IRRIGATION AS A TOOL FOR HEATWAVE MITIGATION: THE EFFECT OF IRRIGATION INTENSITY AND TIMING IN CABERNET SAUVIGNON

Authors: Pietro PREVITALI[1], Luis SANCHEZ[1], Nick DOKOOZLIAN[1]

[1]*E. & J. Gallo Winery, Winegrowing Research, 600 Yosemite Boulevard, Modesto, CA 95354*

*Corresponding author:*Pietro.Previtali@ejgallo.com*

Abstract:

Context and purpose of the study – Heatwave events, defined as 2 or more days reaching ≥ 38 °C, are an increasingly frequent phenomenon threatening grape production worldwide. Heat stress has been shown to have negative consequences on grapevine physiology, leading to increased evaporative demand and intensified water stress. Due to heatwaves overlapping with important stages of grapevine reproductive development, spanning from berry set to the ripening stage, severe heat can potentially compromise yield and grape quality. The physiological response of grapevine to heat stress suggests a potential use of irrigation to mitigate heatwaves, however there is limited information regarding the irrigation amounts and timings needed for this purpose. Following up on a pivotal trial conducted between 2019 and 2022, in this study irrigation treatments with varying intensity and timing of application were refined to determine their potential mitigation of heat-associated damage to yield and fruit composition.

Material and methods – The experiment was conducted in 2022 in two commercial Cabernet Sauvignon vineyards located in Lodi and Sonoma AVAs, CA. Vines were submitted to six experimental treatments which differed to the control (80% evapotranspiration [ET]) by the irrigation amount (120 % and 160 % ET) and/or the timing (0, 1 or 2 days) of the application of supplemental irrigations prior to the anticipated beginning of the heatwave event. Each treatment was replicated four times. Diurnal changes in grape water status and gas exchange were monitored during the heatwave, and berry samples collected before and after the heatwave were used to characterize treatment effects on berry weight and grape chemical composition. At harvest, yield components were measured and grape chemical composition analyzed. Wines from each treatment were also produced.

Results – Increased irrigation amounts and earlier initiation of additional irrigation were able to improve the water status of Cabernet Sauvignon vines during heatwave events (highest temperatures recorded: Lodi, 44.5 °C; Sonoma, 47 °C). Diurnal measurements of gas exchange revealed that additional irrigation mitigated reductions in photosynthesis and stomatal conductance caused by extreme heat events. Similarly, increasing amounts of water demonstrated to be generally more effective at reducing berry dehydration, limiting yield losses at harvest. Irrigation regimes affected fruit composition, most importantly C6 compounds, IBMP, anthocyanins and tannins, which was partly explained by various levels of berry dehydration. Non-linear relationships were observed between irrigation levels and several yield and fruit composition parameters, and treatment efficacy was not always stable across the two sites. These results indicate the importance of calibrating water amounts based on singular growing conditions to maximize yield and preserve fruit quality with respect to desired production targets.

Keywords: Heatwave mitigation, water stress, grapevine physiology, yield, grape chemistry, Cabernet Sauvignon.

1. Introductions

Increased heatwave frequency and severity are one of the most concerning aspects of a changing climate, as shown by rising maximum temperatures as well as number of days with extra-ordinary heat (temperature > 34 °C) across wine regions worldwide (Parker *et al.*, 2020; Gambetta and Kurtural, 2021). Heat stress impacts grape production rapidly and substantially, with effects ranging from vine physiology to the final yield and quality depending on the time and intensity of heat stress. Temperature affects vine physiological performance, via a direct inhibition of photosynthesis at T > 35 °C and indirectly by increasing vine transpiration and affecting soil water availability (Greer and Weedon, 2013). With regards to the reproductive cycle of grapevines, negative effects of heatwaves can be limited to yield losses but up to the full production when heat stress occurs between fruitset and veraison. Post-veraison heatwaves have a major impact on yield and quality, affecting quality markers for winemaking at multiple levels. Elevated temperature, especially if combined to water stress, result in advanced ripening and decouple kinetics of accumulation of sugars and other specialized metabolites in the fruit, namely organic acids, anthocyanins and aroma compounds (Previtali *et al.*, 2021; Sadras and Moran, 2012; Sweetman *et al.*, 2014).

The evidence of heatwaves negatively affecting grape production leads to the need of identifying mitigation strategies. These have to be aimed at preserving yield whilst maintaining grape and wine quality, alongside being cost-effective and easy-to-use. Irrigation plays a main role in shaping grape and yield quality, and appropriate calibration of water in vineyards is key to achieve the production goals (Chaves *et al.*, 2007; McCarthy, 1997). Due to how heatwaves affect grapevine physiology, irrigation is a good candidate for heatwave mitigation. Previous research has reported the benefits of applying increased irrigation amounts during heatwave on berry weight and fruit quality components (Forrestel, 2022). However, in the same study excessive irrigation caused a dilution effect on main quality markers for wine. The present trial attempted to further elucidate the timing and intensity of irrigation that can aid to mitigate heatwaves. In addition, a multi-site approach was adopted in this study to compare treatment effectiveness in two AVAs in California, namely Lodi and Sonoma.

2. Material and methods

Plant materials – The experiment was conducted in two commercial vineyards located in the Alexander Valley (38°45'21''N, 122°59'3''W) and Lodi (38°17'40''N, 121°6'39''W) AVAs. In the Alexander Valley, Cabernet Sauvignon (clone FPS 5 on 1103 Paulsen rootstock) was planted in 2010 and trained as a high-wire bilateral cordon with 1.8 and 3.0 m vine and row spacings. In Lodi, the vineyard was planted with Cabernet Sauvignon (clone FPS 47 on 1103 Paulsen rootstock) in 2018 and trained as a quadrilateral cordon with 1.8 and 3.3 m as vine and row spacings.

Experimental treatments – Variable irrigation was applied during post-veraison heatwaves at both sites. Heatwaves were defined as two or more days with T ≥ 38 °C based on the forecast temperature. Three irrigation levels were compared: control (80 % ET), 1.5x (+ 50% irrigation, 120 % ET) and 2x (double irrigation, 160 % ET) and 1.5x and 2x irrigation were started 2 days prior (2dp), 1 day prior (1dp) or the first day of the heatwave (0dp). Variable irrigation was maintained throughout the heatwave and stopped on the first day with T < 38 °C. Different irrigation amounts were achieved by changing the irrigation duration (i.e. number of irrigation hours). Each treatment was applied to four replicates of 180 vines each.

Plant measurements – Vine physiology was monitored during the heatwave by measuring leaf (Ψ_L) and stem (Ψ_S) water potential with a pressure chamber (PMS, Albany, OR) and leaf temperature with an infrared thermometer (Apogee, North Logan, UT). Gas exchange was measured using a LI-6800 portable photosynthesis system (LI-COR Biosciences, Lincoln, NE). All measurements were taken on a diurnal fashion three times per day, namely 1000, 1300 and 1600. Berry samples (100 berries) were collected before and after each heatwave for the measurement of berry weight (BW) and Total Soluble Solids (TSS). Yield components were recorded on the day of harvest.

Statistical analysis – Treatments were compared using linear mixed models with irrigation treatments fitted as a fixed effect and block as random factor. Statistical analyses were conducted in R (R4.2.2, Foundation for

Statistical Computing, Vienna, Austria).

3. Results and discussion

3.1. *Heatwave patterns at the two experimental sites*

Temperatures recorded at the two experimental sites indicated the occurrence of two post-veraison heatwaves (**Table 1**). The first heatwave (HW1) occurred in mid Aug and the duration and maximum temperature were 4 days and 40.2 °C in Sonoma and 5 days and 40.1 °C in Lodi. The second heatwave (HW2) occurred in early Sep and was characterized by longer duration (Sonoma: 6 days; Lodi: 9 days) and higher maximum temperatures (Sonoma: 46.4 °C; Lodi: 45.2 °C).

3.2. Effect of variable irrigation on vine physiology during heatwaves

At both sites, implementation of selected irrigation regimes had little effects of vine performance during HW1, which occurred in the middle of fruit ripening (**Table 2**). In contrast, there was a strong impact of increasing irrigation on vine physiology during the late and more severe HW2. Inconsistencies between the two sites, Sonoma and Lodi, were likely determined by different weather conditions as well as vine growing conditions and practices implemented, involving smaller canopies and lower vigor in the Sonoma region. In Lodi, increasing irrigation during HW2 resulted in higher levels of water potential and lower leaf temperature, indicating effective mitigation of heat-induced water stress. Diurnal curves (**Figure 1**) showed improved water status of Cabernet Sauvignon in Lodi, where protective irrigation at 120% and 160% ET resulted in higher levels of Ψ_L and lower leaf temperature in the afternoon. While all treatments experienced a reduction in photosynthesis rate and stomatal conductance around midday, these processes were less affected when protective irrigation was applied, with best mitigation being achieved using 120% ET applied 2 days prior to the heatwave or all 160% ET. The same treatments increased gas stomatal conductance and photosynthesis in the afternoon, suggesting a recovery effect occurring under long irrigation cycles.

3.3. Effect of variable irrigation during heatwaves on berry maturation and yield

Similar to vine measurements, the irrigation treatments implemented were most effective during HW2. The late timing and extreme severity of HW2 dramatically impacted BW and fruit quality at both sites. In the control treatment (80% ET), drops in BW were observed up to 18% in Sonoma and 22 % in Lodi, with final values of 0.8 g and 0.95 g in the respective regions (**Table 3**). The irrigation treatments were largely ineffective in Sonoma, while protective irrigation demonstrated to be an effective tool to reduce berry dehydration up to about 8.8 % when 160% ET was applied 1 or 2 days prior HW2. TSS data highlighted the benefits of irrigating at 120 and 160% ET to reduce rapid TSS increases caused by berry dehydration. Increased irrigation consistently reduced rates of TSS increase from pre- to post-heatwave, from 18% (control) to 14% in HW1 and from 21% (control) to up to 12% in HW2 in Lodi. A similar pattern was observed in Sonoma only for HW2, where the highest rate of TSS increase was 24% in the control (80% ET) but was halved to less than 12% in vines irrigated at 160% starting 1 day prior the heatwave. Both vineyards were harvested about 1 week after the end of HW2, and there were no significant differences in yield in Sonoma (**Table 4**). In Lodi, yield data collected at harvest were consistent with BW trends, with a positive trend of increase of yield in 120% ET 2 days prior and 160% ET treatments.

4. Conclusions

When heatwaves occur, grapevines are affected not only at the physiological level, but detriments to yield and several quality parameters are to be expected. The present study shows the benefits of increased irrigation for heatwave mitigation and recommends appropriate calibration of irrigation cycles to preserve yield and improve quality of grapes under heat extremes.

5. Acknowledgments

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Tables and Figures

Table 1: Summary of heatwaves recorded at two experimental sites in 2022.

	Sonoma		Lodi	
	Heatwave 1	**Heatwave 2**	**Heatwave 1**	**Heatwave 2**
Date interval	Aug 15 – Aug 19	Sep 1 – Sep 8	Aug 15 – Aug 19	Aug 31 – Sep 8
Days with T > 38 °C	4	6	4	9
Maximum T (°C)	40.2	46.5	40.1	44.5
Hours with T > 38 °C	7	33	4	45

Notes: heatwave summary calculated from hourly temperatures recorded at the two sites.

Table 2: Effect of variable irrigation during heatwaves on the vine physiology of Cabernet Sauvignon.

	***p*-value (Irrigation regime)[a]**			
	Sonoma		**Lodi**	
	Heatwave 1 (36.1°C)[b]	**Heatwave 2** (39.9°C)	**Heatwave 1** (38.1°C)	**Heatwave 2** (41.5°C)
Vine physiology				
Midday Ψ_L (MPa)	0.902	**0.007(**)**	**0.012(*)**	**<0.001(***)**
Midday Ψ_S (MPa)	0.645	0.206	0.102	**0.010(*)**
Leaf temperature (°C)	0.867	**0.001(**)**	0.904	**<0.001(***)**
Gas exchange				
A (µmol m^{-2} s^{-1})	0.485	0.269	0.668	**0.003(**)**
Gs (mol m^{-2} s^{-1})	0.414	0.206	0.969	**<0.001(***)**

Abbreviations: Ψ_L, leaf water potential; Ψ_S, stem water potential, A, assimilation; Gs, stomatal conductance.
Notes:
[a] *p*-values were computed using linear mixed models with irrigation as fixed term and block as random term
[b] Air temperature at the time of sampling (average between start and end of sampling round)

Table 3: Effect of variable irrigation regimes applied during heatwaves on changes in berry weight (BW) and total soluble solids (TSS) of Cabernet Sauvignon grapes in Lodi and Sonoma (CA).

	Sonoma		Lodi	
	Heatwave 1	Heatwave 2	Heatwave 1	Heatwave 2
TSS increase (%)[a]				
80% ET (Control)	24.2	24.3 b	18.3 a[d]	21.5 a
120% ET, 0 dp[b]	24.9	21.9 b	18.8 a	19.7 a
160% ET, 0 dp	24.8	17.2 ab	15.8 ab	14.6 ab
120% ET, 1 dp		16.5 a	17.2 ab	17.2 ab
160% ET, 1 dp		16.4 a	14.2 b	11.8 b
120% ET, 2 dp				15.2 ab
160% ET, 2 dp				14.8 ab
p-value[c]	0.953	0.127	**0.005(**)**	**0.004(**)**
BW increase (%)				
80% ET (Control)	4.4	-17.8	6.8	-21.7 a
120% ET, 0 dp	4.1	-15.0	11.0	-17.0 ab
160% ET, 0 dp	-0.9	-14.9	14.5	-13.6 ab
120% ET, 1 dp		-10.5	13.2	-15.2 ab
160% ET, 1 dp		-18.1	5.9	-8.8 b
120% ET, 2 dp				-11.6 ab
160% ET, 2 dp				-8.7 b
p-value	0.145	0.447	0.200	**0.030(*)**

Notes:
[a] Rate of increase calculated as percentage between pre- and post-heatwave values
[b] dp: day(s) prior the heatwave (i.e. first day with T ≥ 38 °C)
[c] *p*-values computed using a linear mixed model (fixed effect: irrigation; random effect: block)
[d] Different letters denote significant differences according to Tukey's adjusted post-hoc test at $p < 0.05$

Table 4: Effect of variable irrigation regimes applied during heatwaves on yield of Cabernet Sauvignon vines in Lodi and Sonoma (CA).

	Sonoma	Lodi
Yield (kg/vine)		
80% ET (Control)	7.07	8.94
120% ET, 0 dp[a]	9.03	8.75
160% ET, 0 dp	7.89	10.62
120% ET, 1 dp	8.35	8.34
160% ET, 1 dp	8.33	12.14
120% ET, 2 dp		11.19
160% ET, 2 dp		10.47
p-value[b]	0.530	0.067

Notes:
[a] dp: day(s) prior the heatwave (i.e. first day with T ≥ 38 °C)
[b] *p*-values computed using a linear mixed model (fixed effect: irrigation; random effect: block)
[d] Different letters denote significant differences according to Tukey's adjusted post-hoc test at $p < 0.05$

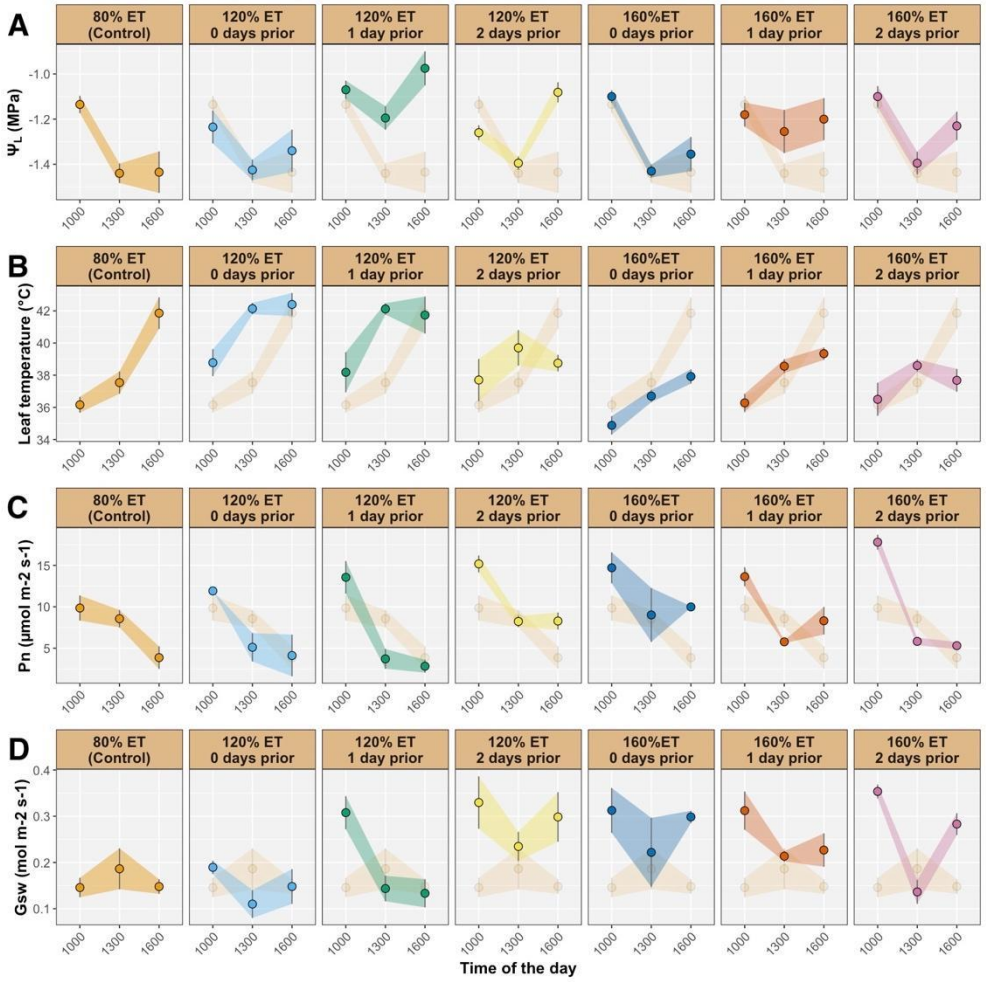

Figure 1: Diurnal changes in **(A)** leaf water potential (Ψ_L), **(B)** leaf temperature, **(C)** net photosynthesis (Pn) and **(D)** stomatal conductance (Gsw) in Cabernet Sauvignon vines submitted to variable irrigation treatments during heatwave 2 at the Lodi site. Points and error bars represent means and standard error by treatment (n = 3) at three sampling times: 1000, 1300 and 1600. Shaded orange trends represent changes in the control and are reported in all treatments to facilitate comparisons.