

Mitigating Summer Heat Stress on Cabernet Sauvignon Vines Grown in Central California

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Abstract. Rising temperatures pose a significant threat to grape production in regions like Central California, making it essential to identify sustainable and easily implementable solutions to mitigate these impacts. In this trial, an untreated control (C) was compared to the application of diatomaceous earth (D), pinolene (P), and shoot twisting of the apical portion of the shoots (T). Parameters such as leaf area, light interception, gas exchange, and water potential were monitored, along with quantitative and qualitative production characteristics. T induced desiccation in the upper portion of the shoots, reducing leaf area without overexposing the clusters. Stem water potential measurements indicated that T partially alleviated stress conditions in particularly hot periods. D decreased stomatal conductance without significantly reducing net assimilation, thereby improving water use efficiency. All treatments resulted in higher acidity and lower pH levels, while no difference in crop load was observed. This trial demonstrates the feasibility of using easily mechanizable techniques to mitigate summer heat stress and improve water use efficiency in regions characterized by hot and arid regions, such as California's Central Valley.

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1 Introduction

California, like other warm regions, faces significant challenges to terroir and grape production due to global warming, including increased sunburn and ripening imbalances [1].

Reducing the leaf area-to-yield ratio helps delaying berry ripening [2] as in the case of late shoot topping [3,4,5]. However, canopy manipulation practices must be carefully reconsidered to avoid the risk of sunburns and overexposure, especially in high-irradiance environments [5,6].

The application of pinolene, by limiting gas exchange, improves vine water status and delays berry ripening [7,8].

Diatomaceous earth is a natural nanomaterial derived from sedimentary rocks, already used for pests' management [9]. It has been also observed that it protects plants from abiotic stress, improving water use efficiency, similarly to kaolin [10,;11].

This study aims to evaluate different strategies for delaying berry ripening and improving vines tolerance to heat stress, focusing on their respective effects on plant physiology and grape quality. The objective is to identify practical, easily mechanizable tools for wine growers operating in the hot climate of Central California

2 Materials and Methods

2.1 Plant material and experimental conditions

The trial was carried out at California State University Fresno (Fresno, CA) in a twenty-five-year-old experimental vineyard planted with *Vitis vinifera*, L. cv. Cabernet Sauvignon grapevines grafted onto Freedom, during the 2023 growing seasons. Plants were spur-pruned on a bilateral cordon and trained in a California Sprawling system. Rows were oriented East-West and vine spacing was 1.8 m between the plants and 3.6 m between the rows.

2.2 Treatments and experimental design

The trial was conducted using a randomized block design, with four treatments and four replicates of 6 vines each (24 vines per treatment), and only the four central vines were sampled. Treatments consisted of: i) untreated control (C), ii) diatomaceous earth application (D), iii) a pinolene application (P) and iv) a shoot-twisting (T). All treatments were applied manually on August 3, after veraison.

Vines (D) were sprayed with the particle film forming DEsect CROP (EP Naturals, Reno, Nevada, USA), with an 85% content of silicon dioxides from diatomaceous earth at a 5% concentration on both sides of the canopy. Vines (P) were sprayed with the film-forming antitranspirant Vapor Gard® [a.i.di-1-p-menthene(C₂₀H₃₄)] (Miller Chemical & Fertilizer, Hanover, Pennsylvania, USA), with a 96% content of pinolene at 5% concentration covering both sides of the

canopy. Shoot-twisting (T) was performed by breaking the canopy portion above the last wire. The dried portions of the shoots were not removed but left in place to provide shade against direct sunlight.

2.3 Canopy measurements and vine physiology

Leaf gas exchange was measured during the central hours of the day (11:30 - 14:30 local time) using a LI-COR 6800 Portable Photosynthesis System (LI-COR, Inc, Lincoln, Nebraska, USA). In each replicate, four mature and sun-exposed leaves from four grapevines were sampled from the middle section of the main shoot. Net assimilation (A_N , $\mu\text{mol CO}_2 \text{ m}^{-2}\text{s}^{-1}$) and stomatal conductance (g_s , $\text{mol H}_2\text{O m}^{-2}\text{s}^{-1}$) were acquired by measuring inlet and outlet CO_2 (set at 410ppm) and H_2O relative concentration (following ambient relative humidity at the time of the measurement). The intrinsic water use efficiency (WUE_i , $\mu\text{mol CO}_2 \text{ mol}^{-1}\text{H}_2\text{O}$) was then derived by making the ration between net assimilation (A_N) and stomatal conductance (g_s).

Stem water potentials (Ψ_{stem}) was measured on one fully expanded leaf per vine on four vines per replicate, eight times throughout the growing season, from the application of the treatments to harvest. One mature leaf was sampled from a main shoot, the leaf was bagged in Mylar® to reduce leaf transpiration and equilibrate leaf-xylem water potential. After 30 minutes, leaves were removed from the plant to measure plant water status using the pressure chamber [12].

The total leaf area per shoot was determined for the C and T treatments on September 22nd using a leaf area meter (LI-3100, LiCOR, NE, USA) on four shoots per replicatesampled from four different vines. Light canopy interception was measured at noon on September 15th using a line quantum sensor (LI-191R, LiCOR, NE, USA) inserted in the fruit zone and rightly above and parallel to the cordon on four plants per replicate. Prior to data acquisition in each experimental unit, ambient light was acquired in an open road close to the field.

2.4 Berry ripening and grape production

Berry ripening was monitored from July 28th until harvest. 48 berries per replicate were taken as a sample. The juice was used to determine total soluble solids (TSS, as °Brix), through digital refractometry (Fisherbrand, Thermo Fisher Scientific Inc.), pH was measured through a pHmeter (Accumet, AB315, Thermo Fisher Scientific Inc.), and the titratable acidity (TA) was measured through automatic titration with NaOH, 0.1N until a pH of 8.2 (Easy Plus, Mettler-Toledo, LLC, OH, USA). The maturity index was calculated as the ratio between TSS and TA.

Harvest took place on October 6th. Yield per plant was quantified by weighing clusters. On the same occasion, the grape composition was determined on samples of 48 berries per replicate, as described before.

2.5 Statistical analysis

Statistical analysis was performed using R version 4.3.1 – package “Agricolae” [13]. Data were subjected to one way analysis of variance (ANOVA). When the results of ANOVA were significant at $p \leq 0.05$, data were then subjected to Tukey’s HSD test. The graphical representations were obtained using the same software.

3 Results and discussion

Shoot-twisting, causing the desiccation of the terminal portion of the shoots and halting its growth, significantly reduced leaf area by around 50% compared to the control (Table 1). However, contrary to traditional late topping [5, 6], leaving the dried portions on top of the vines provided shade to the fruiting zone, preventing grape overexposure, as indicated by light interception values (Table 1).

Table 1. Total leaf area per shoot (TLA/shoot) and light interception in the fruiting zone. When ANOVA was significant, different letters indicates differences between treatments with p -value ≤ 0.05 (T-test). C indicates control, D indicates diatomaceous earth, P indicates pinolene, T indicates shoot-twisting.

	C	D	P	T
TLA/shoot (m²)	1.43 a	nd	nd	0.71 b
Light interception (%)	5.7 a	4.8 a	3.9 a	3.9 a

Stem water potential is depicted in Figure 1. Values were particularly low on September 8 due to high temperatures and prolonged water stress. On this occasion, T presented the best results, alleviating stress conditions compared to control vines. Similarly to traditional topping, shoot twisting can contain water stress in particularly hot and dry periods thanks to the reduction of the leaf area. At the end of the season, stress conditions were reduced in all treatments, as temperature decreased. One week later, stress conditions were partially alleviated due to the cooler temperatures compared to the previous week.

Diatomaceous earth has been shown to protect against abiotic stresses [10, 11], and the results from this study generally align with these findings, as D partially alleviated stress conditions towards the end of the season. In contrast, P exhibited the worst conditions among all treatments, raising questions about its effectiveness in particularly hot and dry regions like the one where this trial was conducted.

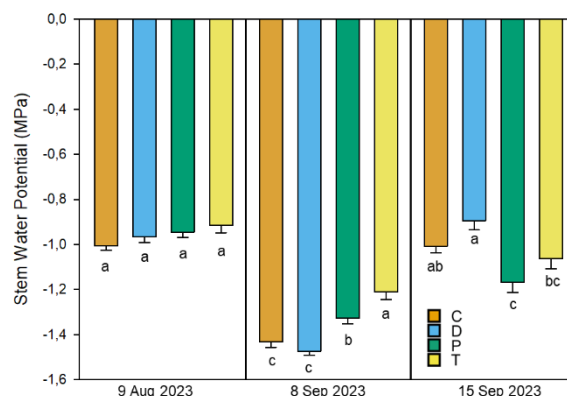


Fig. 1. Midday stem water potential. When ANOVA was significant, different letters indicates differences between treatments with p -value ≤ 0.05 (T-test). C indicates control, D indicates diatomaceous earth, P indicates pinolene, T indicates shoot-twisting.

Leaf gas exchange values are presented in Table 2. Stomatal conductance (g_s) and net assimilation (A_N) were generally higher in T, likely due to an overcompensation effect from the reduced canopy size. In contrast, although the differences were not statistically significant, net assimilation was consistently lower in D compared to the control. Additionally, D exhibited lower g_s than control vines, suggesting that the diatomaceous earth application may have limited gas exchange, similar to the effects observed with kaolin [10,11]. Furthermore, D consistently showed the highest water use efficiency among all treatments, indicating positive effects in regulating gas exchange in treated leaves.

Table 2. Net assimilation (A_N), stomatal conductance (g_s) and intrinsic water use efficiency (WUEi) on treated vines. When ANOVA was significant, different letters indicates differences between treatments with p -value ≤ 0.05 (T-test). C indicates control, D indicates diatomaceous earth, P indicates pinolene, T indicates shoot-twisting.

		C	D	P	T
9 Aug 23	A_N ($\mu\text{mol CO}_2 \text{ m}^{-2}\text{s}^{-1}$)	10.1 a	9.5 a	10.6 a	10.5 a
	g_s ($\text{mol H}_2\text{O m}^{-2}\text{s}^{-1}$)	0.14 a	0.12 a	0.15 a	0.18 a
	WUEi ($\mu\text{mol CO}_2 \text{ mol}^{-1}\text{H}_2\text{O}$)	67 ab	80 a	69 ab	64 b
29 Sep 23	A_N ($\mu\text{mol CO}_2 \text{ m}^{-2}\text{s}^{-1}$)	7.6 a	6.0 a	6.8 a	7.6 a
	g_s ($\text{mol H}_2\text{O m}^{-2}\text{s}^{-1}$)	0.11 ab	0.08 b	0.11 ab	0.12 a
	WUEi ($\mu\text{mol CO}_2 \text{ mol}^{-1}\text{H}_2\text{O}$)	73 a	80 a	72 a	68 a

Berry ripening was assessed using the maturity index, calculated as the ratio of total soluble solids to titratable acidity (Figure 2). While no significant

differences were observed at harvest, the control vines displayed significantly higher maturity index values from a couple of weeks after the treatments were applied to the end of the season. This suggests that all treatments effectively delayed berry ripening by slowing down sugar accumulation and the depletion of organic acids, consistently with other findings [3, 4, 5, 7, 8]

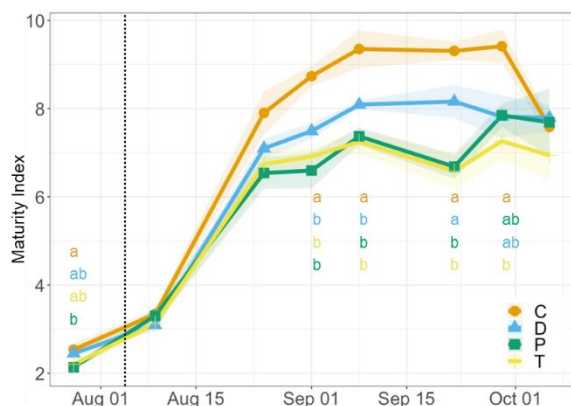


Fig. 2. Maturity index evolution. When ANOVA was significant, different letters indicates differences between treatments with p -value ≤ 0.05 (T-test). C indicates control, D indicates diatomaceous earth, P indicates pinolene, T indicates shoot-twisting. The dotted line indicates the treatments application. Shaded ribbons indicate the standard error of the mean.

None of the applied treatments negatively affected grape production, as there were no observed differences in total yield per vine or berry mass at harvest (Table 3). The total soluble solids content also remained consistent across treatments, averaging around 22 °Brix. Notably, while maintaining the same sugar concentration, all treatments significantly reduced berry juice pH, which is important for enhancing microbiological stability during fermentation. Additionally, although not statistically significant, T resulted in the highest titratable acidity (TA) among all treatments, aligning with the trend observed throughout the ripening period, as it generally exhibited the lowest maturity index values.

Table 3. Vine production and grape composition at harvest. When ANOVA was significant, different letters indicates differences between treatments with p -value ≤ 0.05 (T-test). C indicates control, D indicates diatomaceous earth, P indicates pinolene, T indicates shoot-twisting.

	C	D	P	T
Yield/vine(kg)	19.4 a	21.2 a	19.4 a	17.6 a
Berry weight (g)	1.67 a	1.69 a	1.71 a	1.65 a
Total soluble solids (°Brix)	22.5 a	22.6 a	21.8 a	21.7 a

Titratable acidity (g/L)	2.97 a	2.91 a	2.94 a	3.20 a
pH	4.29 a	4.11 b	4.17 b	4.17 b

4 Conclusions

As expected, shoot twisting reduced leaf area while effectively preventing overexposure in the fruiting zone by retaining the dry apical portions on top of the canopy. This led to an overall improvement in plant water status, as indicated by stem water potential measurements, likely due to the reduced water demand per vine. Diatomaceous earth limited gas exchange, primarily by reducing stomatal conductance, which enhanced water use efficiency.

All treatments effectively delayed berry ripening. All treatments resulted in lower pH values at harvest without negatively impacting vine productivity or sugar concentration.

The findings of this study provide valuable insights into sustainable management practices for growers in hot climates. Adapting certain traditional late-season canopy management techniques appears well-suited to California’s hot and dry conditions, improving vine water status and delaying berry ripening. Based on the evaluation in this study, shoot twisting and diatomaceous earth emerged as the most effective solutions, enhancing vine tolerance to heat stress and maintaining acidic composition without compromising yield. Further studies are needed to better understand the dynamics of these techniques and explore their potential for mechanization.

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