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Adapting viticulture to climate change: A four-year field trial on the role of water restriction in mitigating temperature increases in Malbec and Bonarda

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ABSTRACT

Understanding the impact of rising environmental temperatures on *Vitis vinifera* is crucial for the wine industry in the context of global warming. This study investigated the combined effects of elevated daytime temperatures (ET) and moderate irrigation restriction (IR) at post-veraison, over four seasons in two widely cultivated cultivars in Argentina: Malbec and Bonarda. An open-top chamber with a passive air heating system was used to increase average daytime temperatures by approximately 2 °C. In general, vegetative growth parameters were not affected by ET or IR throughout the study, indicating no cumulative effects. Bonarda yield was reduced by ET due to fewer berries per bunch, and lighter berries and clusters, but remained unaffected by IR. In contrast, Malbec maintained stable yields under both ET and IR, suggesting greater adaptability. In both cultivars, ET led to increased sugar accumulation and higher alcohol content in wines, but also reduced wine colour intensity, colour index, and co-pigmented anthocyanins, while there were cultivar-specific differences. Despite these common negative effects, Malbec showed favourable traits under ET, including improved anthocyanin stability (higher proportions of acylated forms) and increased hue. The IR treatment restored colour intensity and increased the total polyphenol index in both cultivars, and also recovered colour index in Malbec. Overall, our findings suggest that Malbec exhibits greater phenotypic plasticity and potential for high-quality wine production under moderate post-veraison water stress and elevated temperature, compared to Bonarda. This irrigation strategy may help mitigate some of the adverse effects of elevated temperature by preserving wine colour and stability without significantly compromising vine growth or yield.

KEYWORDS: red wine, elevated temperature, anthocyanin profile, *Vitis vinifera* L., water stress, wine composition

INTRODUCTION

Plant physiology is influenced by climatic factors such as temperature, precipitation, and air and soil moisture. Climate change is already increasing the variability of these factors, which have significant impacts on agricultural yields (Ray *et al.*, 2019). Under an intermediate greenhouse gas emission scenario (SSP2-4.5), the Intergovernmental Panel on Climate Change (IPCC) predicts an average surface temperature increase of up to 3 °C for the Argentinean Cuyo region (between 28° and 35° south latitude) by the end of this century (IPCC, 2023). The magnitude and variability of this temperature increase will affect other critical aspects of plant physiology. These include the frequency of temperatures exceeding historical averages, the duration of heat waves, the number of days with temperatures above 35 °C, annual mean temperatures, and the frequency, duration, and intensity of droughts (Alexander *et al.*, 2006; Deis *et al.*, 2015; Jones *et al.*, 2010; Chiang *et al.*, 2021).

Viticulture plays a central role in several regional economies in Argentina, covering approximately 226,000 hectares. Around 46 % of this cultivated area is planted with *Vitis vinifera* L. red cultivars, with Malbec and Bonarda occupying half of this area. The production of premium red wine, in particular, requires grapes with an adequate quantity and composition of phenolic compounds (Waterhouse, 2002). These molecules, from a physiological standpoint, have essential roles as constitutive cell protectants and are highly induced under abiotic and biotic stress conditions (Saigo *et al.*, 2020). Moreover, from an oenological perspective, anthocyanins are key contributors to wine colour, aroma, flavour, nutraceutical value, and ageing potential (Radeka *et al.*, 2022). In berries, the phenolic profile and accumulation are a result of enzymatic reactions that are influenced by both genetic and environmental factors. Among these, temperature has a particularly strong influence on the expression and activity of enzymes involved in the phenolic biosynthesis pathway, ultimately shaping the phenolic profile of berries and the resulting wine.

It is commonly accepted that high temperatures and water deficit are two key environmental factors influencing grapevine physiology and berry composition. Various approaches have been used to study the impact of rising temperatures on the physiology of grapevines, including comparisons between seasons and regions, or controlled experiments in greenhouses and growth chambers (Bonada & Sadras, 2015). However, direct comparisons between studies can be challenging due to differences in experimental design and methodology, such as temperature treatments, environmental conditions, and cultivar choice.

Elevated temperatures have consistently been shown to accelerate phenological development (Dominguez *et al.*, 2024; Cameron *et al.*, 2022; Sadras & Moran, 2013b), leading to earlier harvest and a potential mismatch between sugar accumulation and phenolic maturity, as observed in Sadras and Moran (2012). In terms of berry composition, high temperatures typically reduce acidity and phenolic content, including anthocyanins (Arrizabalaga-Arriazu *et al.*, 2020; Ryu *et al.*, 2020; Greer & Weston, 2010; Cohen *et al.*, 2008; Mori *et al.*, 2007; Yamane *et al.*, 2006). For instance, anthocyanin accumulation is suppressed above 30–33 °C in *V. labruscana* × *V. vinifera* hybrids (Matsuda *et al.*, 2021). In addition, temperature increases can modify anthocyanin profiles, favouring a higher proportion of acylated forms (De Rosas *et al.*, 2017; Tarara *et al.*, 2008). Moreover, genotype × temperature interactions play a significant role in shaping the phenolic composition of berries (Arrizabalaga-Arriazu *et al.*, 2020; Sadras & Moran, 2013a; Deis *et al.*, 2012). Yield responses to elevated temperature are more variable. Some studies report increases (Agosta *et al.*, 2012), others reductions (Dominguez *et al.*, 2024), and some no effect under simulated heatwaves (Sadras & Soar, 2009). Similar to what has been observed for berry composition, these discrepancies highlight the importance of genotype × environment interactions, particularly in relation to phenolic content and composition (Arrizabalaga-Arriazu *et al.*, 2020; Sadras & Moran, 2013a; Deis *et al.*, 2012).

Water deficit is another critical factor, with equally complex effects on grapevine physiology and berry traits. In irrigated vineyards, moderate water stress is often used as a management strategy to limit plant vigour (Shellie, 2014) and improve berry quality, particularly in red cultivars (Ojeda *et al.*, 2002). However, the effects of water deficit depend strongly on its timing, intensity, and cultivar sensitivity. When applied after veraison, moderate water deficit has been shown to enhance anthocyanin accumulation in several red wine grape cultivars, such as Sangiovese, Syrah, and Cabernet-Sauvignon (Dayer *et al.*, 2013; Tisseyre *et al.*, 2005; Deis *et al.*, 2011). At the transcriptional level, Castellarin *et al.* (2007) showed that water deficit promoted fruit maturation and enhanced anthocyanin biosynthesis in Merlot. Regarding berry size, the response to water deficit depends on the phenological stage at which stress occurs. Ojeda *et al.* (2002) found that moderate to severe stress applied after fruit set in Syrah caused an irreversible reduction in berry size. When stress occurred between veraison and harvest, the reduction was intermediate compared to control and post-fruit set stress, and anthocyanin accumulation in the skin was enhanced. Keller *et al.* (2016) reported similar results in Cabernet-Sauvignon, where plants exposed to severe pre-veraison water deficit and then irrigated showed changes in fruit composition, attributed not only to smaller berry size but also to altered canopy structure and microclimate. These results emphasise the multifactorial nature of vine responses to water deficit.

The interaction between elevated temperature and water deficit introduces additional complexity. These factors can be either synergistic or antagonistic, depending on their timing, intensity, and the genetics of the cultivar involved. For example, combined heat and water stress has been observed to reduce vegetative growth and yield (Kizildeniz *et al.*, 2015), while in other cases, the combined stress may promote the accumulation of phenolic compounds (Sadras & Moran, 2012; Castellarin *et al.*, 2007). The effects of climate and management practices will not manifest uniformly across regions or cultivars; instead, their impact will depend

on the complex interplay between local environmental conditions and the genetics of the plant material. Therefore, understanding these interactive effects at the regional level is essential for predicting grapevine responses under climate change scenarios.

Currently, long-term field studies examining the effects of increased temperatures on the physiology and wine quality of Malbec and Bonarda are scarce, which limits our ability to predict their behaviour under future climate change scenarios or during unusually hot seasons. Given this lack of data, we explored whether applying moderate water stress from veraison onwards could help mitigate the potential negative impacts of elevated temperatures on the wines of these cultivars. To test this hypothesis, we used an open-top chamber to simulate a daytime temperature increase according to the SSP2-4.5 scenario, combined with different irrigation levels from veraison to harvest. The experiment was conducted over four consecutive seasons. While the primary focus was on evaluating wine quality, we also assessed other variables related to growth and yield in order to provide a comprehensive understanding of the effects. The results are discussed in relation to these objectives. Furthermore, to our knowledge, this is the first report combining temperature and water manipulation in a commercial Malbec and Bonarda vineyard in Argentina, thereby setting a foundation for future research in this area.

MATERIALS AND METHODS

1. Plant material and experimental design

The experiment was conducted over four consecutive growing seasons in a commercial vineyard located at 1200 m a.s.l. in Ugarteche (33° 15' 49" S, 68° 57' 48" W), Mendoza, Argentina. The seasons were designated as follows: 1st (2011–2012), 2nd (2012–2013), 3rd (2013–2014), and 4th (2014–2015). The region's climate is classified as dry desert (BWk) according to the Köppen classification. The vineyard is situated on an Entisol, characterised by an unstructured soil with a loamy-clay texture extending to a depth of approximately 1 m. The study used four-year-old Bonarda and five-year-old Malbec own-rooted vines, cultivated as separate plots, both trained with vertical shoot positioning (VSP) and bilateral spur cordons (Bonarda: 2.2 m × 1.5 m; Malbec: 2.2 m × 1.2 m). The vineyard was equipped with permanent Grembiule hail protection and a drip irrigation system (2.2 L h^{-1}). Winter pruning was performed according to standard practices for this vineyard (20 buds per plant), and topping (shoot trimming) was performed once in mid-December. The experiment followed a multifactorial randomised complete block design with two temperature levels, two water levels, and four replicates. Each experimental unit (plot) consisted of five consecutive Bonarda plants and seven consecutive Malbec plants, arranged between untreated plots and rows. Treatments were randomly assigned to experimental units using Excel's randomisation function. This design was chosen to account for potential variability caused by factors such as irrigation, slope, or proximity to the vineyard headland, ensuring that these sources of variation were included in the experimental error. Phenological stages were classified following Coombe (1995).

2. Temperature and irrigation treatments

The *elevated temperature treatment* (ET) was applied using an open-top chamber constructed with translucent polycarbonate walls. The chamber design, adapted from Sadras and Soar (2009) and shown in Figures 1 and 2, included a key modification: a dark green/black plastic shade net positioned vertically within the chamber to

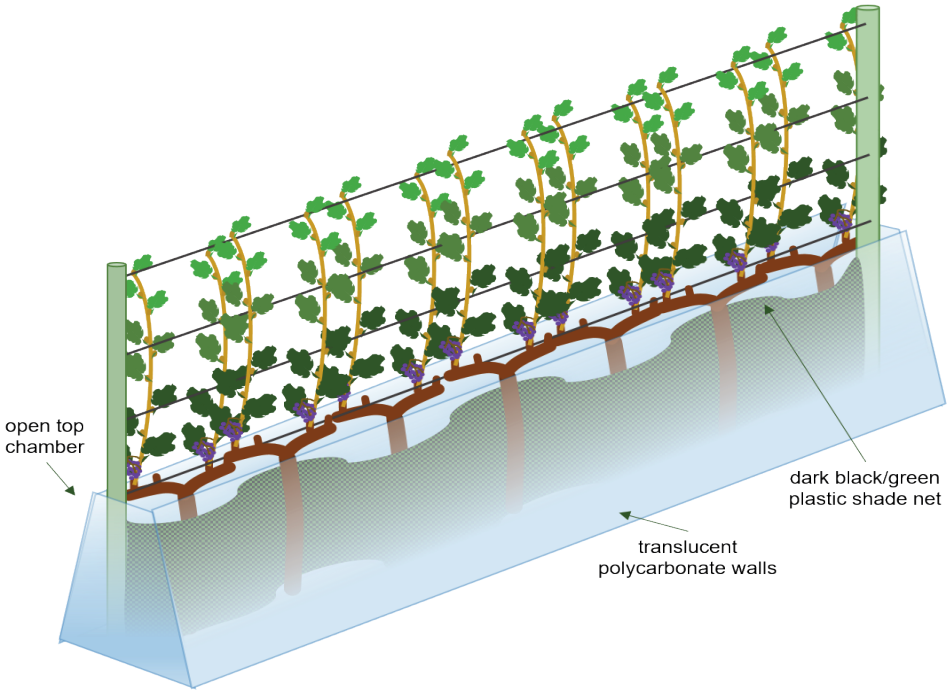


FIGURE 1. Scheme of the open top chamber utilised in this trial.



FIGURE 2. Images of the open top chambers installed in the vineyard. a) Vineyard landscape. b) Dark black/green shade net without the polycarbonate chamber. c) Polycarbonate chamber walls with the shade net inside. d) Final setup of open-top chambers installed with the anti-hail net down. (e) Temperature sensors shielded by plastic shelters (highlighted in pink circles).

improve thermal efficiency. The walls were made of 4 mm polycarbonate sheets (alveolar type), the shade net was a 50 % weave plastic material, and the chamber was handmade. The *control temperature treatment* (CT) involved plots that included the shade net, as in the ET plots, but without the chambers. The shade net was included to ensure that the observed effects could be attributed solely to the use of the open-top chamber, and not to any unintended influence of the net itself on the plant. Temperature treatments were applied from bud-burst (E-L 4 stage) through to harvest (E-L 38 stage). Temperature data were recorded hourly using iButton sensors (1-Wire® Thermochron®, Maxim Integrated, USA). The sensors, shielded from direct sunlight by plastic shelters, were placed within the canopies at the cluster level. Average daily temperature for ET and *CT* was calculated separately for daytime (from 08:00 to 20:00) and nighttime (from 20:00 to 08:00). Across all seasons, the daytime temperatures in the ET treatment were on average 2.175 °C higher than those in the CT (Table S1). At night, ET was approximately 0.125 °C higher than CT temperatures (Table S1). This pattern reflects the performance of passive air heating systems, which primarily influence daytime temperatures due to their dependence on convective airflow driven by incident solar radiation. Averages of monthly temperatures (minimum, maximum, mean, and thermal amplitude), growing degree days, and hours above 35 °C from October to March are presented in Table 1. GDD was calculated using a base temperature of 10 °C, following the formula: GDD = ∑(T mean – T base). The ET treatment consistently showed higher values for these thermal variables. Mean monthly temperature from October to March for all seasons and both cultivars is presented in Figures S1A and S1B.

In terms of irrigation, vines in both ET and CT treatments were irrigated to reach field capacity until the initiation of veraison, at which point the irrigation treatments began. The setting point was chosen to avoid negative effects on plant growth while improving oenological parameters, according to Ojeda *et al.* (2002) and Deis and Cavagnaro (2013). *Control irrigation treatment* (CI) was based on a light water restriction, and *Restricted irrigation treatment* (RI) on a medium water restriction. These restriction levels were assessed by the vines' midday leaf water potentials (Ψ_{MD}), with reference values from Ojeda *et al.* (2008), based on the works of Carbonneau (2002), Williams and Araujo (2002), and Sibille *et al.* (2005). Leaf water potential was measured following Turner and Long (1980). Briefly, leaves were enclosed in a plastic bag for 30 seconds before excision to prevent dehydration. The excised leaf was placed in a Scholander-like pressure chamber (Model 4, Biocontrol, Argentina), with gas flow regulated at 0.2 bar per second. Water potential was recorded at the time xylem sap emerged, just before bubble formation. The CI treatment involved irrigating when Ψ_{MD} values fell between –0.6 and –0.8 MPa, representing the standard irrigation practice for this vineyard. The RI treatment involved watering when Ψ_{MD} values were between –1 and –1.2 MPa. Water potential values were measured five times per season at intervals of 10 to 15 days. These values, along with precipitation data and the amount of water applied in each irrigation treatment, are presented in Figure S2. Rainfall did not influence water potential values, and the irrigation treatments remained the determining factor in water availability for the vines. Across all seasons and both cultivars, the RI treatment resulted in an average reduction of 44.5 % in the total water applied compared to CI. Linear mixed models showed that neither temperature nor the interaction between temperature and irrigation significantly affected water potential ($p > 0.05$).

3. Growth, gas exchange, chlorophyll, and yield-related variables

Shoot length was measured on two randomly selected shoots from the three central plants per plot at the pea-sized stage (E-L 31; before topping). Leaf area per shoot (cm^2), leaf area index, and specific leaf area ($cm^2\ g^{-1}$; calculated as leaf area divided by leaf dry weight) were measured 70 days after bud break using a portable area meter (LICOR, LI-3000A, USA). Measurements were taken on three representative shoots per plot, and leaf area index was calculated using the average shoot leaf area and the mean number of shoots per plant. Leaves and shoots were dried at 60 °C until a constant weight was reached to determine dry weight, from which specific leaf area was calculated. Net photosynthesis (mmol CO_2 $m^{-2}s^{-1}$) and stomatal conductance (mmol H_2O $m^{-2}s^{-1}$) were measured at midday, under ambient light and temperature, on leaves from the third to fifth node of a main shoot. Measurements were taken using an open-circuit CIRAS-2 Portable Photosynthesis System (PP Systems, Hertfordshire, UK) equipped with an automatic cuvette [PLC6 (U), CRS121, PP Systems] enclosing a 2.5 cm^2 leaf area. The reference CO_2 concentration was set at 350 ppm. Chlorophyll relative content (SPAD units) was determined with a SPAD-502 Chlorophyll Meter (Minolta Corp., Ramsey, NJ, USA), in all leaves from nodes two to five, counting from the base of the shoot. These parameters were measured at different times and expressed as days after bud break (DAB) or days after veraison to standardise the measurements, as different seasons had slightly different phenology. Yield-related variables were assessed in all plants at 22 °Brix (E-L 38 stage). This included the number of clusters per plant, the number of berries per cluster, fresh berry weight, cluster weight, and yield. In winter, pruning mass was recorded, and the Ravaz Index (yield/pruning mass) was calculated.

4. Wine composition

When the commercial establishment harvested the untreated plants, all clusters from each treated plant were microvinified according to the standard methods outlined by the International Organization of Vine and Wine (OIV, 2008). The routine operations included analysing °Brix and pH shortly after crushing. The must was fermented in 20 L plastic barrels at 24 °C with a 10-day maceration period. Actiflore® F-33 yeast (Laffort, France) was used, pH was adjusted to 6.5 g L^{-1} with tartaric acid, and 50 mg L^{-1} of sulphur dioxide was added. The wine was then bottled and stored at 10 °C until analysis. Three months after bottling, the alcohol content (*v/v*) and pH of the wine were measured according to OIV (2008) methods. Wine

TABLE 1. Averages of monthly temperatures (minimum, maximum, mean, and thermal amplitude), growing degree days, and hours above 35 °C from October to March across growing seasons for Malbec and Bonarda.

Bonarda

Season	Treatment	Mean temperature °C	*sig*	GDD	*sig*	Minimum temperature	*sig*	Maximum temperature	*sig*	Thermal amplitude	*sig*	N° of hours >35° C day^{-1}	*sig*
1	ET	20.31	a	917.69	a	11.45	a	33.60	a	22.14	a	304.00	a
	CT	19.74	a	844.46	a	10.93	a	31.21	b	20.28	b	143.00	a
	p-value	0.13		0.23		0.20		0.0001		0.0001		0.05	
2	ET	21.18	a	977.46	a	11.70	a	34.05	a	22.35	a	278.33	a
	CT	19.68	b	857.69	a	10.47	b	30.09	b	19.61	b	61.67	a
	p-value	0.0010		0.0660		0.0050		0.0001		0.0010		0.0540	
3	ET	21.26	a	1,056.12	a	11.49	a	34.27	a	22.78	a	361.67	a
	CT	20.32	b	959.90	a	10.86	a	31.30	b	20.44	b	130.33	b
	p-value	0.0400		0.1560		0.1490		0.0001		0.0001		0.0302	
4	ET	22.23	a	1,100.08	a	12.51	a	39.05	a	27.15	a	579.33	a
	CT	21.30	b	1,000.10	a	11.90	a	32.90	b	20.39	b	194.33	b
	p-value	0.0420		0.1560		0.2030		0.0001		0.0001		0.0077	

Malbec

Season	Treatment	Mean temperature °C	*sig*	GDD	*sig*	Minimum temperature	*sig*	Maximum temperature	*sig*	Thermal amplitude	*sig*	N° of hours >35° C day^{-1}	*sig*
1	ET	22.30	a	1,051.56	a	12.76	a	36.52	a	23.93	a	348.67	a
	CT	21.72	a	992.01	a	12.59	a	32.88	b	20.12	b	168.00	b
	p-value	0.1390		0.3090		0.7020		0.0001		0.0001		0.0219	
2	ET	21.32	a	990.44	a	12.10	a	34.91	a	22.81	a	273.33	a
	CT	19.89	b	862.54	a	11.22	b	30.17	b	18.95	b	65.67	b
	p-value	0.0010		0.0530		0.0340		0.0001		0.0001		0.0482	
3	ET	21.13	a	1,053.22	a	11.47	a	34.73	a	23.25	a	337.00	a
	CT	20.65	a	993.33	a	11.46	a	31.28	b	19.82	b	201.00	b
	p-value	0.3120		0.3780		0.9670		0.0001		0.0001		0.0348	
4	ET	21.36	a	1,019.95	a	11.97	a	35.41	a	23.69	a	343.00	a
	CT	20.51	a	929.92	a	11.73	a	30.66	b	18.69	b	68.00	b
	p-value	0.0540		0.1700		0.5950		0.0001		0.0001		0.0456	

sig = significance. Different letters indicate significant differences based on the DGC test at a significance level of $\alpha < 0.05$.

colour intensity was calculated as the sum of absorbance at 420, 520, and 620 nm, while hue was determined as the ratio of absorbance at 420 nm to 520 nm. The colour index was calculated as colour intensity divided by hue, multiplied by 1000. The total polyphenol index (TPI) was determined by spectrophotometry at 280 nm from a 1:100 (*v/v*) wine-water dilution. Spectrophotometric measurements in the visible spectrum were conducted using 10 mm path length cuvettes, while the measurement of TPI at 280 nm was performed using quartz cuvettes with a 1 mm path length. Co-pigmented, free (monomeric anthocyanins), and polymerised anthocyanins, as well as red colour, were quantified according to Boulton (2001). Anthocyanins in the wine were identified by using HPLC-DAD (SPD-M10 AVP, Shimadzu) following the method described by Otteneder (2004), using a Licrosorb reverse-phase column (RP18, 250 mm × 4.6 mm, 5 µm). The anthocyanin profile was analysed through various ratios of identified anthocyanins as described by de Rosas *et al.* (2017).

5. Statistical analyses

Linear mixed models (LMMs) with a factorial design were applied to analyse thermal variables, ripening, wine-related variables, and water potential values. For thermal variables, the model included temperature treatment (ET and CT), growing season (1st, 2nd, 3rd, and 4th), and their interactions as fixed effects, with blocks (inherent to the design) as a random

TABLE 2. Total soluble solids and pH of Bonarda and Malbec musts across different seasons.

Treatment	Total soluble solids (°Brix)				pH			
	Bonarda		Malbec		Bonarda		Malbec	
Temperature (T)								
CT	22.71	b	22.75	b	3.72	b	3.71	b
ET	23.75	a	23.5	a	3.86	a	3.84	a
Irrigation (I)								
CI	23.2	a	22.96	a	3.81	a	3.77	a
RI	23.29	a	23.29	a	3.77	a	3.79	a
Season (S)								
1	24.86	a	25.6	a	3.73	b	3.63	c
2	23.34	b	23.6	b	3.75	b	3.77	b
3	22.18	c	21.81	c	3.74	b	3.77	b
4	22.59	c	21.49	c	3.92	a	3.94	a
MLM *p*-values								
p-value $_{(T)}$	0.0009		0.0032		<0.0001		<0.0001	
p-value $_{(I)}$	0.7571		0.1734		0.1319		0.3026	
p-value $_{(S)}$	<0.0001		<0.0001		<0.0001		<0.0001	

CT = Control temperature; ET = Elevated temperature; CI = Control irrigation; RI = restricted irrigation; T = temperature; I = Irrigation and S = season. Different letters indicate significant differences based on the DGC test at a significance level of $\alpha < 0.05$.

effect. The analysis of water potentials involved an LMM with irrigation treatment, DAB, and growing season as fixed effects, and blocks and plants (to account for repeated measurements over time) as a random effect. LMMs were used to analyse gas exchange, chlorophyll, growth, and yield-related variables, with temperature treatment, irrigation treatment (CI and RI), DAB, and growing season as fixed effects, and blocks and plants as random effects. For wine-related variables, temperature, irrigation treatments, and growing season were fixed effects, while blocks and plants were random effects. Anthocyanin ratios were analysed using multivariate generalised linear mixed models (GLMMs) with a binomial family and logit link function.

Means were compared using the DGC method at $\alpha = 0.05$ (Di Rienzo *et al.*, 2002). Statistical analyses were conducted with InfoStat® version 2018p and R® version 3.3.2 (Di Rienzo *et al.*, 2014). Only significant results (*p*-value < 0.05) are presented and discussed.

RESULTS

1. Growth, physiology, and yield-related variables

Overall, the temperature treatment did not significantly affect growth-related variables such as shoot length, number of leaves, leaf area per shoot, related calculations, or leaf dry weight (*p*-value > 0.05). However, in Bonarda, elevated temperatures led to a decrease in leaf area per shoot (72 ± 2 cm^2 $shoot^{-1}$) compared to the control treatment (78 ± 2 cm^2 $shoot^{-1}$) (*p*-value = 0.0445). The irrigation treatment also showed no significant effect on these variables, and there was no significant interaction between irrigation and season (*p*-value > 0.05). Physiological variables, including chlorophyll relative content, net photosynthesis, and stomatal conductance, showed minimal differences across temperature and irrigation treatment, or their interaction, except in specific years (Tables S2–7). In contrast, interactions with the date of measurement were more frequent, although these small differences did not appear to affect the growth-related variables. Only temperature and season affected °Brix in both berry cultivars (Table 2). Elevated temperatures increased pH by an average of 0.135 units in both cultivars. In Bonarda, plants subjected to the ET condition had fewer berries per cluster, and both the berries and clusters were lighter compared to those under CT (Table 3). Bonarda yield was also reduced in the ET treatment compared to the control condition (Table 3). All yield-related variables were significantly affected by the season, while irrigation treatment had no significant impact (Tables 3 and 4). In both cultivars, ET had a significant effect on pruning mass, which was approximately 15 % lower compared to CT. However, the Ravaz Index was not statistically affected by the temperature or irrigation treatment, nor their interactions in both varieties (Table 4). In Malbec, IR treatment resulted in lighter clusters, and the interaction of CT × CI led to fewer clusters per plant compared to any other temperature and irrigation combination (*p*-value (T × I) = 0.0365; CT × CI = 28; CT × RI = 31; ET × CI = 33; ET × RI = 30 clusters per plant). The combined temperature and irrigation treatments did not affect any other yield-related variables in either cultivar.

2. Wine composition

Elevated temperature treatment increased alcohol content in both cultivars (Table 5). Additionally, when elevated temperature was combined with restricted irrigation, Bonarda wines exhibited higher pH levels, whereas under control temperature conditions, restricted irrigation led to a decrease in Malbec wine pH (Table 5).

Regarding colour parameters, elevated temperature reduced colour intensity and colour index in both cultivars. In Bonarda, the reduction in colour intensity was approximately 12 % and ~26 % in colour index. In Malbec, this reduction was ~11 % in colour intensity and ~22 % in colour index (Table 5). In contrast, restricted irrigation increased colour intensity by ~19 % in Bonarda and ~15 % in Malbec, as well as colour index by ~22 % specifically in Malbec. Moreover, elevated temperature increased Malbec's hue by approximately 5 %, although restricted irrigation under control temperature conditions decreased it by about 5 % (Table 5).

As shown in Table 6, elevated temperature decreased co-pigmented anthocyanins by ~23 % in Bonarda and ~18 % in Malbec compared to control temperature conditions. In terms of free anthocyanins, the combination of control temperature and control irrigation in Bonarda showed levels ~29 % higher than the average of the other treatments, while control temperature combined with restricted irrigation increased their levels in Malbec by ~19 %. Polymeric anthocyanins also showed cultivar-specific responses: in Bonarda, elevated temperature with control irrigation increased their levels by ~64 % compared to the average of the other combinations, whereas in Malbec, elevated temperature combined with restricted irrigation increased them by ~17 %. Restricted irrigation conditions increased TPI by approximately 9.8 % on average across both cultivars, while red colour was not affected by any treatment.

As demonstrated in Table 7, total anthocyanin content decreased in Bonarda under elevated temperature by ~25 %. In Malbec, total anthocyanins increased by ~16 % under the combination of control temperature and restricted irrigation (CT × RI = 240.9; CT × CI = 217.6; ET × CI = 208.3; ET × RI = 195.6; *p*-value = 0.0223). Furthermore, elevated temperature increased the Me/NoMe (methoxylated/non-methoxylated) F3'5'H ratio by ~19 % and the blue/red ratio by ~29 % in Malbec compared to control conditions. However, while elevated temperature decreased red anthocyanins by ~33 % in Bonarda and ~30 % in Malbec, as well as blue anthocyanins by ~29 % in Bonarda, in Malbec blue anthocyanins increased by ~18 % under control temperature combined with restricted irrigation (CT × RI = 195.7; CT × CI = 177.4; ET × CI = 164.7; ET × RI = 154; *p*-value = 0.0177). Me/NoMe F3'H was not affected by any treatment.

All variables presented in Tables 5, 6, and 7, except for the Me/NoMe F3'5'H ratio, were significantly influenced by the season. Finally, elevated temperature increased the relative content of coumaroylated anthocyanins and decreased non-acylated anthocyanins in both cultivars (Figure 3). Additionally, this treatment increased acetylated anthocyanins in Malbec.

TABLE 3. Mean values of yield and yield components of Bonarda and Malbec across different seasons.

Treatment	Yield (kg plant^{-1})		Clusters per plant		Clusters fresh weight (g)		Berries per cluster		Berries fresh weight (g)	
	Bonarda	Malbec	Bonarda	Malbec	Bonarda	Malbec	Bonarda	Malbec	Bonarda	Malbec
Temperature (T)										
CT	4.47 a	2.39 a	32 a	30 a	156 a	82.3 a	114 a	64.8 a	1.87 a	1.34 a
ET	3.82 b	2.42 a	31 a	31 a	131 b	75.9 a	93.8 b	67.8 a	1.32 b	1.18 a
Irrigation (I)										
CI	4.38 a	2.61 a	31 a	31 a	148 a	86.3 a	107 a	67.7 a	1.71 a	1.33 a
RI	4.18 a	2.21 a	31 a	31 a	139 a	71.6 b	102 a	64.9 a	1.49 a	1.21 a
Season (S)										
1	5.15 a	1.71 c	30 c	28 c	169 a	60.5 c	101 b	55.9 b	1.82 b	1.19 a
2	3.13 c	2.14 b	19 d	22 d	172 a	103 a	82.7 b	59.9 b	2.26 a	1.72 a
3	4.22 b	2.66 a	37 b	31 b	114 b	80.5 b	140 a	77.4 a	0.89 d	1.08 b
4	4.61 a	3.12 a	39 a	42 a	118 b	72.1 b	92.7 b	72.2 a	1.41 c	1.05 b
MLM *p*-values										
p-value $_{(T)}$	<0.0001	0.1966	0.4705	0.0509	0.0002	0.1941	0.0056	0.5511	<0.0001	0.0623
p-value $_{(I)}$	0.3457	0.2902	0.9958	0.928	0.1599	0.0063	0.4675	0.581	0.0783	0.1157
p-value $_{(S)}$	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0123	<0.0001	<0.0001

CT = Control temperature; ET = Elevated temperature; CI = Control irrigation; RI = restricted irrigation; T = temperature; I = Irrigation and S = season. Different letters indicate significant differences based on the DGC test at a significance level of $\alpha < 0.05$.

TABLE 4. Mean values of prune mass and Ravaz Index of Bonarda and Malbec across different seasons.

Treatment	Prune mass (kg plant^{-1})				Ravaz Index			
	Bonarda		Malbec		Bonarda		Malbec	
Temperature (T)								
CT	1.01	a	0.84	a	5.44	a	3.47	a
ET	0.83	b	0.72	b	5.51	a	3.73	a
Irrigation (I)								
CI	0.91	a	0.81	a	5.61	a	3.51	a
RI	0.93	a	0.76	a	5.22	a	3.71	a
Season (S)								
1	0.86	b	1.01	a	6.28	a	1.79	b
2	1.22	a	0.63	b	2.81	c	3.99	a
3	0.92	b	0.72	b	4.71	b	4.23	a
4	0.66	c	0.75	b	7.86	a	4.38	a
MLM *p*-values								
p-value $_{(T)}$	0.0036		0.0125		0.8838		0.5279	
p-value $_{(I)}$	0.5662		0.3272		0.4244		0.6278	
p-value $_{(S)}$	<0.0001		<0.0001		<0.0001		<0.0001	

CT = Control temperature; ET = Elevated temperature; CI = Control irrigation; RI = restricted irrigation; T = temperature; I = Irrigation and S = season. Different letters indicate significant differences based on the DGC test at a significance level of $\alpha < 0.05$.

TABLE 5. Mean values of alcohol, pH, Colour Index, Colour Intensity, and Hue of Malbec and Bonarda wines across seasons.

Treatment	Alcohol				Wine pH				Colour Index				Colour Intensity				Hue			
	Bonarda		Malbec		Bonarda		Malbec		Bonarda		Malbec		Bonarda		Malbec		Bonarda		Malbec	
Temperature (T)																				
CT	13.25	b	13.41	b	4.03	b	3.76	b	2,882.9	a	2,364.1	a	2.03	a	1.41	a	0.66	a	0.57	b
ET	13.84	a	14.07	a	4.13	a	3.86	a	2,135.6	b	1,842.6	b	1.79	b	1.26	b	0.7	a	0.6	a
Irrigation (I)																				
CI	13.17	a	13.7	a	4.05	b	3.83	a	2,462.4	a	1,899.4	a	1.78	b	1.24	b	0.7	a	0.6	a
RI	13.48	a	13.78	a	4.1	a	3.79	a	2,556.1	a	2,307.3	b	2.12	a	1.43	a	0.65	a	0.57	b
Season (S)																				
1	14.87	a	15.33	a	4.08	b	3.78	b	3,639.4	a	3,527.4	a	2.28	a	1.95	a	0.54	b	0.49	c
2	13.57	b	14.01	b	4.26	a	3.72	c	3,003.1	a	2,121.5	b	2.3	a	1.22	b	0.67	a	0.53	b
3	12.32	c	12.83	c	3.76	c	3.96	a	1,984.2	b	1,835.3	b	1.52	b	1.17	b	0.73	a	0.57	a
4	12.78	c	12.81	c	4.14	b	3.79	b	1,410.3	b	929.27	c	1.35	b	0.99	b	0.81	a	0.75	d
T × I interaction																				
CT × CI	13.14	a	13.37	a	4.05	b	3.8	a	2,885.9	a	2,030.1	b	2.02	a	1.31	a	0.67	a	0.59	a
CT × RI	13.36	a	13.45	a	4.02	b	3.71	b	2,880	a	2,698.1	a	2.04	a	1.5	a	0.64	a	0.54	a
ET × CI	13.2	a	14.02	a	4.05	b	3.86	a	2,232.3	b	1,916.5	b	1.55	a	1.16	a	0.72	a	0.61	a
ET × RI	13.6	a	14.12	a	4.28	a	3.87	a	2,038.9	b	1,768.8	b	2.27	a	1.36	a	0.66	a	0.6	a
MLM *p*-values																				
p-value (T)	0.0051		0.0004		0.004		0.0001		0.0005		0.0003		0.012		0.04		0.489		0.002	
p-value (I)	0.1953		0.6164		0.023		0.0918		0.6416		0.0036		0.002		0.009		0.464		0.007	
p-value (S)	<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		0.02		<0.0001	
p-value (T × I)	0.6986		0.9717		0.016		0.0419		0.6209		0.0571		0.196		0.93		0.626		0.072	

CT = Control temperature; ET = Elevated temperature; CI = Control irrigation; RI = restricted irrigation; T = temperature; I = Irrigation and S = season. Different letters indicate significant differences based on the DGC test at a significance level of $\alpha < 0.05$.

TABLE 6. Phenolic composition of Malbec and Bonarda wines across seasons.

Treatment	TPI		Co-pigmented anthocyanins		Free anthocyanins		Polymeric anthocyanins		Red colour	
	Bonarda	Malbec	Bonarda	Malbec	Bonarda	Malbec	Bonarda	Malbec	Bonarda	Malbec
Temperature (T)										
CT	63.5 a	55.21 a	6.09 a	3.93 a	6.15 a	3.75 a	3.51 a	1.99 a	15.75 a	9.67 a
ET	64.3 a	56.62 a	4.72 b	3.24 b	5.05 b	3.46 a	5.12 b	2.26 b	14.88 a	8.97 a
Irrigation (I)										
CI	61.27 b	53.45 b	5.17 a	3.44 a	5.81 a	3.43 a	4.86 b	2.03 a	15.84 a	8.9 a
RI	67.55 a	58.38 a	5.65 a	3.73 a	5.38 a	3.78 b	3.77 a	2.22 a	14.79 a	9.73 a
Season (S)										
1	81.4 a	97.4 a	7.91 a	5.74 a	6.72 a	5.86 a	4.09 b	2.94 a	18.72 a	14.54 a
2	58.78 b	44.18 b	6.42 b	3.7 b	6.95 a	3.57 b	3.94 b	1.83 b	17.31 a	9.1 b
3	55.4 b	43.23 b	4.31 c	3.2 b	4.46 b	3.09 c	2.82 c	1.96 b	11.59 b	8.25 b
4	48.57 c	38.85 c	2.99 d	1.7 c	4.25 b	1.9 d	6.4 a	1.79 b	13.63 b	5.83 c
T × I interaction										
CT × CI	62.1 a	53.09 a	5.61 a	3.68 a	6.74 a	3.41 b	3.63 b	2.07 b	15.99 a	9.16 a
CT × RI	66.51 a	57.33 a	6.65 a	4.19 a	5.55 b	4.08 a	3.39 b	1.9 b	15.5 a	10.17 a
ET × CI	60.44 a	53.81 a	4.72 a	3.2 a	4.88 b	3.45 b	6.09 a	1.99 b	15.69 a	8.64 a
ET × RI	69.63 a	59.43 a	4.73 a	3.28 a	5.21 b	3.47 b	4.14 b	2.54 a	14.08 a	9.29 a
MLM *p*-values										
p-value (T)	0.9195	0.3001	0.0037	0.0016	0.0009	0.0788	<0.0001	0.0172	0.2698	0.1181
p-value (I)	0.0016	0.0007	0.2886	0.1592	0.1718	0.035	<0.0001	0.1022	0.1829	0.0678
p-value (S)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
p-value (T × I)	0.5269	0.6746	0.3004	0.3002	0.0178	0.0473	0.0005	0.0024	0.4703	0.684

CT = Control temperature; ET = Elevated temperature; CI = Control irrigation; RI = restricted irrigation; T = temperature; I = Irrigation and S = season. Different letters indicate significant differences based on the DGC test at a significance level of $\alpha < 0.05$.

TABLE 7. Anthocyanin profiles and ratios in Malbec and Bonarda wines across seasons.

Treatments	Total anthocyanins		Me/NoMe F3′H		Me/NoMe F3′5′H		Blue anthocyanins		Red anthocyanins		Blue/Red	
	Bondarda	Malbec	Bondarda	Malbec	Bondarda	Malbec	Bondarda	Malbec	Bondarda	Malbec	Bondarda	Malbec
Temperature (T)												
CT	293.4 b	229.2 b	15.9 a	25.2 a	26.6 a	35.2 a	247.7 b	186.5 b	3.9 b	3 b	124.0 a	78.0 a
ET	219.4 a	201.9 a	17.9 a	20.0 a	36.1 a	42 b	175.6 a	159.4 a	2.6 a	2.1 a	101.1 a	100.5 b
Irrigation (I)												
CI	271.9 a	212.9 a	15.2 a	22.7 a	33.1 a	40.7 a	222.1 a	171 a	3.0 a	2.3 a	123.0 a	81.5 a
RI	250.1 a	218.2 a	18.8 a	22.6 a	27.3 a	36.3 a	209.7 a	174.9 a	3.9 a	2.8 a	100.1 a	96.5 a
Season (S)												
1	180.3 a	182.9 a	14.3 a	25.2 b	20.1 a	20.6 a	150.2 a	148.9 a	2.3 a	67.5 a	67.5 a	44.9 a
2	287.7 b	270.3 c	11.8 a	11.5 a	18.7 a	28.7 a	244.0 c	213.1 c	6.6 b	42.2 a	42.2 a	76.7 b
3	333.2 c	231.4 b	19.9 b	27.1 b	62.6 b	41.1 b	274.2 c	184.1 b	1.5 a	287.1 b	287.1 b	111.3 c
4	268.7 d	206.0 a	20.1 b	27.1 b	28.1 a	65.5 c	211.9 b	145.7 a	2.4 a	97.3 a	97.3 a	125.7 c
MLM *p*-values												
p-value (T)	<0.0001	0.0009	0.461	0.0665	0.1789	0.0219	<0.0001	<0.0001	0.02	0.0006	0.2621	0.0109
p-value (I)	0.0879	0.4908	0.1459	0.9342	0.44	0.1367	0.0835	0.5148	0.19	0.0679	0.1839	0.126
p-value (S)	<0.0001	<0.0001	0.005	0.0004	0.2218	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

CT = Control temperature; ET = Elevated temperature; CI = Control irrigation; RI = restricted irrigation; T = temperature; I = Irrigation and S = season. Different letters indicate significant differences based on the DGC test at a significance level of $\alpha < 0.05$. Significant interactions are described in the text.

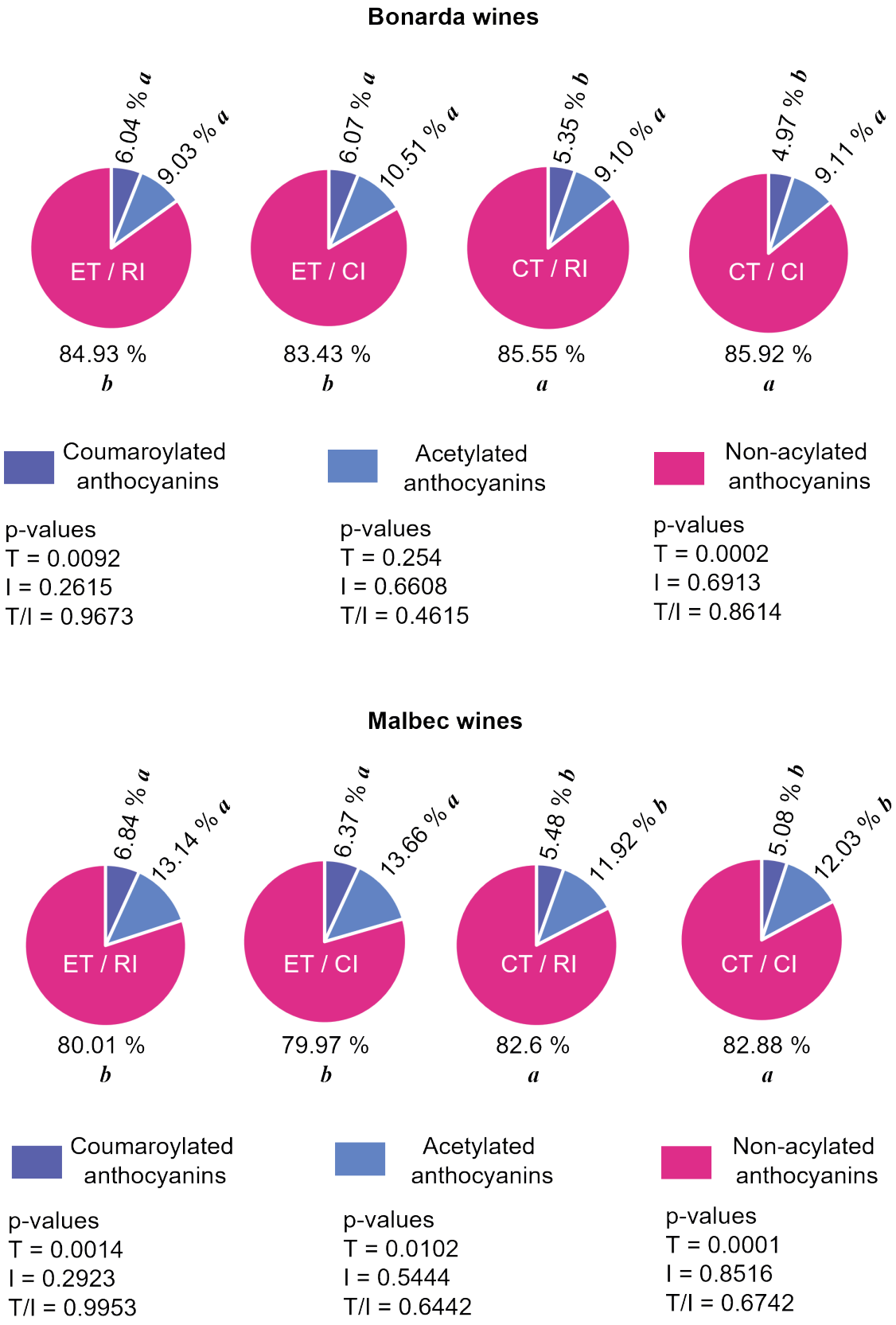


FIGURE 3. Proportions of coumaroylated, acetylated and non-acylated anthocyanins in Malbec and Bonarda wines over four seasons. CT = control temperature; ET = elevated temperature; CI = control irrigation and RI = restricted irrigation. GLMM comparisons were conducted separately for each classification of anthocyanins. Different letters indicate significant differences based on the DGC test at a significance level of $\alpha < 0.05$.

DISCUSSION

1. Effectiveness of the passive heating system

Numerous studies, as reviewed by Bonada and Sadras (2015), have investigated the impact of increased temperatures on grapes. However, as detailed by these authors, many experimental methods not only elevate temperatures but also alter other environmental variables, such as a lack of wind or alterations in DPV and radiation, complicating the interpretation of results. In this context, the open-top chamber passive air heating system represents a reliable tool that minimally influences other environmental factors (Sadras *et al.*, 2012). In the present study, our heating system led to a significant rise in average daytime temperatures (approximately +2 °C). Moreover, our system improves compared to those proposed by other researchers (*e.g.*, Marion *et al.*, 1997; Sadras *et al.*, 2012) by incorporating a dark shade net within the chamber. The use of the dark net improved the thermal performance by absorbing light and converting it into heat energy that would otherwise be lost. For the same reason, this innovation increases night-time temperatures compared to the control by approximately 0.5 °C on windless nights (data not shown). The temperature followed the natural daily, monthly, and annual fluctuations in surface temperatures. Even though the temperature rise in the ET depended on the existing environmental conditions, the treatment effect was consistent across seasons.

2. Effects of elevated temperature on grape composition

The consistent temperature rise had a direct impact on grape ripening. At harvest, as expected, °Brix of both cultivars increased under elevated temperature. Additionally, at harvest, both cultivars exhibited higher juice pH compared to the control, consistent with the findings of Sadras and Moran (2013b) in other red cultivars. This rise in pH could be attributed not only to increased respiration but also to photorespiration, as both pathways are tightly connected and regulated by temperature (Obata *et al.*, 2016). The interaction of photorespiration with the TCA cycle, particularly under elevated temperatures, has been shown to affect the levels of organic acids such as malate and succinate in other species (Obata *et al.*, 2016; Sicher, 2015). While direct evidence for *V. vinifera* is still lacking, it is plausible that similar mechanisms could operate in grapevine and thus contribute to the observed pH increase. This remains a hypothesis that warrants further investigation. Consistent with Sweetman *et al.* (2014), pre-veraison warming, particularly warmer nights, was associated with higher malate, whereas heating during veraison and ripening reduced malate. This pattern agrees with the review by Sweetman *et al.* (2009), in which it is well established that exposure of ripening grape berries to warmer climatic conditions leads to lower malate levels at harvest, and also with reports linking high sunlight exposure to reduced malate, most likely due to elevated berry temperature. In our case, the increase in pH most likely reflects the stronger thermal impact during post-veraison, given its longer duration (≈45–55 *vs*. 25–30 days).

3. Effects of water deficit on grape composition

In our study, restricted irrigation did not affect pH levels, aligning with the findings of Deis and Cavagnaro (2013), who conducted their trial in the same geographical area and under similar soil conditions (Zárate & Mehl, 2018). This stability may be partly explained by the high natural potassium availability (as no fertilisation is required and deficiency symptoms are rarely observed), and by the sandy-loam texture of the soils, which could have favoured stable uptake dynamics under water restriction (Mpelasoka *et al.*, 2003). In contrast, studies reporting pH changes under water deficit (*e.g.*, Santesteban *et al.*, 2011; Gamero *et al.*, 2014; Leibar *et al.*, 2017) were conducted under different irrigation volumes, stress severity or timing, soil potassium content, or other unmeasured environmental and physiological variables.

4. Effects on vegetative growth

In terms of vegetative growth, elevated temperature reduced pruning mass in both cultivars and decreased leaf area per shoot in Bonarda. This could be explained by prolonged exposure to temperatures exceeding 35 °C in the ET treatment, leading to reduced net photosynthesis by increasing respiration, photorespiration, and/or decreasing gross photosynthesis rates on specific days not measured. This could have potentially restricted the accumulation of wood reserves. Although gas exchange data were collected, measurements were limited to specific dates before veraison and may not reflect the full impact of elevated temperatures throughout the season. Sadras and Moran (2013a) observed that elevated temperatures reduced starch concentration in trunks, which aligns with our findings of reduced pruning weight. In contrast to the findings of Dayer *et al.* (2013) in Malbec, restricted irrigation in our trial did not negatively impact pruning mass. This discrepancy may arise from differences in water stress intensity and rootstock performance. Dayer's study used vines grafted onto 101-14 MGt, a low-vigour and drought-sensitive rootstock, whereas our vines were own-rooted. Importantly, despite the observed reduction in pruning mass in Bonarda, the Ravaz index remained unchanged in both cultivars, suggesting that the balance between reproductive and vegetative growth was maintained.

Neither temperature nor irrigation treatments significantly influenced the rest of the growth-related measured parameters. This was observed even after the fourth consecutive season, suggesting no cumulative effect of increased environmental temperatures from previous cycles. Since the water restriction treatment was applied post-veraison, its lack of impact on growth-related variables aligns with grapevine physiology, as during this period photoassimilates are prioritised for reproductive growth over vegetative growth (Williams & Matthews, 1990). Furthermore, there was no observed interaction between irrigation and growing seasons,

indicating that the moderate deficit treatment did not produce any cumulative internal effects.

5. Yield and yield components

Based on our results, Bonarda yields are expected to decline in future warmer vintages due to reductions in yield components, such as berries per bunch and berry and cluster weight. This decline is consistent with temperature-dependent processes like fruit set and carbon allocation (Keller *et al.*, 2022; Tombesi *et al.*, 2022).

According to our data, the changes in yield-related variables induced by elevated temperature in Bonarda appeared unaffected by the moderate water stress applied. This is consistent with findings in Cabernet-Sauvignon by Acevedo-Opazo *et al.* (2010) and Keller *et al.* (2016), where mild deficit irrigation preserved yield. In this cultivar, after veraison, growth may be more influenced by temperature-driven increases in vapour pressure deficit (VPD) than by soil water availability. According to Keller (2020), xylem hydraulic conductivity in the rachis may be impaired under certain conditions, forcing the plant to increasingly rely on phloem pathways for water supply. As cuticular transpiration continues, influenced by VPD, berry water status and final size tend to be more sensitive to atmospheric conditions than to soil moisture.

Interestingly, unlike Bonarda, Malbec appears more tolerant to increased temperatures in terms of yield, despite a reduction in pruning mass. This can be observed in Malbec's capacity to maintain its yield levels under ET similar to those under control conditions. In addition, under restricted irrigation, Malbec grew lighter clusters compared to control-irrigated vines; however, overall yield was not affected. This suggests that, although there were variations in cluster weight, the lack of significant changes in other yield components led to no statistically significant difference in total yield.

In both cultivars, yield-related variables were not significantly affected by any interactions among season, irrigation, and temperature treatments. This suggests that the simple effects of these factors remain consistent across seasons, allowing reliable yield predictions. Overall, for these variables, Malbec, known for its high adaptability (de Rosas *et al.*, 2022; Calderón *et al.*, 2024), showed greater physiological phenotypic plasticity than Bonarda, particularly in its ability to maintain yield under combined heat and water stress, despite reductions in individual yield components.

6. Wine composition

In terms of wine composition, both Malbec and Bonarda are expected to exhibit common negative effects under future warmer seasons (SSP2-4.5 scenario; conditions similar to our ET treatment): a decline in colour index, colour intensity, and co-pigmented and red anthocyanin content. Additionally, a shift in anthocyanin profile may occur, with higher proportions of coumaroylated forms and lower proportions of non-acylated anthocyanins becoming a shared characteristic. The temperature increases most likely downregulated the anthocyanin metabolic pathway, possibly due to prolonged exposure to temperatures exceeding 35 °C (Mori *et al.*, 2007; Azuma *et al.*, 2012). However, the lack of modification in the total polyphenol index suggests changes in other flavonoids and/or non-flavonoid polyphenols not accounted for in this study. Moreover, the increase in temperature is also expected to result in more alcoholic wines for both cultivars.

In addition to the negative common effects shared with Malbec, Bonarda experienced a reduction in total, free, and blue anthocyanins under the elevated temperature treatment. This alteration is consistent with observations in other red cultivars (Tarara *et al.*, 2008; Deis *et al.*, 2012). These changes suggest a potential deterioration in wine colour attributes as climate change progresses.

However, if a moderate deficit irrigation strategy like the one applied in this study were implemented in Bonarda under the warming conditions projected by the SSP2-4.5 scenario, it could help restore colour intensity and increase the total polyphenol index. Both parameters might even surpass the values observed under control conditions. Polymeric anthocyanins were lower under elevated temperature combined with restricted irrigation than under elevated temperature with full irrigation. However, their levels remained comparable to those observed under current conditions (control temperature). Beyond this, no other anthocyanin groups were negatively affected by the irrigation restriction. Similar results were reported for Cabernet-Sauvignon berries by Deis *et al.* (2011). Finally, the resulting wines would have a slightly higher pH, an undesired but manageable effect.

On the other hand, in Malbec, under the predicted temperature increase, despite sharing some negative traits with Bonarda, wines may benefit from greater hue, elevated blue/red and Me/NoMeF3'5'H ratios, and higher proportions of acylated anthocyanins. Besides the colour beneficial effect, acetylated anthocyanins are known to be more stable after three years of ageing (Mateus & De Freitas, 2001), making Malbec wines more suitable for long-term ageing processes. Under the predicted warmer conditions, if a moderate restricted irrigation strategy like the one in our experiment were applied from veraison, Malbec wine alcohol content would reflect only the effects of elevated temperature. Additionally, pH would remain comparable to current levels (*i.e.*, control temperature and irrigation). At the same time, this water management would restore colour intensity as well as colour index values to levels comparable to those observed under current (non-heated) conditions. These colour improvements may result from the observed increases in total polyphenol index and polymeric anthocyanins. In addition, a concentration effect associated with reduced cluster weight, likely due to smaller cluster size and consequently a lower pulp-to-skin ratio found under moderate water deficit, may have also contributed. Moreover, the stability provided by polymeric anthocyanins (Boulton, 2001) would further enhance long-term colour stability, beyond what is achieved by temperature increase alone. At the same time, although

elevated temperature increased hue in Malbec, applying a moderate deficit irrigation strategy reduced it by a similar proportion, bringing values back to levels observed under current conditions. Nevertheless, it is important to consider that wine colour expression is also shaped by the complexity of the wine matrix, influenced by pH, association phenomena, polymerisation and copigmentation, along with temporal evolution (Boulton, 2001; Versari *et al.*, 2008; Buscema & Boulton, 2015). Additionally, seasonal variations influenced most phenolic compounds in both wines, as reported by Urvieta *et al.* (2021) for Malbec in the study area.

This study provides evidence that the combined effects of elevated temperature and moderate water stress applied post-veraison shape wine composition and vine performance in distinct ways depending on the cultivar. Since water restriction was applied post-veraison, when vegetative growth had mostly ceased (*i.e.*, maximum canopy development), overall vine growth was not significantly compromised. Similarly, Bonarda yield was unaffected by irrigation, while Malbec showed only minor reductions. Wines from both cultivars exhibited negative effects of elevated temperatures, although Malbec showed some beneficial responses. At the same time, the moderate water restriction provided additional benefits to Malbec wines compared to Bonarda. These results suggest that Malbec may be more adaptable and suitable for obtaining premium wines under a projected 2 °C rise in daytime temperatures. This is important, especially considering the plasticity of Malbec vines across Argentina's diverse viticultural regions.

This study supports moderate water deficit applied after veraison as a viable strategy to improve wine quality under the projected SSP2-4.5 scenario, at the local level, without significantly compromising vine growth or vegetative/reproductive balance. However, careful management, particularly during unusually hot summers or extensive heatwaves, is essential for an effective implementation. Otherwise, the practice may impair the vines' physiological performance. This approach aligns with the criteria described by Prieto *et al.* (2024), supporting that adaptation strategies must be locally appropriate, capable of delivering acceptable wine quality, and be both economically and environmentally sustainable. Future research should investigate additional factors, such as hormones and phenology, to develop comprehensive viticultural strategies for a warming climate.

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