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Coping with heatwaves: management strategies for berry survival and vineyard resilience

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Abstract. This article summarises recent findings on the impact of high and extreme high temperatures on berry physiology and composition in order to better predict when berries are most at risk, helping growers to fine-tune the timing of mitigation strategies for more optimal and cost-effective protection. This knowledge provides thresholds to aim at, through canopy management and heat mitigation interventions in the vineyard. This will indicate which strategic interventions during which critical phenological stages can significantly mitigate the adverse effects of heatwaves on berry quality and yield. In the longer term, it provides a planning threshold at which such actions will no longer be sufficient to counteract rising temperatures, and a more informed approach for relocating vineyards or re-planting with more heat-tolerant varieties.

1. Introduction

Climate change is leading to an increase in average temperature and in the frequency and severity of heatwaves that is already significantly affecting grapevine phenology and berry composition. This is compounded by water stress, which is well known to increase the vulnerability of grapevines and berries to heatwaves. In hot climate regions like Australia, grape production is only possible due to relatively secure supplies of water for irrigation. However, well-watered grapevines remain vulnerable to heat and the upper temperature limits for berry survival is dependent on several abiotic factors and developmental stage.

Heatwaves are known to significantly impact on grapevines and can cause significant loss of yield, as seen in 2009 in south-eastern Australia [1], and in 2019 in the south of France where losses accounted for up to 80% of the crop for the most affected vineyard block [2]. Although heatwaves can be predicted in advance, they are particularly challenging for wine grape producers as their intensity remains at times unexpected. A three-day prediction may still be insufficient to implement effective cooling strategies, especially in large vineyards where logistics can be complex, or when water resources for irrigation or misting systems are limited.

The aim of this project was to investigate the sensitivity of several primary and secondary berry metabolites to high (>35 °C) and extreme high (>40-45 °C) temperatures and to determine the upper temperature limits for berry survival of well-watered Shiraz grapevines. These metabolites included the most abundant of each flavonoid found in grapes and in the subsequent wine: malvidins (anthocyanins), quercetins (flavonols), catechins (flavan-3-ols) and tannins (polymers of flavan-3-ols). While the synergistic effect of light and temperature on anthocyanins has been intensively examined, more knowledge was required for berry tannins.

2. Impact of heatwaves

To determine the specific impact of temperature on berry physiology and composition, experimental methods have been designed to minimise the influence of light and water, which also affect berry composition and in particular flavonoid biosynthesis. Researchers have commonly used direct methods, such as altering the temperature of the fruit or entire vine, in controlled environments like glasshouses, growth chambers, and cold rooms [3]. Over the past decade, open-top chambers in vineyards have become popular for simulating increased temperatures throughout the grape growing season in real life conditions.

This section provides a summary of the effects of high (>35 °C) and extreme high (>40-45 °C) temperatures on grape composition and in particular flavonoids, adapted from the original publication [4].

2.1. Effect of long-term high temperature

In this first part, examples of research from the last decade on the effect of high temperature on berry composition by experimental conditions including phenological stage, duration, intensity, diurnal temperature ranges are described (Table 1).

Table 1. Examples of experimental parameters in long-term temperature studies on flavonoids (adapted from Gouot *et al* [4]).

Experimental parameters: **Duration, Tmean (°C), dT, Tmax (°C)**	**Variety-stage**	**Results**	**Ref.**
Whole season 28/18, +4, CE	Tempranillo - Berry development and ripening	Significant decrease of anthocyanins for most of the clones	[5]
49 days 22.2, +2, 36	Sangiovese - Berry ripening	Significant decrease of anthocyanins	[6]
52 days 26.4, +5.1, 41.7	Sangiovese - Berry ripening	Significant decrease of flavonols and anthocyanin concentrations. No effect on tannins	[7]
14 days 35, +9, 39	Cabernet Sauvignon – Before, at, and after véraison	Small decrease of anthocyanins	[8]

dT = delta temperature between heated and control, CE = Controlled Environment

Overall, high temperatures have varied effects on flavonols, anthocyanins, and flavan-3-ols/tannins in grapes. Flavonols seem to be indirectly affected by temperature through changes in primary and secondary metabolism rather than directly impacted. This is likely due to alterations in gene expression within the phenylpropanoid pathway. In contrast, anthocyanins, crucial for grape colour, are significantly reduced by high temperatures, particularly during véraison, when biosynthesis is most active. The negative impact of temperature on anthocyanin concentration and profile is well-documented, though malvidin derivatives, the most abundant anthocyanins, are less affected. Research on flavan-3-ols and tannins is limited, with no definitive conclusions on how temperature influences their biosynthesis or accumulation. Early berry development stages, like flowering, have not been adequately studied, and the effects on tannins remain unclear, with no consistent patterns observed [4].

2.2. Effect of short extreme high temperature

In this second part, results of the research conducted over the last decade are compiled and a summary of more intense temperature treatments is provided. Most results are extracted from Gouot *et al*, [9-11] where Shiraz berries were heated directly using fan heaters during 3 days at 3 key phenological stages and at different temperature maxima spanning 40 - 55 °C (Figure 1).

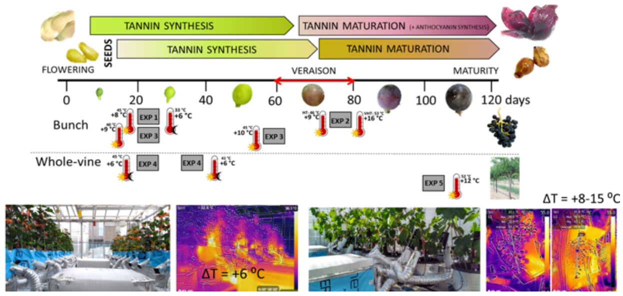

Figure 1. Experiment summary adapted from Gouot [12].

Results showed that as long as berries were not shrivelled, grape quality was not impaired at harvest by the sole effect of temperature (Table 2). The experiments highlighted the importance of phenological stage, heat intensity and their interaction on the level of damage observed. The phenological stage at which the heat treatments were conducted was the most critical parameter, and the fruit set period was more sensitive than véraison.

Table 2. Summary of Shiraz grape berry flavonoid responses in short-term and intense temperatures (adapted from Gouot [12])

Experimental parameters: **Duration, Tmean (°C), dT, Tmax (°C)**	**Variety & Stage**	**Results**	**Ref.**
24 h, 45, +20, 45	Cabernet Sauvignon – Berry ripening	Modulation of berry composition	[13]
3 days, 37.2, +5.6, 45.5	Shiraz - Whole-vine - E-L 31	Small effect on seeds	[9]
3 days, 36.0, +4.5, 40.9	Shiraz - Whole-vine - E-L 32	No effect on berry composition	[9]
3 days, 36.2, +7.8, 44.6	Shiraz - Bunch – E-L 31	Small effect on seeds	[10]
3-39 h, 39.3, +8.9, 45.9	Shiraz - Bunch – E-L 36	No effect	[11]
3-39 h, +17.2, 53.7	Shiraz - Bunch – E-L 36	Major changes in berry composition	[11]
3 days, +9.0, 39.7	Shiraz - Bunch – E-L 31	No effect	[12]
3 days, +9.5, 44.6	Shiraz - Bunch – E-L 34	Small effect on skin composition	[12]

dT = delta temperature between heated and control

Berry metabolism responses were, as expected, more pronounced under extreme temperatures, although the actual temperature survival threshold varied with the phenological stage. Tannin accumulation showed an elastic response to extreme high temperatures [12].

2.3. Other approaches to determine the impact of elevated temperatures

2.3.1. Treatment scale

For research purposes, temperature treatments can be applied at different treatment scales: to the whole vine, individual bunches, or detached berries/cell suspensions. Whole-vine heating is often used to study long-term effects on photosynthesis and berry composition, while chamber-free systems focus on the impact of temperature on berry metabolism independently of the canopy. *In vitro* studies with detached berries or cell suspensions provided more detailed insights into flavonoid degradation.

2.3.2. Duration, intensity and timing.

Two main categories depending on the duration of the treatment can be differentiated: short-term (for a few hours, or several days, up to 14 days) and long-term (weeks to months or entire growing seasons). Temperature changes can range from a few degrees Celsius to simulate future climate conditions (effect of high temperature), to extreme differentials replicating heatwaves (effect of more extreme high temperature). These treatments can also be timed differently across day and night cycles.

2.3.3. Phenological stage

The developmental/ripening stage at which berries are exposed to heat stress is likely the most critical factor, as responses vary depending on the phenological stage. Long-term studies have examined the impact of higher average temperatures over the entire season, from flowering to maturity, or even year-round with breaks during winter. Other studies have focused on specific growth stages, targeting particular phases in berry development or ripening. Early-stage experiments are uncommon, with most research beginning just before or after véraison—the 24-hour phase when berries start to change colour. Véraison is recognised as a particularly sensitive period for abiotic stress and anthocyanin biosynthesis. In contrast, late-ripening experiments have shown minimal or no effect on flavonoid profiles but have influenced concentrations due to degradation and changes in berry water content and size from shriveling.

3. Strategies for managing heatwaves

Several mitigation strategies have been developed over time which are mainly divided into maximising transpirational cooling and minimising incoming radiation [14]. Examples (Figure 2) include increased irrigation before and during a heatwave, canopy management (e.g. pruning and trellis type, leaf removal, shoot positioning), artificial shading (shade cloth, solar panels), mid-row management, use of reflective sprays or in-canopy misters, vineyard design (row orientation, cover crops, mulching) and grape material choices (variety, rootstocks). However, not all of these can be quickly deployed in the advent of a heatwave, and all present advantages and limitations, especially with regards to how much heat can be dissipated.

Excessive radiation, in combination with heat, can also result in sunburn necrosis, especially on the exposed side of the canopy [15]. Sun exposure and the microclimate of the bunch dictate berry temperature and, therefore, careful manipulation of the canopy may play an important role in berry attributes, and indeed berry survival during an extreme temperature event.

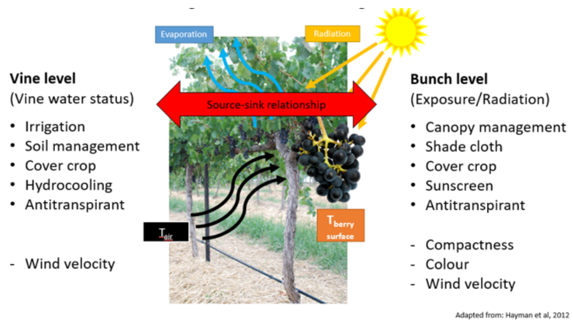

Figure 2. Examples of heatwave mitigation strategies.

These strategies also have different levels of efficiency and can be ranked according to the air/canopy temperature reduction range as well as berry or leaf surface temperature reduction range (Figure 3).

In studies, air/canopy temperature are always measured while surface temperature are not well documented. The surface temperature of non-exposed and exposed berries to direct sunlight, air within the canopy or air above the canopy, measured at different heights, can vary. Significant differences have been found between air temperature measured by data loggers in weather shelters and berry surface temperature measured by thermal imaging or portable handheld noncontact infrared thermometer spanning 10-17 °C [16, 17].

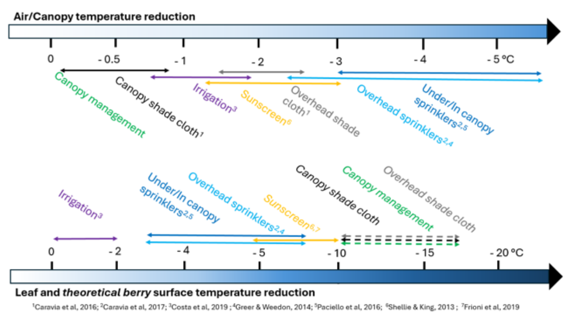

Figure 3. Heatwave mitigation strategies ranked by temperature reduction at the canopy, leaf and bunch level.

The use of shade cloth (overhead, full canopy, bunch or soil shade) has been shown to have a moderate impact on canopy air reduction [18] with overhead shade being the most effective method tested, achieving reductions ranging from 1.5 to 2.5 °C. Overall, the decrease in maximum canopy air temperature ranged from 1.1 °C to 5 °C across studies. Sprinkler under or within the canopy can achieve a more substantial cooling effect, lowering the air inside the canopy by 2.4 to 5 °C [19]. In this study, results are compared with other studies using overhead sprinklers and reducing air temperature by 2.3–2.6 °C in grapevines and up to 5.9 °C in apples. When overhead sprinkler systems were used in Semillon vines, temperature reduction by 7–8 °C were observed [20]. Greater decreases in leaf temperature in wetted areas, reaching 16.5 or even 22 °C, were also reported in other studies. Another study using a nebulized water spraying system showed a drop of air temperature up to 7 °C [21]. Irrigation could also have an effect on leaf temperature because of evaporative cooling. Some studies reported decrease in temperature up to 2 °C while other also suggested a decrease greater than 2 °C [22, 23]. Sunscreen applications also contribute to reduction of leaf temperature of up to -6 °C depending on studies [24, 25].

While all these methods can mitigate heat stress to some degree by lowering air temperature within the canopy, data on berry surface temperatures remain limited. Canopy management and shade cloths are expected to provide the most significant cooling for berries by shielding them from direct sunlight, with potential temperature reductions of up to 17 °C under certain conditions. Leaf surface temperatures were reported in some studies, showing that sprinklers could reduce temperatures by as much as 6.9 °C [19].

Knowing these details coupled with the threshold temperatures for sub-lethal and lethal damage, growers can better choose the right mitigation method for each developmental stage. Adapting to climate challenges will likely require a dynamic combination of approaches, balancing immediate threats with long-term sustainability goals. Combining multiple strategies for integrated management approaches is required for greater resilience.

4. Outlook for the industry

4.1. Implications for viticulture

Understanding berry compositional responses and even survival thresholds of the most widely planted varieties in the world will be essential to plan future adaptation strategies for the grape industry in the various climates. This knowledge would establish thresholds to target through combined canopy management and heat mitigation strategies in the vineyard, enhancing the ability to adjust the winemaking process or wine styles when dealing with heat-affected fruit. In the long term, it offers a benchmark for when these actions may no longer be effective in countering rising temperatures, supporting more informed decisions on relocating vineyards or replanting with more heat-tolerant varieties.

When heatwaves are anticipated, prioritising berry survival is crucial. Research on Shiraz vines shows that green berries suffer damage at lower temperatures (40-45 °C) compared to red berries (50-53 °C) [12]. Similar results were found for field-grown irrigated Riesling in Washington where the first lethal damage appeared after 15 min of exposure at 53.8 ± 1.1 °C [26]. While maintaining vine water status and providing adequate canopy shade are essential, there are few viable short-term mitigation options available. Strategies such as artificial shading may not be cost-effective on a large scale, and hydro-cooling is unlikely to be sustainable due to water use concerns. As temperatures continue to rise, some grape-growing regions may become unsuitable for current grape varieties, particularly if the economic return is insufficient to justify the resources needed for protection. To date, one of the most efficient and most cost-effective method is canopy management with different pruning and trellis types and shoot positioning to provide shade to the bunches. For new planting, row orientation can also be carefully selected to optimize conditions and prevent bunches from being exposed to direct midday sunlight.

This research highlights the existence of maximum temperatures that grapes cannot tolerate, varying by phenological stage. It also raises concerns about practices that delay ripening into cooler months, potentially exposing berries to higher summer temperatures, which could lead to early desiccation or poor fruit set. This practice can also expose inflorescences which are even more susceptible to heat at lower temperatures [27]. Late heatwaves may cause shriveling and accelerate sugar concentration, yet still allow for harvestable fruit.

4.2. Implications for winemaking

From a winemaking perspective, understanding and predicting how temperature affects berry composition, including flavonoids, and extractability can help in adapting winemaking protocols. If berries are only mildly affected, with flavonoid levels impacted, winemakers can use techniques like enzyme addition, higher fermentation temperatures, and cold soaking to enhance flavonoid extraction [28]. If berries are damaged close to harvest, such as those with necrosis but incomplete desiccation, they can still be used in small quantities, either for blending or producing lighter red wines where a mix of damaged and undamaged berries may balance the flavonoid content.

However, if grapes are severely damaged and desiccated, winemaking could be compromised to the point where harvesting is not worthwhile unless an alternative use is found.

4.3. Further opportunities

The degree of heat-stress tolerance varies significantly among grape varieties, making it essential to expand this study to include other cultivars known for their heat resilience, such as Touriga Nacional and Nero d'Avola. Additionally, widely grown varieties like Cabernet Sauvignon or Chardonnay should be tested to determine their specific temperature thresholds and the critical duration of exposure that impacts production viability.

Ongoing research is already delving into the genetic and phenotypic responses of grapevines to heat stress, aiming to identify key genes or compounds that confer heat tolerance [8], or expanding work to leaves [29]. Such knowledge could be pivotal for breeding new, heat-resistant grapevines or optimising the selection of varieties that can thrive in increasingly warm climates.

Furthermore, it is crucial to explore practical and economically viable solutions that can be readily adopted by the industry. This includes conducting a comprehensive feasibility and financial analysis on the potential impact at winery scale from fully desiccated berries and the potential for corrective winemaking techniques tailored to heat-stressed fruit. This should be evaluated on a larger scale, such as using 100-liter tanks with fruit sourced from commercial vineyards, before being implemented commercially. Comparative studies of different must treatments, including enzyme additions and variations in maceration temperatures and duration, would provide valuable insights, with the final wines subjected to rigorous sensory evaluation by trained panels.

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