruit composition and maturation (Kliewer and Torres 1972) may be caused by decreased partitioning of photosynthates to clusters (Sepúlveda et al. 1986). Acids in berries are respired at greater rates when temperatures are increased, consequently, acid levels tend to be lower and pH higher when clusters are sun-exposed or grown at high air temperatures (Kliewer and Lider 1968, 1970, Kliewer 1973). The balance of acids are also affected by berry temperatures and tartrate:malate ratios tend to increase in response to high temperatures or heat events (Kliewer and Lider 1970, Kliewer 1971, Matsui et al. 1991).

Ideal temperature ranges for grape production are difficult to define for a number of reasons. Firstly, grapevine responses to temperature are influenced by variety, phenological stage, intensity and duration of the heat event and temperature conditions prior to the heat event. Williams et al. (1994) and Greer and Weston (2010) summarise reported reproductive development responses to temperature regimes, highlighting the interactions with phenological stage and variety. Williams et al. (1994) concluded that short periods of air temperatures of up to 40 °C would not be a major limiting factor for grape production, provided vines were well-watered, due to limited impacts on photosynthesis. Morell and Wample (1995), meanwhile, showed that increased thermotolerance occurs when grapevines have experienced earlier exposure to heat. Secondly, optimum temperatures will differ for different parameters. Kliewer and Schultz (1973) point out that optimum temperatures for photosynthesis tend to be higher than optimum temperatures for fruit quality attributes. Finally, few vineyards monitor canopy or fruit temperatures, instead relying on predictions of air temperature to assess risk of heat damage and, as explained in Section 2, air temperature alone is not necessarily a good indicator of canopy or fruit temperature. Despite these limitations to identifying optimum plant temperatures, it can be generally stated that canopy and fruit temperatures below 35 °C are desirable for wine production and that the risk of fatal heat stress injury of cells is high at canopy and fruit temperatures above 40 °C.

3.1 Irrigation effects on canopy temperature

Canopy temperature differences between well-watered and deficit-irrigated grapevines provide an indication of the capacity of transpiration to mitigate heat stress by evaporative cooling. Canopy temperature differences will be influenced by the degree of water deficit and environmental conditions (e.g. wind and radiation). Theoretically, large temperature differences could occur between well-watered and non-irrigated grapevines, as indicated by modelling of wet and dry reference leaf temperatures under a range of atmospheric conditions (Figure 1). More modest canopy temperature differences would be expected between well-watered and deficit-irrigated grapevines.

Canopy temperatures of Cabernet Sauvignon grapevines in the Riverland differed by < 1 to ~10 °C in response to five irrigation treatments where seasonal applications ranged from 0.6 to 6.7 ML/ha (Loveys 2008). Afternoon canopy temperatures of well-watered Thompson Seedless grapevines in California were more than 12 °C lower than that of non-irrigated grapevines (Figure 2A, Williams et al. 1984), and similar differences were observed between irrigated and non-irrigated Shiraz grapevines in the Riverina (Figure 2B, Freeman et al. 1980). Canopy temperature differences between well-watered and deficit-irrigated grapevines were less (Williams et al. 1994, Figure 2A) and differences between grapevines irrigated to match or exceed potential water use (1.0 and 1.4 treatments) appeared negligible (Figure 2A). Van Zyl (1986) observed that canopies of irrigated Colombar grapevines (irrigated when soil water depleted to 90 % of plant available water) were, at most, 3.2 °C cooler than deficit-irrigated grapevines (irrigation withheld for four, five or seven week periods).

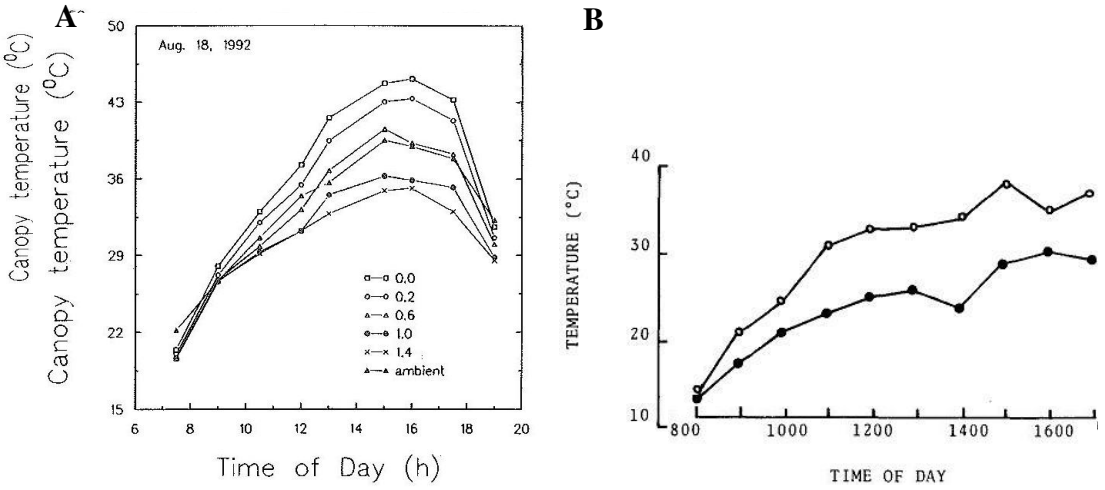


Figure 2. Canopy temperature responses to irrigation regimes. **A** Canopy temperature of 'Thompson Seedless' grapevines in the San Joaquin Valley, California, irrigated at daily intervals to supply a fraction of grapevine evapotranspiration. From Williams et al. (1994). **B** Canopy temperature of Shiraz grapevines irrigated at 0.6x Class A pan evaporation at two or three day intervals (solid symbols) or non-irrigated (open symbols) in the Riverina, New South Wales. From Freeman et al. (1980).

3.2 Irrigation effects on canopy function

Few studies have investigated the influence of irrigation on grapevine response to high temperatures. High temperature x irrigation experiments were conducted as part of the GWRDC Soil and Water Initiative project 'Optimising canopy function to increase yield while maintaining wine quality with efficient use of resources'. Subsequently, Edwards et al. (2011) reported the combined effects of deficit irrigation and high air temperatures on physiological function of Cabernet Sauvignon leaves (summarised below). This work is continuing and will aid the development of efficient heat management practices (Edwards 2011).

Heat events (maximum daytime air temperatures in excess of 40 °C and night-time temperatures above 20 °C for two days) were imposed on well-irrigated and deficit-irrigated Cabernet Sauvignon grapevines in a glasshouse (Edwards et al. 2011). Stomatal conductance and leaf water potential responses to heat events were greater in deficit-irrigated grapevines than well-watered vines. In fact, heat events did not affect stomatal conductance of well-watered grapevines but increased transpiration due to increased evaporative demand. Lower leaf water potentials, observed in both well-watered and deficit-irrigated vines in response to heating, may have been caused by increased soil evaporation and subsequent lower soil water content. Photosynthesis was decreased 90 % by the combination of heat and water deficit whereas deficit irrigation alone had substantially less affect. Similarly, heating of well-watered grapevines tended to decrease assimilation but changes were not significant (Figure 3). Decreased photosynthesis, due to disruption of photochemical and biochemical reactions and changes to sub-cellular structures, is a common heat stress response (Wahid et al. 2007). Decreased photosynthesis increases the risk of photooxidative damage (Foyer et al. 1994, Sharma et al. 2012) which would exacerbate heat damage.

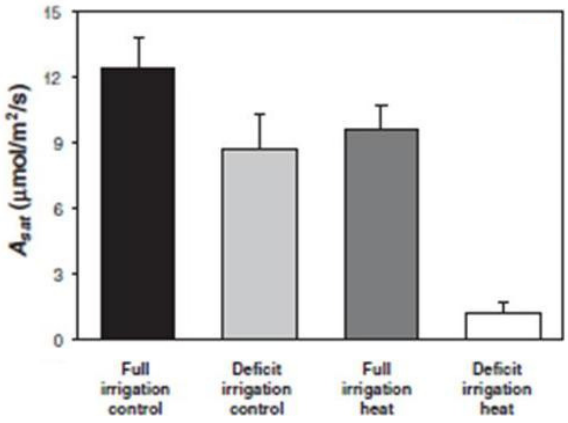


Figure 3. Canopy responses of Cabernet Sauvignon grapevines to irrigation level and heat: assimilation under saturating light (A_{sat}). Each bar is a mean of 12 measurements on separate plants + standard error. From Edwards et al. (2011).

Deficit-irrigated vines suffered leaf loss in response to heat treatments (Edwards et al. 2011) as has been previously reported following heatwaves (Webb et al. 2009). This lower leaf area may have contributed to recovery of stomatal conductance after the heat events but could result in decreased whole-vine carbon accumulation due to lower photosynthetic capacity (Edwards et al. 2011).

Soar et al. (2009) suggested that certain varieties of grapevine, particularly those reported to demonstrate anisohydric behaviour, such as Shiraz, may keep stomata open during heat events to maintain evaporative cooling, provided water supply is not limiting. Stomatal conductance, photosynthesis and leaf transpiration were either not affected or increased when recently irrigated, field-grown Shiraz vines were heated for three day periods (Soar et al. 2009). However, leaf temperatures of heated vines were seldom observed to be greater than 35 °C in the season (2007/08) for which these results are reported, suggesting that grapevine temperatures did not reach the point at which temperature increases are generally associated with decreased photosynthesis (Williams et al. 1994). When comparing irrigated and non-irrigated Shiraz grapevines, Freeman et al. (1980) reported low leaf water potentials (-17.5 bars at 1400 h). It was concluded that the leaf water potential response in the irrigated treatment was induced by high atmospheric demand rather than soil water limitations as increasing irrigation would have led to water-logging. Irrigated grapevines maintained lower canopy temperatures (30.0 °C) than non-irrigated grapevines (37.7 °C) (Freeman et al. 1980), suggesting that transpiration and, consequently, evaporative cooling were maintained at lower leaf water potentials in irrigated grapevines. This supports the suggestion that grapevines can maintain evaporative cooling, provided they are well-watered. Varietal differences in stomatal response to soil water availability and plant water status may elicit different responses to high temperatures.

3.3 Irrigation effects on berry temperature

Similar to leaf temperatures, berry temperatures will be strongly influenced by radiation levels, bunch exposure and wind speed as well as other factors including berry size and colour and bunch structure (Millar 1972, Smart and Sinclair 1976). However, Van Zyl (1986) noted that berry temperatures were usually different to leaf temperatures, an expected observation given the lack of transpiration from berries. In fact, Smart and Sinclair (1976) considered that transpirational cooling of grape berries need not be included in calculations of predicted berry temperature. Thus, effects of irrigation on berry temperature will be largely indirect via effects on bunch exposure and air temperature.

Freeman et al. (1980) installed thermocouples within shaded bunches of Shiraz grapevines in the Riverina. Maximum temperatures of shaded bunches on irrigated grapevines were typically 4.1 °C lower than on non-irrigated grapevines (Freeman et al. 1980, Figure 4). Increased vegetative growth in irrigated treatments resulted in denser canopies (Freeman et al. 1979) and there may have been differences between irrigated and non-irrigated treatments in the diurnal extent of bunch shading. Millar (1972) observed similar differences in surface temperatures of berries (measured with a thermistor) between irrigated and non-irrigated 'Carignane' grapevines. Bunch temperatures on irrigated grapevines were typically 4 °C higher than canopy temperatures, whereas bunch temperatures of non-irrigated grapevines were similar to canopy temperatures (Freeman et al. 1980). In other studies, temperature sensors (hypodermic thermistors or thermocouples) have been inserted in berries (Kliewer and Lider 1968, Gilbert et al. 1971, Spayd et al. 2002, Tarara et al. 2008) to monitor berry temperature rather than the microclimate within bunches. However, this technique is yet to be used to compare irrigation effects.

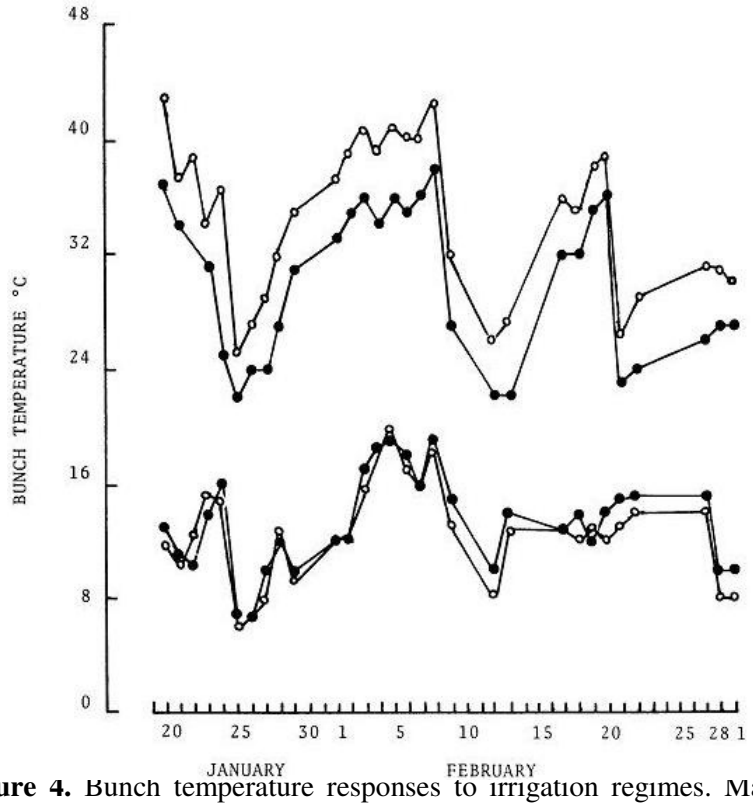


Figure 4. Bunch temperature responses to irrigation regimes. Maximum and minimum temperatures of shaded bunches on Shiraz grapevines irrigated at 0.6x pan A evaporation at two or three day intervals (solid symbols) or non-irrigated (open symbols) in the Riverina, New South Wales. From Freeman et al. (1980

Deficit-irrigation is sometimes used to control vegetative vigour, this can increase bunch exposure. Field measurements of sunlit green berries revealed afternoon temperatures of approximately 12 °C above air temperature while shaded berries were typically 2.4 °C warmer than air temperature (Smart and Sinclair 1976), the maximum temperature difference (berry - air temperature) measured by these authors was 15.7 °C on a calm, sunny day. Millar (1972) reported that surface temperatures of sunlit berries were up to 7.3 °C above air temperature, whereas shaded berries were up to 4.4 °C below air temperature. Similarly, Kliewer and Lider (1968) and Spayd et al. (2002) observed that shading by the canopy decreased berry temperatures by up to 11 °C and 13 °C, respectively, compared to sunlit berries, and shaded berry temperatures were similar to or slightly below air temperature. In addition to increasing berry temperatures, bunch exposure increases variability in berry temperatures within clusters and has been linked to uneven ripening (Kliewer and Lider 1968).

4. Limitations to evaporative cooling by transpiration of grapevines

Irrigation can reduce grapevine and vineyard temperatures by cooling from plant transpiration and, potentially, soil evaporation. However, the extent of cooling will be influenced by the ability of plants to access, take up and transpire water in response to increasing evaporative demand at times when heat damage may impair physiological processes and cause cell death. Under extreme conditions, irrigation may be ineffective in mitigating heat stress simply because evaporative demand exceeds the capability of grapevines to access or utilise applied water. Anecdotally, deficit-irrigated grapevines suffer greater damage than well-irrigated vines in heat events. This may be due to difficulties in adequately replenishing soil water contents, impaired function of the grapevine hydraulic system or increased susceptibility or sensitivity to heat stress.

4.1 Evaporative demand

Potential transpiration is primarily driven by evaporative demand, whereas actual transpiration is a function of evaporative demand and soil moisture content. In addition, the soil-plant-atmosphere relationship is influenced by root system development, soil hydraulic properties and soil water holding capacity (Ritchie 1981, Taylor et al. 1983). Qualitative data of Denmead and Shaw (1962) and others has suggested that rather than there being a single threshold soil moisture content at which crop transpiration begins to decline, decreases in transpiration rate will occur at "higher and higher soil moisture contents as the potential transpiration rate increases" (Denmead and Shaw 1962). The theory supporting this observation describes the relationships between pressure gradients along the soil-plant-atmosphere system and plant responses to decreasing turgor pressure and dehydration (i.e. stomatal closure and decreased transpiration). In short, turgor pressure will decline and plants will close stomata in response to low soil moisture contents (high soil moisture suctions) but, because turgor pressure is also lost in response to evaporative demand, "the soil moisture content at which plants wilt should also increase as the [evaporative demand] increases" (Denmead and Shaw 1962), even when soil moisture would usually be considered to be adequate (Figure 5). In other words, under conditions of high evaporative demand (that would be expected during extreme high temperature events) transpiration rates may be lower than potential transpiration, even if water is considered to be 'readily available'. Ritchie (1981) asserts that this response depends on the environmental history of the crop and that, under field conditions, decreases in transpiration are generally driven by soil moisture content rather than evaporative demand, with substantial decreases in soil moisture content often occurring before any decrease in transpiration. Despite this, Ritchie (1981) notes that, although quantitative evidence is lacking, it is generally thought that higher temperatures during critical phenological stages will decrease yield regardless of soil moisture content.

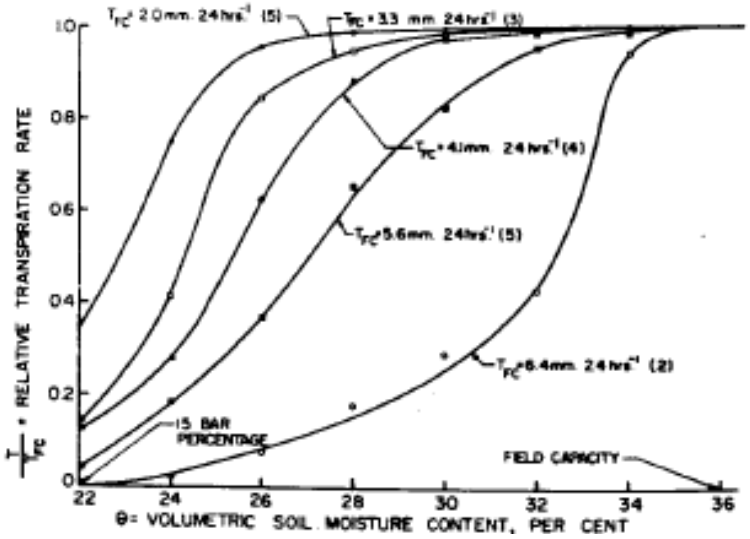


Figure 5. Relative transpiration rate of corn as a function of soil moisture content for different potential transpiration conditions (potential transpiration was transpiration of plants where soil moisture content was equal to field capacity). The soil type was silty clay loam. Numbers in parentheses refer to the number of days of observations. From Denmead and Shaw (1962), with permission, copyright American Society of Agronomy.

4.2 Impairment of root-system function by deficit-irrigation

Changes to root biomass, anatomy, gene expression and hydraulic conductance in response to soil drying have been observed (North and Nobel 1991, Vandeleur 2007, Vandeleur et al. 2009, Edwards and Clingeleffer 2011). Deficit-irrigation has been shown to decrease root biomass (Edwards and Clingeleffer 2011) and, as such, could decrease capacity for a vine to maintain water uptake under high demand conditions, even when soil water is readily available. Although, concomitant decreases in leaf area are likely to mitigate effects of lower root biomass on uptake capacity by lowering potential transpiration Studies using potted grapevines have shown that hydraulic conductance of grapevine root systems decreases in response to water deficits (Lovisolo and Schubert 2006, Vandeleur et al. 2009). While grapevine root systems may be able to recover from changes that decrease hydraulic conductance, the rate of recovery of deficit-irrigated grapevines may be too slow to allow irrigation to mitigate heat stress (Dr S. Tyerman, pers. comm. 2/12/10). Decreased hydraulic conductance of Chardonnay and Grenache (Vandeleur et al. 2009) and Pinot noir (Lovisolo and Schubert 2006) roots in response to water stress had not fully recovered one day after rewatering. Vandeleur et al. (2009) suggested that Grenache may be better able to take advantage of rainfall or irrigation than Chardonnay following water stress due to up-regulation of particular aquaporins. Aquaporin research is relatively new and few studies have utilised perennial horticulture species. Dr Stephen Tyerman has led research utilising grapevine root systems with support from the CRC for Viticulture, the University of Adelaide and GWRDC (see Tyerman 2007, 2010). Improved understanding of factors affecting hydraulic conductivity of grapevines can help us to understand grapevine responses to water deficits (Schultz 2003), and, potentially, better manage irrigation and recovery from water stress. In the longer term, such research may have implications for breeding for increased water use efficiency of grapevines (Vandeleur 2007).

By contrast, studies of field grown grapevines suggest that deficit irrigation per se does not impair water uptake capacity. Under well-watered conditions, evaporative demand and canopy size are major determinants of grapevine water use (Williams and Ayars 2005, McClymont et al. 2009).

Furthermore, Edwards and Clingeleffer (2011) reported that canopy size, evaporative demand (reference crop evapotranspiration) and soil moisture accounted for differences in sap flow of well-irrigated and deficit-irrigated Cabernet Sauvignon grapevines, indicating that deficit irrigation did not significantly impair uptake capacity.

5. Additional management options and tools

The focus of this review is the potential of irrigation management to effectively mitigate effects of severe heat events. While it is not within scope of this review to assess in detail additional management options, such options are briefly addressed in this section. Additional information and recommendations regarding longer-term vineyard management strategies, including rootstock and scion selection, row orientation and trellis design can be found in the 'Bunch exposure management' series of extension material provided by GWRDC (Dry 2009a,2009b).

5.1 Cover crops and mulching

Maintaining cover crops or mulch in the inter-row can reduce grapevine temperatures and decrease heat stress (Webb et al. 2009, Hilder et al. 2010) by decreasing indirect radiation. The effectiveness of this approach will be relative to the reflective properties of the pre-existing ground cover. Furthermore, Orlandini et al. (1995) demonstrated that maintenance of active cover crops can increase grapevine temperatures (compared to clean tilled or weed controlled inter-rows) and attributed this to reduced soil water availability. Where possible, Dry (2009a,b) recommends mowing or spraying out winter cover crops to provide a mulched inter-row while avoiding competition for water.

5.2 Cooling by sprinklers

Cooling of crops by the use of overhead or undervine sprinklers to induce convective (air) or evaporative cooling has previously been reviewed by Swinburne (2003). Evaporative cooling of grapevines by overhead sprinklers has been shown to reduce canopy temperatures by 8 to 22°C depending on atmospheric conditions (Gilbert et al. 1971, Kliewer and Schultz 1973, Aljibury et al. 1975) and temperatures of exposed berries by up to 11 °C (Gilbert et al. 1971, Kliewer and Schultz 1973), making this an effective method of mitigating heat stress. However, careful management is required to avoid disease problems, excessive water use and leaf burn from saline water. Berry weights were increased by sprinkler cooling (Kliewer and Schultz 1973, Aljibury et al. 1975). This suggests possible yield increases although applied water may have been excessive in these studies. In terms of fruit composition effects, sugar accumulation was delayed and there was a tendency for total acid to be higher and pH to be lower when grapevines were sprinkler cooled (Gilbert et al. 1971, Kliewer and Schultz 1973, Aljibury et al. 1975). Improved information regarding volumes of water required and application practices and scheduling would aid growers to evaluate the appropriateness of this option.

Gilbert et al. (1971) recommended pulsing the operation of sprinklers (3 min on, 15 min off) with an effective application rate of 0.25 mm/hr. Preliminary calculations, using air temperatures recorded at Griffith, suggest that estimates of water requirements of 1 to 1.6 ML/ha (Swinburne 2003) for the period December to February in inland areas of Australia are conservative over-estimates. Based on the same threshold temperatures (sprinklers operated when air temperatures exceeded 35 °C) and the method of application described by Gilbert et al. (1971), 0.4 and 0.3 ML/ha would have been required in the 2005/06 and 2006/07 seasons, respectively.

5.3 Artificial shading

Shading grapevines reduces direct radiation (Cartechini and Palliotti 1995). Greer et al. (2010) reported that canopy temperatures (logged hourly) of unshaded Semillon grapevines in the Riverina

were similar to air temperatures and exceeded 40 °C in mid-summer. Shading vines with neutral density shade cloth (70 %) lowered canopy temperatures by approximately 2 °C over the growing season, with mid-afternoon canopy temperatures commonly being 4 to 6 °C lower than air temperature, and maintained canopy temperatures below 40 °C. Unfortunately, a strong negative effect on biomass accumulation was observed (Greer et al. 2011).

Several studies have noted negative effects of low light intensity on photosynthesis of grapevines and subsequent yield and soluble solids reductions when grapevines are shaded for long periods (Kliewer and Lider 1970, Smart et al. 1988, Cartechini and Palliotti 1995, Greer et al. 2011). Short periods of shading (15 days) have been shown to increase bud necrosis of Thompson Seedless grapevines (Kliewer and Perez 1990). Therefore, shade systems that can be imposed during heat events and removed easily or that transmit a large proportion of photosynthetically active radiation would be desirable. Two temporary shade options are retractable shade netting, as used in orchards (Lolicato 2011), or temporary plastic covers such as those placed over table grape crops. Different types of shade cloth or covers will transmit different levels and proportions of photosynthetically active radiation and total solar irradiance. Shahak et al. (2008) report that plant responses to netting can be manipulated by using different coloured netting but responses may vary between crops, cultivars and environmental conditions. Yellow and white netting increased berry and cluster weight of 'Superior' table grapes whereas grey netting reduced cluster weight compared to the uncovered control (Shahak et al. 2008). Soluble solids accumulation was also affected by net colour (Shahak et al. 2008). When bunch numbers were adjusted to the same levels, white, red and black netting delayed sugar accumulation of Red Globe table grapes (Shahak et al. 2008). The effects of duration of shading on grapevine performance and of different types of shade material on grapevine performance and temperature are largely unreported for winegrapes under Australian conditions.

5.4 Protective sprays

Particle films or 'sunshield' products allow leaves to intercept photosynthetically active radiation while reflecting ultraviolet and infrared radiation (Glenn and Puterka 2005). The aim of such products is to decrease heating of the canopy and fruit and alleviate symptoms of heat stress without inhibiting photosynthesis. Leaf temperature differences between grapevines sprayed with kaolin-based particle film and those without were generally less than 2 or 3 °C (Cooley et al. 2008, Cabernet Sauvignon in Sunraysia; Glenn et al. 2010, Merlot and Viognier in Idaho).

Manufacturers commonly claim that their products reduce sun damage and heat stress and can decrease yield losses, increase fruit weight, improve fruit quality, reduce water requirements, increase water use efficiency and decrease insect damage in a range of crops. Independent field trials support some of these claims for certain crops. When used in grapevines, particle films have not had consistent effects on plant water status and gas exchange. Stomatal conductance increased (Shellie and Glenn 2008) or decreased (Glenn et al. 2010) and leaf water potential was unchanged (Shellie and Glenn 2008) or tended to increase (Glenn et al. 2010). Likewise, berry size and soluble solids responses have been variable. Glenn et al. (2010) observed that responses to particle films were influenced by variety and irrigation regime and, importantly, concluded that irrigation (well-watered compared to various regulated deficit regimes) was more effective in reducing leaf temperatures than particle films. All protective sprays require multiple applications to maintain protection and some manufacturers advise multiple applications prior to heat events, effectively this means that applications of such products need to be made before heat events are predicted. With the exception of wax-based sprays, protective sprays are not rainfast and cannot be used in conjunction with overhead cooling. Dry (2009a,b) advises that these products may cause wine quality issues and that growers should not use them without approval from their winery.

It is worth noting that certain sun protection sprays were initially developed with particular crops in mind. 'Raynox' (a wax-based UV protectant), for example, was developed to protect apple crops and was designed with consideration of natural protection mechanisms and management practices of these crops (Dr L. Schrader pers. comm. 10/8/2011). Sprays developed specifically for grapevines could optimise protection while minimising inhibition of plant processes and avoiding fruit contamination problems (see discussion of salicylic acid in section 5.5).

5.5 Enhancing thermotolerance

Greater understanding of physiological responses to heat stress may lead to novel strategies for enhancing grapevine thermotolerance (the ability to withstand high temperatures).

Thermotolerance is correlated with the increased production of heat shock proteins (HSPs) in response to heat events (Howarth and Ougham 1993). Woolf and Ferguson (2000) considered it likely that HSPs provide some protection from protein denaturation or dysfunction caused by heat stress. Particular groups of HSPs are involved in repair of proteins by refolding and reactivation of denatured proteins. One of the HSP groups (hsp70), observed by Morrell et al. (1997) to increase following heat shock treatment of Cabernet Sauvignon grapevines, is known to be involved in this repair process (Kotak et al. 2007). HSPs are normally present in grapevines and their levels will fluctuate at different phenological periods – possibly associated with fruit development and particular quality attributes, thus the potential benefits of understanding HSPs go beyond managing heat stress.

While increased induction of HSPs is associated with high temperatures, protein synthesis is prevented when temperatures are too high and in these situations a period of lower temperatures is required to allow synthesis of HSPs (Lin et al. 1984). Further to this, Woolf and Ferguson (2000) suggest that low temperatures can improve the persistence of HSPs and may therefore prolong thermotolerance. Anecdotally, heat damage of grapevines is increased when night-time temperatures are high (Webb et al. 2009). It may be found that cooling vineyards to particular temperature ranges at night would increase thermotolerance and lessen the impact of heat events.

Various plant hormones, including salicylic acid, have been associated with development of thermotolerance, (Wahid et al. 2007). Exogenous applications of salicylcic acid have been reported to alleviate heat or cold stress (as well as water and salinity stress) in a number of plants and may alleviate damage caused by UV radiation (Hayat et al. 2010). Application of salicylic acid to grapevines enhanced thermotolerance in leaves, evidenced by an increase in the heat killing time compared to control plants (Wang and Li 2006a), and alleviated the decrease in photosynthesis under heat stress (Wang et al. 2010). The mechanisms by which salicylic acid effect thermotolerance appear similar to those involved in heat acclimation by exposure to high temperatures (Wang and Li 2006a, Liu et al. 2008) and may involve Ca^{2+} homeostasis, increased antioxidant activity and increased HSPs (Wang and Li 2006a, Wang and Li 2006b, Liu et al. 2008, Wang et al. 2010). Applications of salicylic acid to clusters on field-grown Thompson Seedless grapevines have recently been shown to increase yield and decrease the proportion of unmarketable berries (Marzouk and Kassem 2011). However, considerable research is needed to before a commercial product can be used to enhance heat (or other stress) tolerance in grapevines.

5.6 Modelling

Prediction of grape berry temperatures is possible using models driven primarily by solar radiation, wind speed and fruit size (Smart and Sinclair 1976) or maximum and minimum air temperature and berry exposure (BerryTone, Cola et al. 2009). Such models could be integrated with canopy models that simulate radiation interception and distribution, e.g. Louarn et al. (2008), to investigate effects

of canopy architecture, row orientation or other management practices on berry temperature. Validation for environmental conditions other than those under which the models were developed would be necessary, particularly for the BerryTone model (Cola et al. 2009).

As noted previously, leaf and berry temperature responses to air temperature vary depending on other atmospheric conditions, including radiation levels and wind speed. This has led to the development of a predictive model for risk of sunburn of apple crops in north-west USA, based on air temperatures, cloud and wind conditions and humidity (http://hort.tfrec.wsu.edu/pages/Sunburn and http://das.wsu.edu/readNewsItem.php?id=60). Dependent on grower interest, similar models could be developed for grape crops in Australia.

6. Current recommendations and future considerations

Recent studies funded by GWRDC have reinforced the benefits of ensuring grapevines are well-irrigated when heat events are forecast. Growers need to consider increased transpiration rates and soil evaporation when scheduling irrigations prior to and during heat events. Large wetted root volumes will help avoid limitation of transpiration rates related to rates of water movement through the soil and hydraulic capacity of vines.

Differentiation needs to be made between research regarding the effects of high average seasonal temperatures and *heat events*. Many controlled environment studies impose temperature treatments for much, if not all, of the growing season. Similarly, field studies seldom experience severe heat events. It is reasonable to expect that grapevine responses to temporary, severe heat events will differ from responses to high average temperatures to which they become acclimated. Note that, as much as possible, this review has focussed on studies regarding heat events.

Fair comparison of results from different heat event (or seasonal temperature) studies requires a clear understanding of irrigation management, weather conditions and soil water availability in each study, in addition to physiological responses and economic considerations. Measurement or modelling of canopy and bunch temperatures, as opposed to only air temperatures, is important to understanding and comparing results and assessing the effectiveness or otherwise of different management options.

GWRDC funded studies have begun to illustrate the interactive effects of temperature and water supply on grapevine canopy function (Edwards and Clingeleffer 2011, Edwards et al. 2011). Future work will continue to improve our understanding of physiological responses to heat, including the involvement of HSPs. The interactions of high temperatures and high light conditions in causing photooxidative damage and the natural photoprotective mechanisms of grapevines require greater attention. New research at this sub-cellular level may generate novel approaches to heat management in addition to fine-tuning implementation of current management practices. An improved understanding of effects of heat events on fruit composition and wine quality and the ability of management practices to influence these responses is also needed.

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