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ORIGINAL RESEARCH ARTICLE

Design and evaluation of an active vineyard heating system to simulate temperature increase in the context of climate change

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ABSTRACT

The current study introduces an innovative direct and active heating system designed for precise temperature control in vineyards. This system serves as a valuable tool for investigating the influence of climate change on grapevine physiology and, consequently, the characteristics of the resulting wine. The research took place in an experimental vineyard located in Mendoza, Argentina, with *V. vinifera* cvs. trained to a vertical shoot positioning trellis system over two consecutive growing seasons. The system design utilized electric hot water tanks and polypropylene pipes attached to the foliage catch wires. Over two growing seasons, the system consistently elevated the ambient air temperatures within the canopy by 2.5 ± 0.12 °C compared to the control group. This temperature increase emulated the temperature projections for Mendoza as forecasted by the IPCC by the end of this century. The system displayed heating uniformity, as evidenced by the absence of both vertical and horizontal temperature gradients. Additionally, the significant variation in mean daytime and night-time temperatures between the control and heated treatments highlighted the effectiveness of the system in modifying temperature conditions on a diurnal basis. The heated treatment applied with this system proved to have an effective biological impact on the physiology of grapevines. In both seasons, plants under the heated treatment advanced their bud break and harvest dates. The study showed a significant growth enhancement in the heated treatment, with apical shoots extending significantly longer than those in the control treatment. Additionally, the total soluble solids content increased in the heating treatment, while yield decreased, for both experimental seasons. These results illustrate the robust performance of the system throughout the entire growth period, regardless of fluctuations in atmospheric conditions. This study establishes a new foundation for future research on grapevine responses to climate change. It also opens the door to the implementation of effective adaptation strategies in vineyards, promising a more resilient and adaptable future for grape cultivation.

KEYWORDS: Viticulture, climate change, heating system, temperature increase, Vitis, grapevine physiology

INTRODUCTION

The human-caused climate change, acknowledged by most scientists (Cook *et al*., 2013; Cook *et al*., 2016), imperils societies and ecosystems worldwide. Addressing this problem is often regarded as the most significant economic and environmental challenge of our era (Hornsey and Fielding, 2020). Nevertheless, time is rapidly dwindling to find effective solutions. Temperature increase is a crucial aspect of climate change, impacting virtually all biological processes. Naturally, this has far-reaching implications for agriculture, which is a highly climate-dependent activity. In the case of viticulture, this global phenomenon is affecting productivity and quality at substantial rates (Neethling *et al*., 2019). One of the primary effects is the compression of grapevine phenology, leading to an earlier harvest. This advancement in grape maturity results in accelerated sugar accumulation and malic acid breakdown, ultimately resulting in grapes with reduced acidity (Pastore *et al*., 2022). Consequently, there is a higher likelihood of decoupling technological, phenolic, and aromatic maturity in vineyards (Sadras *et al*., 2012; Merli *et al*., 2016). Furthermore, the temperature rise leading to earlier bud break increases the risk of late frost damage, which is one of the most destructive phenomena in vineyards. This is because early plant growth after warm periods leaves plants vulnerable to subsequent cold events (Gu *et al*., 2008). Climate change also poses a threat to various interacting players in agroecosystems, significantly impacting grape yield and quality. For instance, pests, diseases, and weeds may proliferate under changing climatic conditions, as observed in studies by Bosso *et al*. (2016); Castex *et al*. (2023) and Jabran *et al*. (2020). Conversely, beneficial organisms such as certain fungi and bacteria, which play a positive role in vineyard ecosystems, are also affected by these changes, as demonstrated by Compant *et al*. (2010) and Torres *et al*. (2018). Moreover, climate change can influence regional viticultural zoning, affecting the suitability of specific areas for grape cultivation (Hall and Jones, 2009; Cabré *et al*., 2016). Hence, since the return on investment of the viticulture industry relies on yield and quality, studying the impact of temperature increases on these parameters has become a relevant topic (van Leeuwen and Darriet, 2016).

This concern has been addressed with different approaches. The theoretical ones include modelling simulations such as Cabré *et al*. (2016); Wolfe *et al*. (2008); Ortega-Farias and Riveros-Burgos (2019); Cabré and Nuñez (2020) and Leolini *et al*. (2020), among others. Other studies have addressed the issue with greenhouses practical experiments (e.g. Tissue and Oechel, 1987; Oechel *et al*., 1992; Yamane *et al*., 2006; Salazar Parra *et al*., 2010; Morales *et al*., 2014; Martínez-Lüscher *et al*., 2015; Kizildeniz *et al*., 2015; Galat Giorgi *et al.*, 2019, among others). Finally, the subject has also been studied *in vitro* (e.g. Azuma *et al*., 2012; Deis *et al*., 2012) and field experiments such as those conducted by Tarara *et al*., (2020); Sadras *et al*. (2012); Baby *et al*. (2014); Sweetman *et al*. (2014); Bonada *et al*. (2015); Koshita *et al*. (2015); de Rosas *et al*. (2017) and Bonada *et al*. (2018), among others. The methodology used to study the effects of temperature increase on grapevines can be broadly categorized as either direct or indirect. According to Bonada and Sadras (2015), indirect methods involve comparisons of seasons and locations with varying thermal conditions (e.g. Jones and Davis, 2000; van Leeuwen and Seguin, 2006; Jones and Goodrich, 2008; Zarrouk *et al*., 2012; Fraga *et al*., 2015; Malovini *et al*., 2019). However, while this approach is valuable, the impact of temperature is often confounded with other factors such as solar radiation, vapour pressure deficit, rainfall, management practices, and soil characteristics. On the other hand, direct methods involve experimental manipulations of temperature within greenhouses, growth chambers, or in field settings. These methods can establish cause-and-effect relationships, but they may also generate secondary effects (Bonada and Sadras, 2015). Additionally, these authors also suggest that the artefacts used to induce temperature increases in controlled environments can have implications for plant physiology and the composition of berries. Within direct methods, the passive ones (without external energy input) are known for their cost-effectiveness and simplicity, and prove economical in both initial setup and maintenance. However, their efficacy is constrained by a limited ability to control air conditions accurately, relying greatly on ambient climatic variations. Conversely, active (with external energy input) air heating methods offer a more sophisticated approach, allowing for more precise control over factors such as temperature and humidity. This adaptability makes them well-suited to address specific climatic conditions and accommodate the unique needs of the vineyard. However, these methods are more expensive, both in terms of initial setup and ongoing operational costs. Ultimately, the choice between different methods is based on considerations such as budget, the topography of the vineyard, local climatic conditions, and the specific goals of vineyard research or practice.

In Argentina, Cuyo region (28°–35° south latitude) stands as the major local wine region, renowned for producing premium red wines. According to a multi-model ensemble forced under the SSP2-4.5 scenario, the mean temperature over this region is projected to increase by between 1.5 °C to 2.5 °C by the end of this century (IPCC, 2022). Such projection highlights the importance of finding adaptation strategies to ensure the continued production of high-quality wines while preserving their typicity associated with their origin in a changing climate (van Leeuwen and Darriet, 2016). Given this scenario, it becomes crucial to examine the local effects of temperature increase on grapevines. To achieve accurate results, it is essential to employ realistic direct methods that minimize potential secondary effects on plant physiology. These focused and reliable approaches will facilitate understanding and preparation for the challenges posed by climate change in the viticulture industry. In this paper, we described a methodology to increase the air temperature surrounding the grapevine canopy to mimic one of the climate change effects. Our approach involved creating a controlled temperature rise, well within the range predicted by the SSP2-4.5 scenario, which successfully elicited a plant physiological response. The method involved the circulation of hot water through a serpentine-like structure composed of polypropylene tubes attached to the vineyard structure. This system represents the first open, direct, and active heating technique designed specifically for a field trial in this area, with the potential for adaptation in other regions as well. The presented heating design serves as a foundation for conducting more complex and realistic experiments involving temperature increases on grapevine physiology and the resulting wines.

MATERIALS AND METHODS

1. Vineyard and location

The trial was conducted during the 2019–2020 and 2020–2021 seasons in a teaching-experimental field of Cátedra de Fisiología Vegetal, Facultad de Ciencias Agrarias, Universidad Nacional de Cuyo (–33.00661833267618, –68.87290612494968) in Mendoza Province, Argentina. The experiment was set up in a 12-year-old vineyard with three different own-rooted *V. vinifera* L. cvs. (Bonarda, Malbec, and Syrah), trained to bilateral cordons (2.2 m × 1.2 m) and vertical shoot positioning trellis system (VSP). This vineyard is placed on an Entisol (unstructured soils) with loamy-clay texture (about 1 m depth), vines are hail protected (Grembiule system) and drip irrigated (2.2 mm h^{-1}). Plants were pruned in May and no trimming was applied after bud break. Each treatment was applied across three rows in the vineyard, with each row containing eight plants. In the experimental vineyard, varieties were deliberately not planted consecutively. The first and last plants in a raw were left as buffer plants, ensuring two plants of the same variety per row. As the purpose of this study is to demonstrate the efficacy of the introduced heating system, we only present data for the Bonarda cultivar. The data for the remaining cultivars, along with additional physiological, phenological, and berry and wine quality variables, will be addressed in subsequent works.

2. System performance

Pictures illustrating different stages of the heating system in the vineyard are presented in Figure 1. The installation consisted of three electric hot water tanks (Ecotermo Elec 125 model; 220 V; 9 A; 3000 W; 125 L) inside a shed. These tanks delivered piped hot water (60 ± 1 °C) at an estimated speed of 9.2 m/s to the vineyard canopies, which then returned to the

FIGURE 1. Vineyard heating system. A) Installation stage. Buried polypropylene thermofusion pipes at 0.3 m depth in the front. A heated row (right) next to a control row (left). B) Spring time, shortly after bud break. C) Shoots about 20 cm long. D) Pea size berries. E) Vineyard installation with the shed in the back of the picture.

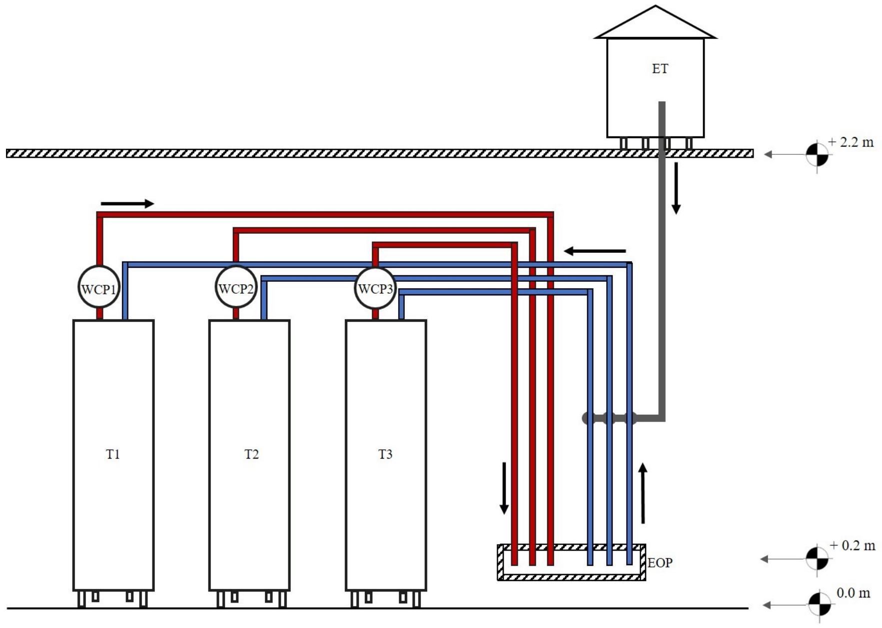


FIGURE 2. Heating system inside the shead (front view). T1-3: Electric hot water tanks; WCP: Water circulator pumps; ET: Expansion tank; EOP: External outlet. Red lines represent pipes circulating hot water from tanks to the vineyard. Blue lines represent pipes transporting cooler water from the vineyard back into the tanks. Grey lines represent pipes which would eventually compensate for pressure loss. Black arrows indicate water flux direction.

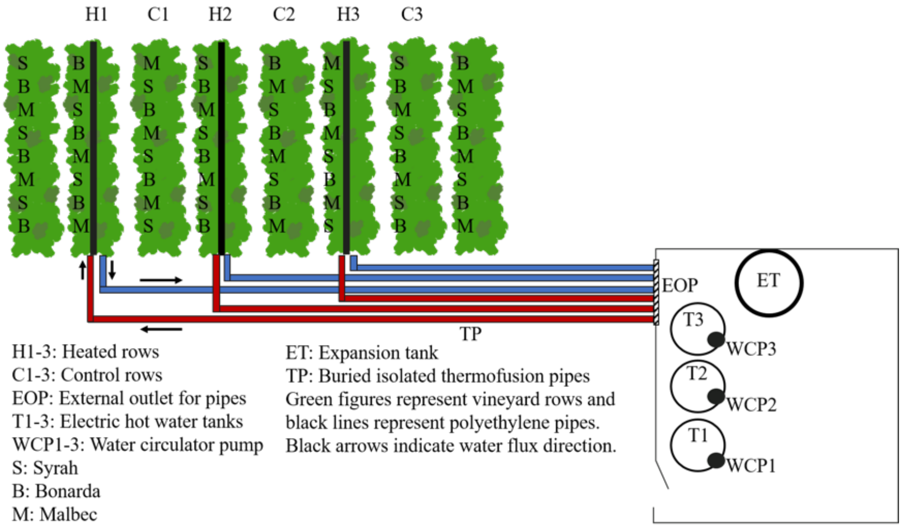


FIGURE 3. Heating system scheme aerial view.

tanks in a closed circuit. In detail, each tank was connected to a circulation pump (Grundfos UPS 15-60 model; 230 V; 100 W; Max: 0.3 MPa; 3 m^3 h^{-1} flow rate), which forced water to run through the pipes. In this way, the hot water was pumped from the tanks to the vineyard and back to the tanks to be recirculated (Figure 2). Another tank, located on the shed roof, served as an expansion tank. Thermally isolated polypropylene thermofusion pipes (3/4 inches; TF) carried hot water from the tanks, exiting the shed through a wall outlet. Once out, they were immediately buried at a depth of 0.3 m (Figure 1A and Figure 3). After distances of 6, 12 and 18 m below the ground (measured from the shed to the rows), they surfaced at the beginning of each of the three heated rows. They were then connected to a flexible polyethylene pipe (3/4 inch; 19 mm internal diameter; PE) using a PVC fitting. Subsequently, the PEs were secured to the VSP structure using metal wire (Figure 1B and Figure 4). In this manner, the PE pipes formed a serpentine-like structure running from one plot end to the other. This assembly was composed of ten PE coils, each separated by 0.15 m, resulting in a total length of 97.35 linear meters. Finally, at the end of the pathway (located at the beginning of the plot, near the canopy top),

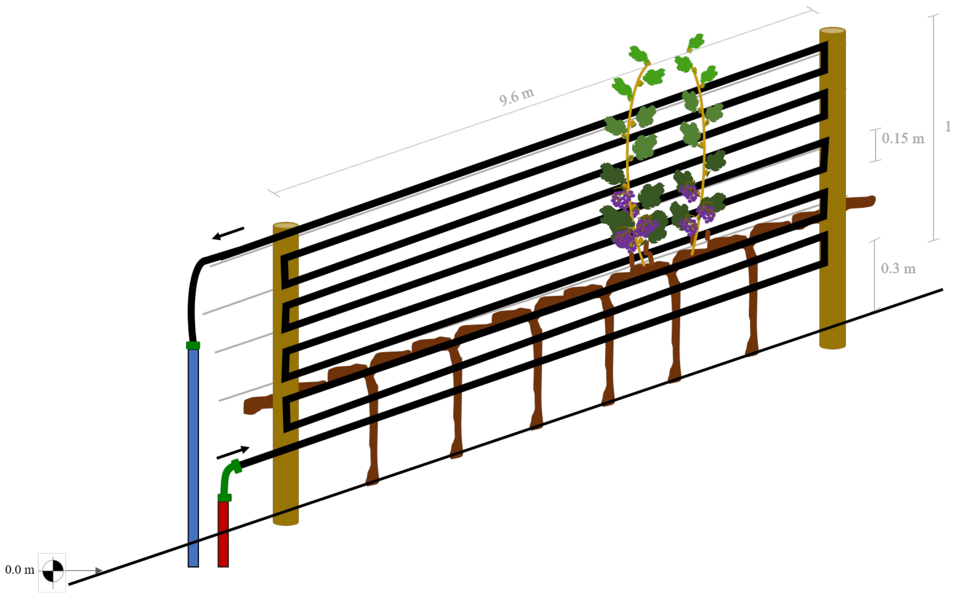


FIGURE 4. Scheme of thermofusion (TF) and polyethylene pipes (PE) in heated rows. Red line represents TF pipe transporting hot water from the tanks to the vineyard; blue line represents TF pipe carrying water from the vineyard into the tanks; black lines represent PE capable of radiating energy to the vineyard. Black arrows indicate the direction of water flow. PCV fittings connecting TF and PE pipes are denoted in green. Gray lines are VSP structural wires.

the PE pipes were connected (with a PVC fitting) to another TF pipe (which was immediately buried) to facilitate the return of water to the tanks (Figure 1A and Figure 4). Hot water from the tanks entered the start of the "PE serpentine" at a height of 0.3 m. As the hot water circulates within the canopy, the released energy raises the temperature of the surrounding air. Finally, this water flowed back from the end of the "PE serpentine" (at 1.65 m height) to the TF pipes, and then back to the water tanks, reinitiating the cycle.

3. Temperature analyses

Data logger sensors (iButton 1 Wire® Thermochron® Maxim Integrated USA; precision 0.5 °C) were installed within the canopy. They were positioned in the middle section of each row at distances of 0.6, 0.9, and 1.2 m from the soil surface. Sensors were protected from direct sun exposure with shelters consisting of a half-litre plastic bottle cut one-third from the top and painted with opaque white to reduce solar heat absorption. It includes ventilation holes for airflow, effectively shielding the iButton sensor from direct sunlight. Temperature readings were recorded hourly and the data from the different heights were averaged within each row. The mean daily temperature was calculated as the average temperature over a 24-hour period, while the monthly temperature was computed as the average of all the recordings within a given month. The system's capacity to elevate air temperature was assessed by comparing the mean daily and monthly temperatures recorded in the heated rows (heated treatment) with those in the non-heated (control treatment). Heating treatments were applied from August to the end of March. Calculations were conducted using data collected from October to March during the growing seasons of 2019–2020 and 2020–2021, with the initial two months excluded due to logistical constraints.

Given the potential heat loss as water moved through PEs, the possible existence of a horizontal and a vertical temperature gradient was calculated. For this purpose, sensors were installed in March 2020 on the second to last plant from each row's extreme (designated as north and south) at heights of 1 and 1.5 m. The horizontal gradient was calculated through a mean difference test applied to the mean daily temperature of the northern and southern extremes over the entire measurement period. The vertical gradient was computed as the mean daily temperature difference across the different heights also over the entire measurement period. To evaluate the heating efficacy throughout the day and night, the mean daytime temperature was calculated as the average of the recordings from 8 AM to 8 PM. Additionally, the mean night-time temperature was calculated by averaging recorded data from 8:01 PM to 7:59 AM in March 2020. Mean hourly temperatures for the same month were also determined to serve as a representation for any other given month. Environmental data used to characterize the experimental seasons was obtained from the Sistema Meteorológico Nacional (https://www.smn.gob.ar/).

4. Grapevine physiological response

To demonstrate the biological impact of the system's temperature increase on the vineyard, the cumulative shoot apical growth was evaluated from bud break until reaching constant length. This assessment was conducted with two apical shoots per plant positioned in the centre of each cordon. Yield was calculated as the mean weight of all bunches per plant (kg plant^{-1}). For total soluble solids (° Brix) measurements, two berries each from the upper, middle, and bottom parts of the bunch were collected from 20 bunches (10 facing east and 10 facing west) per plant. Afterwards, berries were crushed, and total soluble solids were measured using a refractometer (ATAGO Master Refractometer). Phenological stages were recorded according to Eichhorn and Lorenz (1977) with Coombe (1995) modifications.

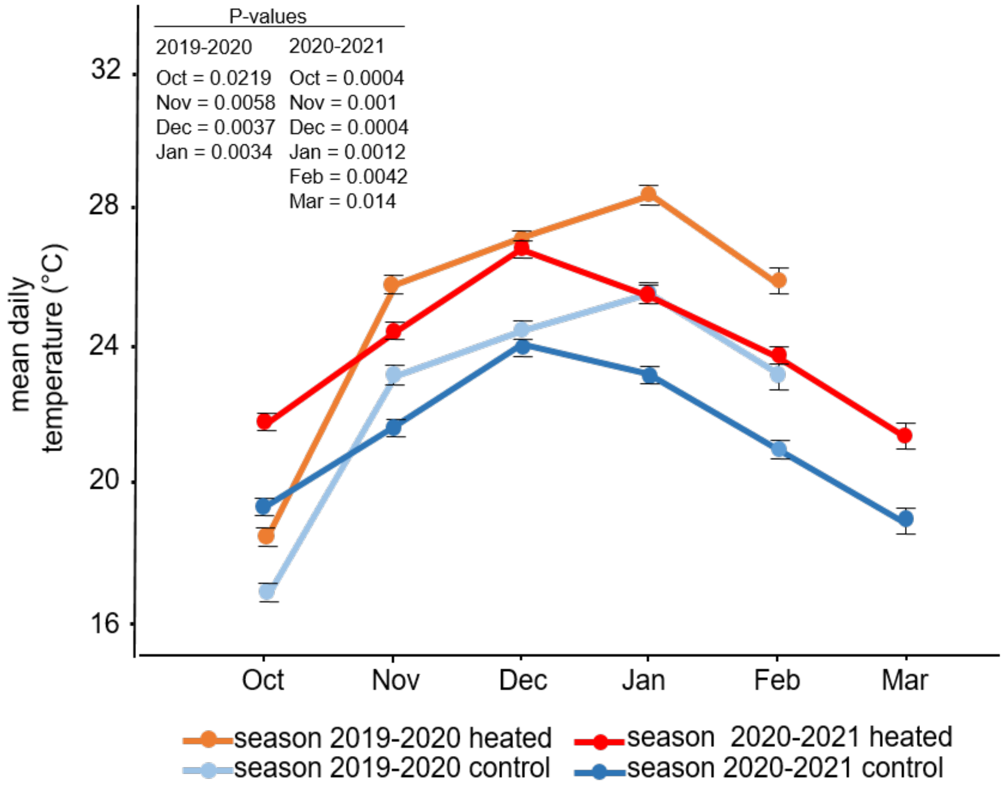
5. Statistical analyses

Temperature-related analyses were calculated with the non-parametric Kruskal–Wallis test and one-way ANOVA. After checking the statistical assumptions, cumulative shoot apical growth, yield, and dissolved solids were assessed using one-way ANOVA and blocking by hot water tanks to account for any non-detected temperature difference. All analyses were performed using InfoStat v. 2020 (Di Rienzo *et al*., 2020). Only significant results are shown.

RESULTS AND DISCUSSION

In general, passive heating methods create a warmer microclimate around grapevines using solar heat. However, their effectiveness is weather-dependent, limited to clear days, excludes nights, and sometimes only heats specific grape areas. In contrast, active heating systems offer more precision in simulating environmental temperature increases. They allow controlled experiments for a better understanding of vine responses. With adjustable intensity and duration, capable of heating day and night, at any time of the season, and able to heat the whole plant, these systems identify early responses to thermal stress, physiology, and phenology. This comprehensive approach provides valuable data for decision-making and contributes to climate change research in viticulture.

Testing our active heating system, throughout the two seasons analysed, the heated treatment effectively led to a significant elevation in the overall canopy temperature (Figure 5). When considering the data from both seasons, the average temperature increment was 2.5 ± 0.12 °C, with monthly mean differences ranging from 1.55 °C as the smallest recorded increment to 2.81 °C as the largest. The observed temperature variations between seasons were in line with the typical interannual environmental fluctuations outlined in Table 1. The higher temperatures recorded in the first season, evident in both the control and temperature treatment, can be attributed to the prevailing environmental conditions, characterized by increased radiation, indicative of a warmer season. Additionally, variations in relative humidity and precipitation were noted between seasons. The temperature increase generated by the system has also proven to be independent of radiation. It was able to heat the air whether it was sunny or cloudy. An example is illustrated in Figure 6, where the temperature difference between the heated and



P-values

2019-2020	2020-2021
Oct = 0.0219	Oct = 0.0004
Nov = 0.0058	Nov = 0.001
Dec = 0.0037	Dec = 0.0004
Jan = 0.0034	Jan = 0.0012
	Feb = 0.0042
	Mar = 0.014

FIGURE 5. Mean daily temperature within the canopy over two seasons from October to March. Dots are average values and bars represent the standard error. ANOVA P-values are shown in the upper left. February and March of the 2019-2020 season were not analysed due to missing data from some sensors.

control treatments was maintained, whether radiation was high or lower (on a cloudy day). These findings underscore the system's reliable performance across the entire growing season, irrespective of the prevailing atmospheric conditions. The uniform heating performance of the system was evidenced by the absence of both vertical and horizontal temperature gradients. Figure 7 (left pane) showed similar temperature values for the sensors located at the extremes (north and south) of the rows in both treatments (Heated treatment P-value = 0.329 and Control treatment P-value = 0.735). Similarly, the right pane of the figure displayed comparable temperature values within the canopies at heights of 1 and 1.5 m for both the Heated treatment (P-value = 0.9269) and the Control treatment (P-value = 0.6856). No statistically significant differences were observed among the various sensor installation heights (P-value > 0.05).

A significant difference in mean day temperature was observed between the treatments (control = 25.36 °C and heated = 27.25 °C; P-value = 0.0003). Similarly, this difference was also evident in the mean night-time temperature (control = 16.15 °C and heated = 20.68 °C; P-value = < 0.0001) (Figure 8 *a*). Similar results were found when temperature was plotted hourly (P-values for all hours < 0.05) (Figure 8b). The variation in temperature increment between day and night can be explained by the fact that a radiating body both absorbs and emits radiation. The net heat flux is directly proportional to the temperature difference between the body and its surroundings. Moreover, during the day, atmospheric turbulence causes the mixing of radiation, whereas, at night, the atmosphere becomes stable due to stratification, resulting in a larger temperature difference between the control and heated plots.

In terms of phenology, heated plants in both seasons exhibited an advancement of 16 days in their bud break date and 14 and 13 days in their harvest time in 2020 and 2021, respectively (Table 2). This is most likely a response to enhanced enzymatic activity in the heated treatment. Such a response to temperature increase is common and has been widely reported (e.g. Keller *et al*., 2004; Keller *et al*., 2010; Tomasi *et al*., 2011; Sadras and Moran, 2013). Comparisons of bud-break dates for Bonarda and other cultivars between 2020 and 2023 in various regions of the province of Mendoza, as well as for Syrah fruitset, showed an advancement of 2 to 3 days (IDR, 2023). This could be attributed to the ongoing temperature rise from climate change. We also observed a slight lengthening of the bud break-to-maturity cycle under elevated temperature conditions (with bud break advancing more than maturity), which differs from current climate change trends in Europe, where the growing season tends to shorten and maturity is advancing more than bud break (García de Cortázar-Atauri *et al*., 2017). This is likely due to Mendoza's continental climate, which contrasts with the maritime influence in European viticultural regions. In our area, temperature increases would accelerate bud break, making plants more susceptible to late frosts. The present heating system could serve to test the effectiveness of frost protection methods, such as micro-sprinkler irrigation. Additionally, this shift in bud break due to the simulation of a warm spring could allow for the assessment of frost protection methods in two different phenological stages (heated and control). This evaluation would consider their impact on both vegetative and reproductive aspects. Furthermore, the simulation of a warmer season provided by our heating system could allow testing the implementation of certain

TABLE 1. Environmental data of Chacras de Coria 2019-2020 and 2020-2021.

season	environmental variable	Sep	Oct	Nov	Dec	Jan	Feb	Mar
2019-2020	mean maximum temperature (°C)	21.33	26.22	29.70	31.56	32.62	29.50	32.30
	mean average temperature (°C)	14.4	19.78	21.51	23.69	25.02	21.84	24.35
	mean minimum temperature (°C)	5.6	13.26	14.10	15.04	16.89	14.76	17.03
	mean maximum humidity (%)	63.67	67	77.31	64.41	77.32	84.59	78.91
	mean average humidity (%)	41.89	43.6	50.62	39.55	48.81	58.59	53.36
	mean minimum humidity (%)	22.65	24.8	28.62	22.28	27.84	34.69	30.18
	accumulated precipitation (mm)	0	3.8	15.69	9.71	37.59	64.27	0.00
	accumulated radiation (Wm^{-2})	161805	195786	217069	247659	231986	183861	170909
2020-2021	mean maximum temperature (°C)	18.57	24.30	28.22	31.23	29.77	27.96	26.16
	mean average temperature (°C)	11.29	16.12	22.44	24.96	23.04	22.15	18.68
	mean minimum temperature (°C)	4.73	7.60	16.02	16.33	15.76	14.01	11.99
	mean maximum humidity (%)	64.43	68.39	62.19	58.77	78.43	86.18	88.73
	mean average humidity (%)	44.86	44.19	43.48	36.71	53.20	58.59	67.00
	mean minimum humidity (%)	24.71	25.29	28.86	23.03	32.38	39.95	41.13
	accumulated precipitation (mm)	0.00	0.00	24.82	3.31	54.00	86.66	59.43
	accumulated radiation (Wm^{-2})	157061	186764	211205	243180	221981	155617	167932

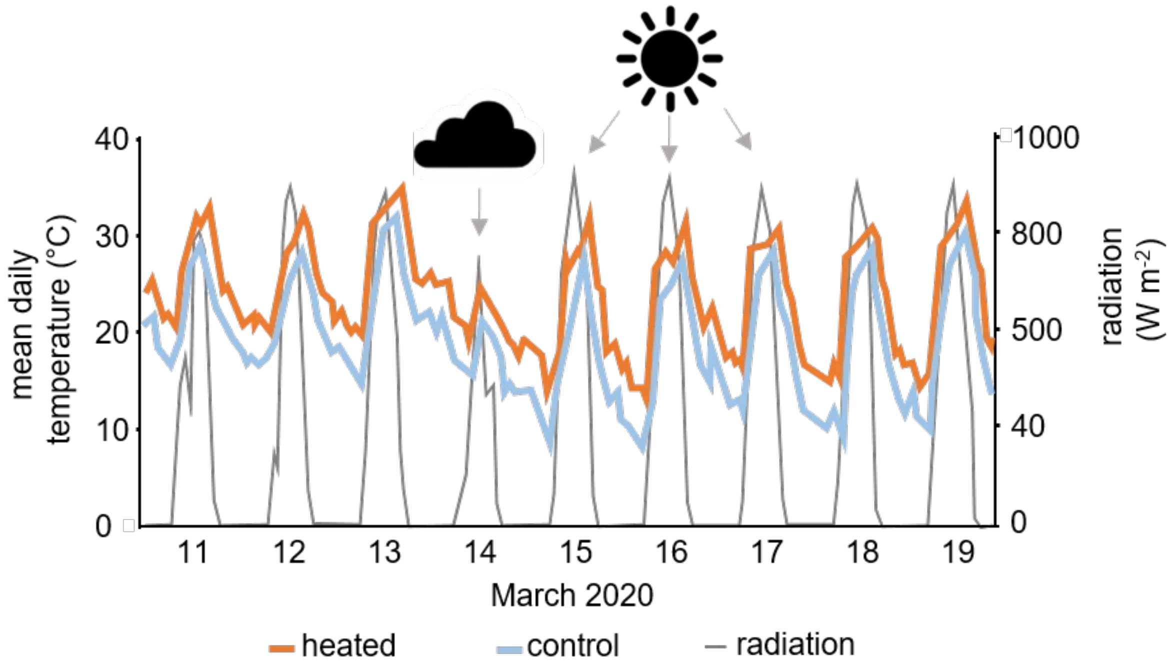


FIGURE 6. Mean daily temperature and radiation for eight consecutive days in March 2020. Lines represent mean values. Arrows indicate a cloudy and some sunny days.

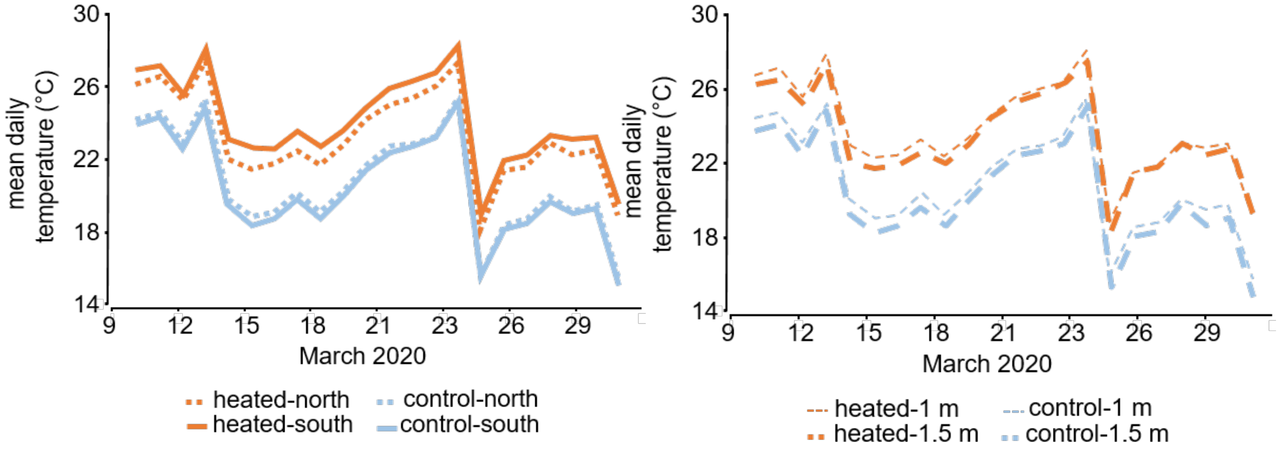


FIGURE 7. Mean daily temperature at the extreme of the rows (left pane) and at different canopy heights (right pane). Lines represent mean values.

cultural practices, such as a late final pruning (Poni *et al.*, 2022), to shift the maturation into a cooler period of the year.

Grapevine reproductive success varies widely, creating challenges for stable yield and fruit quality (Keller *et al.*, 2010). Poorly understood factors impact effectiveness of viticultural practices, leading to unreliable predictions with economic consequences. The temperature increase in our region adds to the lack of understanding of these crucially unknown factors to enhance grape production reliability. In the first experimental season, the heated treatment reduced yield by 42 %, and in the second season by 40 %, compared to the control situation (Figure 9). This was a reflection of a reduction in fruit set under elevated temperature conditions, which led to a significantly lower number of berries per bunch at harvest (data not shown). These results in a scenario of temperature increase align with forecasts from other studies conducted in different areas (Agosta *et al.*, 2012; Bindi *et al.*, 1996; Lereboullet *et al.*, 2014; Fraga *et al.*, 2016; Fraga *et al.*, 2018; Santos *et al.*, 2023). However, some researchers have reported no effect or increases in yield under elevated temperatures (e.g., Sadras and Soar, 2009; Sadras *et al.*, 2017; Moran *et al.*, 2019). These dissimilarities with our results may be attributed to variations in methodologies or other environmental and cultural factors that were not taken into account. This also underscores the importance of relying on active and more realistic heating system approaches. In terms of total soluble solid content, it significantly

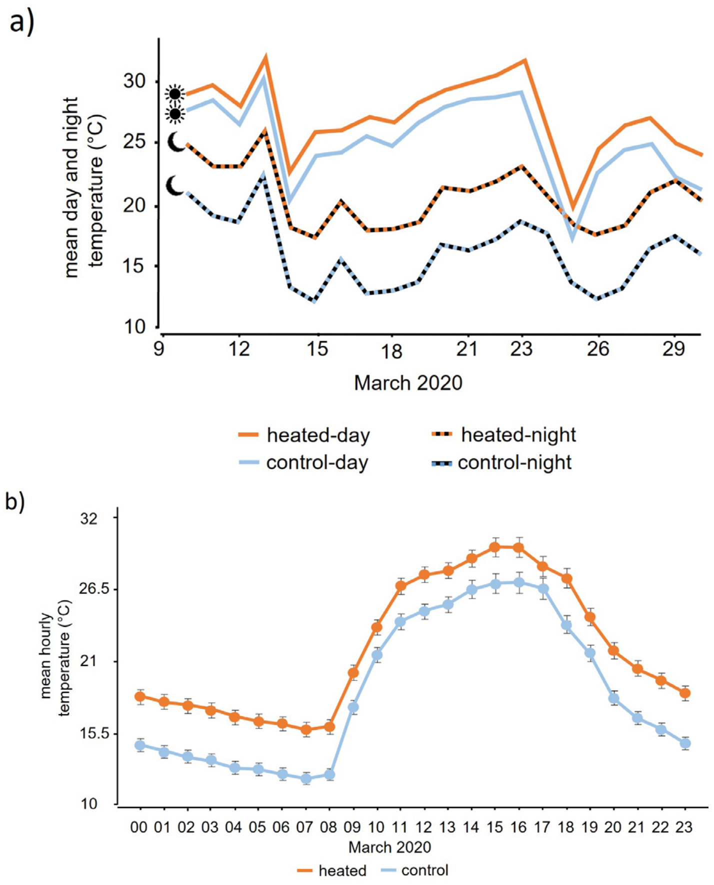


FIGURE 8. Mean hourly and day and night-time temperatures for March 2020. In a)Lines represent mean values. In b) Dots represent meand values and barrs standard errors.

TABLE 2. Bud break and harvest dates of Bonarda cv. for 2019-2020 and 2020-2021 seasons under heated and control treatments.

season	treatment	bud break date	harvest date
2019-2020	control	September the 24th	March the 19th
2019-2020	heated	September the 8th	March the 5th
2020-2021	control	September the 19th	March the 29th
2020-2021	heated	September the 3rd	March the 16th

increased by 9 % and 5 % for the first and second seasons, respectively, with the heated treatment (Figure 9). In seasons with high average temperatures, grapes have shown higher total soluble solids contents (Urhausen *et al.*, 2011; Vršič and Vodovnik, 2012). However, in experiments where ambient temperature was elevated, the effect of this treatment on soluble solids was not consistent across study seasons or among the tested cultivars. Sometimes total soluble solids increased, decreased or remained neutral when temperature was raised (Yamane *et al.*, 2006; Sadras *et al.*, 2013; Greer and Weedon, 2014). Moreover, Greer and Weedon (2014) question whether the grapevine berry ripening phenomenon is a temperature-dependent process. In general, the diverse responses are likely attributed to genetics and environmental conditions, such as the heating method and timing of the treatment. Furthermore, studying the impact of temperature on yield-related variables, such as fruit setting, berry expansion, or pollen viability, would be insightful. Currently, we are evaluating the berry and wine quality of Bonarda, as well as Malbec and Syrah under temperature increase.

By the conclusion of the measurements in both seasons, shoots were 91 % longer under the heated treatment compared to those under the control conditions (Figure 10). This notable disparity in length was the result from substantial growth enhancement observed from September to December. Several other studies have also reported an increase in grapevine

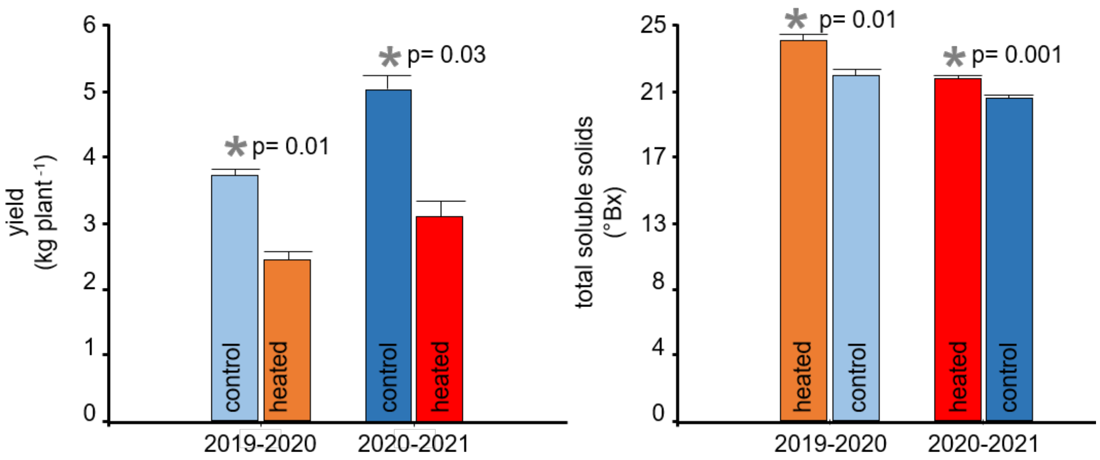


FIGURE 9. Yield (left pane) and dissolved solids content (right pane) under heated and control treatment at harvest in 2020 and 2021. Bars are average values lines represent the standard error. Asterisks represent significant differences calculated using an ANOVA; α < 0.05. Values next to asterisks represent p-values.

shoot length with a temperature increase (e.g. Keller *et al*., 2004; Keller and Tarara, 2010; Kadir *et al*., 2005), which is a normal response to expect since many biological processed involved in growth are temperature enhanced within certain viable thresholds. The elevated temperature likely accelerated key physiological processes, such as cell division and elongation, during this critical growth period. The longer shoots also produced more biomass (data not shown), potentially supplying additional photosynthates and explaining the elevated levels of total soluble solids in the heated treatment.

In conclusion, an innovative approach to enhance temperature through a direct method in vineyards has been developed. Guided by the recommended criteria for such techniques as outlined by (Bonada and Sadras, 2015), the heating system was able to emulate both daily (whether sunny or cloudy, as demonstrated by the different radiation rates in March 2020) and seasonal temperature fluctuations. This technique did not show any significant biological side effects, as the piping are attached to the structure of the vineyard and allow natural exposure of the trunk and canopy to light. Subsequent scrutiny of canopy leaves aimed at identifying potential burnt leaves, especially those located in direct proximity to the flexible polyethylene pipes. However, fewer than 10 burnt leaves were found throughout the entire experiment (i.e, three leaves in control and one leaf in heated treatment in 2019–2020 and two leaves in control and two leaf in heated treatment in 2020–2021 season). This method permits normal cultural practices, such as topping, cluster thinning, pruning, and spraying, among others. It offers an additional benefit as it does not interfere with any irrigation method (furrow or dripping). Therefore, the impact of temperature on grapevine could be conducted in conjunction with irrigation, as water regimens are also affected by climate change. The methodology presented is compatible with different experimental designs, sampling, buffer zones between treatments, and can even replicate heat waves conditions. Furthermore, varying the positioning height of the PEs could facilitate precise temperature elevation within distinct areas of the plants. Another advantage of this heating system is its lack of impact on rainfall distribution. Also, when positioned sufficiently above the soil, the risk of desiccation remains minimal. Furthermore, the combined setup of the aerial piping and the VSP structure establishes a resilient framework capable of withstanding even the most severe local weather conditions, including hail and Zonda wind. We did not measure the impact of wind or rain due to their infrequency in our semi-arid region, where the Zonda wind occurs only occasionally and rain is rare. While it is reasonable to predict that rain could reduce the heating system's efficiency due to increased humidity and potential evaporative cooling, further testing in different climates would be necessary to determine its broader applicability. Finally, this method is compatible with other systems for manipulating the vineyard environment. For instance, it aligns with systems like CO_2 enrichment or the implementation of sprinklers to alleviate heat waves (Wilson *et al*., 2024), an ongoing focus of investigation within our group. Furthermore, the method proves to be cost-effective. The total installation expenses for the entire system, which includes heaters, pumps, pipes, fittings, expansion tank, and metal wires (excluding labour costs), amount to less than 4000 USD. From an environment perspective, this heating system is practically harmless for the vineyards natural flora and fauna. However, we acknowledge the environmental benefits of substituting the hot water tanks utilized in this study with solar water heaters.

In general, both passive and active air heating methods have been proved to be useful in simulating climate change in vineyards. However, the selection of a specific approach will depend on several factors, such as regional climatic conditions, study scale, and the accessibility of resources. It is important to consider the limitations and advantages of each method, as well as possible side effects or impacts on the viticultural ecosystem. According to our current

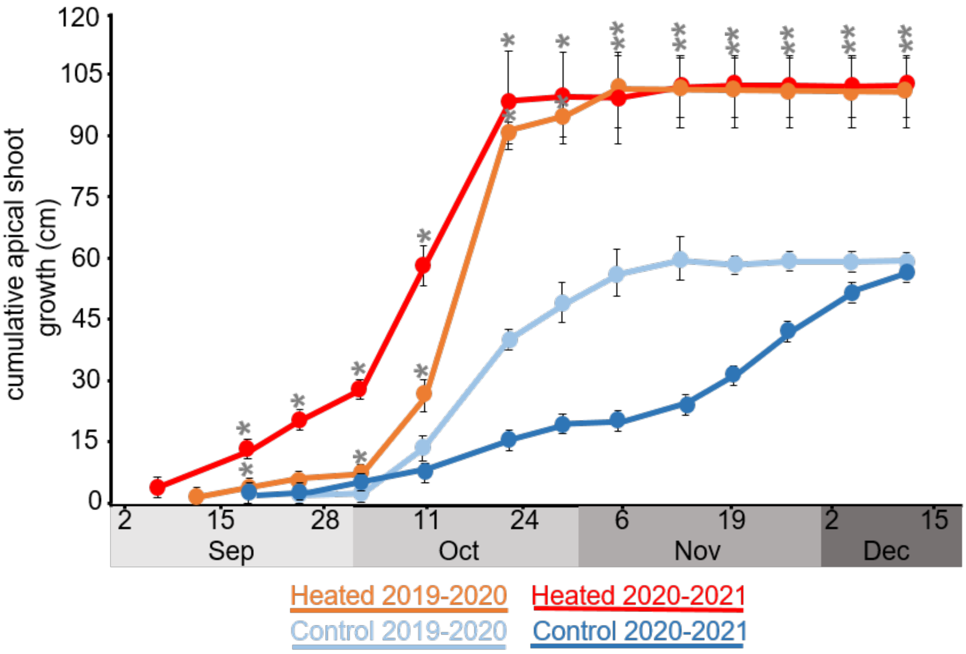


FIGURE 10. Cumulative apical shoot growth (cm) under heated and control treatments, from bud break to constant length, in 2019-2020 and 2020-2021 seasons. Dots are average values of cumulative shoot growth and bars represent the standard error. Asterisks represent significant differences calculated using an ANOVA; $\alpha < 0.05$.

understanding, this design represents the first active and direct method for realistically modifying field temperatures in our region. It provides a robust foundation for studying the intricate and dynamic interactions between temperature and other environmental factors within our vineyards. This study marks a valuable contribution to the collaborative efforts aimed at discovering mitigating solutions for the challenges posed by current and future climate change. As we move forward, this methodology will enable the exploration of multifaceted interactions within grapevine ecosystems, contributing to a more profound comprehension of the impacts of climate change and the formulation of effective adaptation strategies.

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