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Climate change simulation: first season investigation of climate warming impacts on Marlborough Sauvignon blanc

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Executive summary

Climate change simulation: first season investigation of climate warming impacts on Marlborough Sauvignon blanc

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In 2022–23, a first season trial on Sauvignon blanc using replicated passive temperature elevation frames (PTEFs) to increase bunch-zone and canopy temperatures above ambient to simulate future climate change warming, was successfully deployed in a commercial Marlborough vineyard from just prior to budburst to véraison. Across the 4 months and replicated plots (n=4), PTEFs significantly increased average temperature in developing bunch-zones and canopies by 2.4°C compared with ambient season control vines, equating to a future predicted climate change warming for Marlborough circa 2100.

Within 8 weeks, we observed significant shifts in the timing of key phenological events in elevated temperature (PTEF) vines, with the dates of 50% flowering, 50% véraison and harvest (at industry standard target 21.5 °Brix for Sauvignon blanc) being, respectively, 14 days, approximately 2 weeks and 14 days earlier compared with ambient season temperature (control) vines.

Physiologically, we observed significantly earlier shoot growth, indicative earlier season nutrient demand (darker green canopies), and a significant 16% increase in fruit set in elevated temperature (PTEF) compared with ambient temperature (control) vines. Despite good fruit set and 4.8% greater average bunch number per vine in elevated temperature (PTEF) vines, this was offset by a significantly lower average bunch weight, so that there was no significant difference in yield between ambient and elevated temperature treatments.

With PTEFs removed at véraison (part of intended experimental design), berries of both treatments proceeded to mature ‘naturally’ at the same vineyard site under ambient summer/autumn 2023 seasonal temperatures and weather conditions, albeit significantly, several weeks apart. Given the different timings of maturation within the season, we observed significant advances in the accumulation of berry total soluble solids (TSS), significant increase in acidity (pH), and significant decrease in titratable acidity (TA; 1.94 g/L) in vines that had been exposed to elevated temperature (PTEF) treatment up to véraison, compared with ambient (control) vines.

Overall, most significant was the observation that even when harvested at the same target TSS content (but different dates), elevated temperature treated berries had an average TA 1.94 g/L lower than ambient grown berries and higher acidity (pH). Given the importance of the balance between sugars and acidity to any wine, but particularly acidity to the ‘crisp’ Marlborough style of Sauvignon blanc, this is an important observation that merits further investigation and exploration of adaptation solutions, be they vineyard or winery based, or both. An additional important observation was the 16% increase in fruit set (and potential yield) and interaction with temperature, which contributes valuable information to modelling towards the industry ‘holy grail’ of accurate annual yield prediction.

Drone image (looking North) of the single row replicated Climate Change Simulation trial located at the Marlborough Research Centre (MRC) Rowley Research vineyard during season 2022–23. Shown is the arrangement of elevated temperature (PTEF) treatment plots, with ambient temperature control plots interspersed. For scale, the length of plots (one complete PTEF system) was 7.2 m. Image taken on 9 November 2022 and courtesy of Dr Stewart Field, Nelson Marlborough Institute of Technology (NMIT).

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1 Introduction

Successful wine-grape production is highly dependent upon regional climate and weather conditions during each growing season, with grape berry (and subsequent wine quality) composition being particularly sensitive to temperature during development and ripening phases. To varying degrees, anthropogenic-driven climate change manifested as increasing global temperatures, may affect grapevine phenology by advancing budburst, flowering, and accelerating berry development. For example, climate change simulations using a model for the developmental stages of Riesling and Gewurztraminer in Alsace, predict an earlier onset of véraison by up to 23 days by the end of the 21st century, with a mean temperature increase of 7°C during the 35 days post-véraison period (Duchene et al. 2010).

For grape and wine quality, one early indicated impact of temperature relates to grape berry acidity, as higher temperatures (and especially warmer nights) decrease the concentration of organic acids (malic in particular), desynchronising sugar and organic acid metabolism (Rienth et al. 2016) prior to harvest. This is a particular concern for cool-climate grown Marlborough Sauvignon blanc given the significant contribution that acidity naturally present in berries makes to the wine style and consumer expectation. Indeed, anecdotal reports by Marlborough winemakers from vintage 2019 as an example, reported Sauvignon blanc wines from some sub-regions having become increasingly 'Riesling' like (less acidity, more neutral aromas and increasing stone fruit characters), following a particularly warm and dry growing season.

To further investigate, quantify previously modelled climate change impacts and begin to develop adaptation timeframes with more certainty for the Marlborough region, a small pilot study was established on vines of the white grape variety Albariño in the 2021–22 growing season. The key aims of this work were to 1) design, construct and test the efficacy of an in situ and 'real world' vineyard-deployed passive temperature elevation frame (PTEF) system for simulating warmer growing conditions, and 2), make preliminary observations of the effects of any warming on vine phenology and harvest date. Data from temperature sensors located in the developing bunch zone demonstrated that the single pilot system (i.e. not replicated) successfully elevated temperature by an average of 1.4°C during a 4-month trial period, confirming efficacy of the design and approach. Further, we observed (within 7 weeks from deployment) a clear advance in phenology and time to 50% flowering in a warmed canopy compared with ambient control, and likewise advances in time to 50% véraison, to the start of total soluble solids accumulation and to eventual date of harvest (reported in more detail in Theobald et al. 2022).

We now report here on the impacts of simulated climate warming in a commercially managed Marlborough vineyard, on the phenology and grape and wine quality from a replicated (multiple plots and PTEF systems) trial on Sauvignon blanc vines over several months from budburst to véraison during the 2022–23 season. In addition to scaled-up experimental replication and focus on the industry flagship varietal 'Marlborough Sauvignon blanc', other key aims in response to an average 1–2°C warming, were to quantify and gain knowledge of impacts on any time shifts in key phenological events, differences in measured vine physiology, rates of berry maturation, yield parameters, and impacts on standard juice and wine chemistry.

2 Materials and methods

2.1 Study site

The study site was located towards the south-western corner (41°29’29.39”S, 173°57’9.65”E) of the Marlborough Research Centre (MRC) Rowley Research Vineyard just north of Blenheim, at an elevation of 7 m. The soil type is classified as a Selwyn *f* deep silt (former classification Wairau) and characterised as a recent well-drained stoneless deep silty loam of alluvial origin derived from parent hard-sandstone, and with a weakly expressed B horizon containing less than 3% gravel and which provides a rooting depth beyond 1m (https://smartmaps.marlborough.govt.nz/smapviewer/?map=eeeff21e2a664dbeba7e07d5b177d593).

A single row of Sauvignon blanc, of clone Mass Selection (MS) on Riparia Gloire rootstock was chosen for the trial. Vines had been planted in 2008 in a north–south row orientation, with 1.8 m between vines and 2.8 m between rows and were trained using a vertical shoot position system with lower and upper fruiting wires, respectively, at 0.90 and 1.05 m above ground level. Due to the necessity to have experimental infrastructure extending beyond the canopy into the mid-row (see Section 2.2 and Figure 1 below), unlike the remainder of the vineyard block, it was not possible for commercial contractors to make tractor passes to manage the row for the season. Thus, routine spraying of the single row to control pests and diseases was done manually by staff from The New Zealand Institute for Plant and Food Research Limited (PFR) using a hand-pumped knapsack sprayer (Solo 475, Germany), following the same seasonal spray programme applied to remaining vineyard rows by the commercial contractor. Likewise, trimming and leaf plucking was done manually as required during the growing season. Vines were drip irrigated as required following commercial management requirements for the rest of the vineyard block. The inter-row was a mix of planted grasses and weed species, and was petrol mowed periodically as required through the season. Vines were netted against bird damage from the onset of véraison to harvest.

The vineyard is accredited under the official New Zealand Sustainable Winegrowing Programme (https://www.nzwine.com/en/sustainability/swnz).

2.2 Passive temperature elevation frame (PTEF) system

Passive temperature elevation frames (PTEFs) designed for the in situ passive warming of bunch zone and canopy throughout the growing season (Figure 1 below), were based on the original concept and design of Sadras and Soar (2009), but with local modification and successful testing of a prototype in the previous 2021–22 season (Theobald et al. 2022).

Triangular (in cross-section) PTEF sub-frames with a base footprint measuring 1.4 m by 2.4 m were constructed from 32-mm alloy angle (Cuddons, Marlborough, New Zealand) bolted together, and with an approximate 45° angled clear corrugated polycarbonate roof 1.5 m by 2.4 m (Ampelite Solasafe, Mitre 10, New Zealand) to passively capture and maximise incoming radiation. With the locally modified dimensions, three sub-frames placed end to end on either side of a grapevine row were sufficient to span a typical vineyard bay or post to post plot length of 7.2 m, suiting the vine row spacing at the Rowley Research Vineyard. Further, with the apex of PTEFs at 1 m from ground level adjacent to typical fruiting wire height, there is minimal direct modification of the fruit-zone or canopy environment. Instead, a horizontally adjustable 300–400 mm apex gap between facing PTEFs (either

side of the row/canopy), allows passively warmed air from within PTEFs to funnel upwards out and vertically through the developing bunch-zone and canopy, thereby generating an elevated (warmer than ambient) air temperature/future climate warming treatment. A total of 24 sub-frames to cover four vineyard bays were constructed for the 2022–23 season.

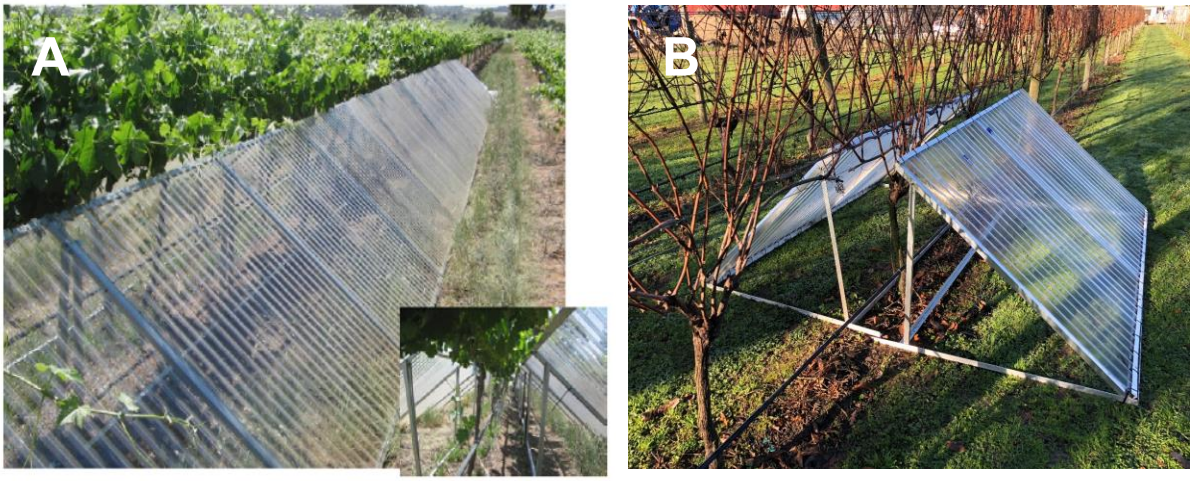

Figure 1**.** Passive temperature elevation frame (PTEF) systems for simulating warmer growing season temperatures; (A) image taken from Sadras and Soar (2009), (B) two locally developed frame sub-units forming part of the PTEF prototype deployed in the Nelson Marlborough Institute of Technology research vineyard during season 2021–22.

2.3 Research treatments

Vines were pruned by a commercial pruning gang the previous winter to a potential of four bi-lateral canes and laid down to fill fruiting wires.

Given the additional logistical needs to manually manage seasonal vineyard tasks within the experimental trial, a short single row of 14 vineyard bays (a vineyard bay typically containing four to six vines between a trellis post at each end) was selected, which was sufficient to accommodate four replicate bays (experimental plots) for each of ambient (control) and elevated temperature (PTEF) treatments, and which were randomly allocated along the row, avoiding three bays containing either single missing or diseased vines (Figure 2 below). The experimental row had buffer rows (remainder of the commercial block) either side, and buffer bays on the row ends. Each experimental plot (spanning one vineyard bay) consisted of four individual vines, with the two middle vines assigned for detailed measurement and assessment, and two outer vines allocated as plot buffers. The exception to this was at harvest when to have sufficient fruit parcel sizes for winemaking, as well as the two middle vines, fruit from the inner halves of the two outer buffer vines was also taken (i.e. fruit from a total equivalent of three vines spanning ‘trunk to trunk’ within the plot).

The PTEFs were deployed to their respective plot positions in the experimental trial row on 27 September 2022, a few days prior to the commencement of budburst. To provide protection from strong spring and summer winds characteristic of Marlborough, PTEFs were held in position using 300-mm plastic tent pegs, ratchet tie down straps (Bunnings, New Zealand) and cable ties. To retain passive heat, open triangular ends of the PTEFs were closed in with clear polycarbonate sheeting cut to fit (Coreflute, Mitre 10, New Zealand). The PTEFs remained in situ until early February 2023 (just prior to véraison), but for periodic removal approximately every 10 days for a few hours on each

occasion, to permit closer canopy access for assessments and management tasks including spraying, leaf plucking and mowing. To help protect against potential frost damage, on the afternoons of 6 and 7 October 2022, lengths of frost cloth (Mitre 10, Blenheim, New Zealand) were carefully draped and deployed over emerging buds along both control and treatment plots and held in place using bulldog clips.

Figure 2. Aerial drone image (looking North) of the single row replicated trial located at the Marlborough Research Centre (MRC) Rowley Research vineyard, showing the arrangement of elevated temperature (PTEF) treatment plots, with ambient temperature control plots interspersed between. For scale, the length of plots (one complete PTEF system) was 7.2 m. Image taken on 9 November 2022 and courtesy of Dr Stewart Field, Nelson Marlborough Institute of Technology (NMIT).

2.4 Vine measurements

2.4.1 Canopy sensors

On 27 September 2022, dual function temperature and humidity sensors (Lascar EL-USB-2, RS Components, New Zealand) set to record and log every 10 minutes, were placed in the middle of each plot (between the two assessment vines) and positioned vertically between the upper and lower fruiting wires of the prospective bunch zone. Each sensor was housed in its own white plastic solar radiation shield (Stevenson screen). Sensors were checked and downloaded approximately bi-monthly through the season.

2.4.2 Bud burst assessment

From 3 October 2022 the percentage bud burst was determined approximately every 4 days on five occasions (dates). All upper and lower canes on each of the two middle vines in each plot were assessed. On each occasion, each node bud (approximately 12 per cane) was given a growth development score based on the BBCH (Biologische Bundesanstalt, Bundessortenamt und CHemische Industrie) scale. For any given bud, successful budburst was characterised to have been achieved when visually assigned a BBCH score ≥9. The proportion of nodes/buds on the same cane with a BBCH score ≥9 gave the percentage budburst for that cane on a given date.

2.4.3 Flowering and fruit set assessment

Visual assessments for the percentage flowering (percentage of open flowers/fallen caps on individual inflorescences) were made approximately twice weekly from the onset of flowering in mid-November, until completion across all treatments towards the end of the third week of December 2022. Each basal inflorescence (where present) on a target of 12 shoots per cane was assessed, with one upper and one lower cane selected on each of the two central vines of each plot. On six (approximately alternate) shoots of each selected cane, in situ basal inflorescences were carefully enclosed within a small (70 x 90 mm) fine white mesh gift bag with drawstring for the capture and collection of caps as they fell during the flowering period. After flowering and fruit-set was complete (approximately 3–4 weeks post-flowering), mesh bags were carefully removed from each inflorescence. The total number of fallen caps collected in each mesh bag was determined using a computer vision cap counting approach developed and validated (against a sub-set of manually counted cap samples) by Sue Neal and Daniel Bentall (PFR Marlborough and Lincoln, respectively). Just prior to harvest, inflorescences/bunches which had been assessed were removed and the number of berries counted. The percentage fruit-set was then determined as the proportion of counted caps (flowers) which had eventuated to a successfully fertilised and developed berry (number of set berries/total number of caps x 100).

2.4.4 Shoot length measurement

From 21 November 2022 shoot length was measured weekly on five occasions until the canopy was first trimmed in late December 2022 in concert with commercial practice in the remainder of the vineyard block. Counting proximally, shoots 3, 6, 9, and 12 were tagged on one upper and one lower bilateral cane on each of the two middle vines in each plot and length measured and recorded using a tailor’s flexible measuring tape.

2.4.5 Canopy greenness (Greenseeker)

A handheld GreenSeeker® Crop Sensor (Trimble Agriculture Division, Westminster, USA) was used to non-destructively determine leaf ‘greenness’, an indicator of vegetation growth and green biomass accumulation, based on a Normalised Difference Vegetation Index (NDVI) and determined from vine canopy reflectance at red (650 nm) and near-infrared (770 nm) wavelengths. The sensor was held in a vertical position 1300 mm above ground level and at 600 mm distance from either the west or east facing (alternated on each measurement occasion) canopy panel of vines in each plot. By facing the canopy panel and slowly side-stepping along the mid-row, the mean value from approximately 40 individual readings (automatically logged and averaged by the instrument) were recorded in a single pass that took 20–25 seconds per plot. Measurements occurred on an approximate weekly basis on four occasions from mid-November 2022.

2.4.6 Grape maturity assessment

Grape maturation was assessed approximately weekly from 13 February 2023 on nine occasions by collecting a 30-berry sample (five berries selected from top, middle, and bottom) from each of six randomly selected bunches per treatment vine. The berry samples, which were collected in small plastic zip-lock bags, were counted and weighed (to give an average berry mass), hand-squashed within the bag, and then sieved to recover available juice. Total soluble solids content (°Brix) was determined using a handheld digital refractometer (Atago, Tokyo, Japan). Acidity (pH) and acid concentration (titratable acidity; TA) were determined on a Mettler Toledo (Columbus, Ohio, USA) T70 auto-titrator. Acid concentration was determined using an end-point titration to pH 8.2. Aqueous sodium hydroxide (0.1 M) was used as titrant and TA was expressed as tartaric acid equivalents (g/L) (Iland 2004).

2.4.7 Harvest parameters

Harvest date for the variety Sauvignon blanc was determined to be at a typical Marlborough industry target total soluble solids (TSS) of 21.5 °Brix, the rate of progress to target being tracked taking account of weekly grape maturity assessments and accounting for late season intermittent rainfall and occasional overcast growing conditions in the 2022–23 season. On each harvest date (which was different for the two treatments), fruit from each plot (equivalent to three vines ‘trunk to trunk’) were hand harvested, and bunches counted and weighed. From this fruit parcel per plot, a further 30-berry vineyard sample was taken to confirm that harvest target TSS had been reached.

2.4.8 Fruit processing to pre-fermentation settled juice

Later the same day that fruit parcels arrived at the PFR Research Winery, a 13.0-kg subsample of grapes per plot was crushed and destemmed in an Enoitalia crusher/destemmer (Eno 1S, Italy). A standard sulfur dioxide (SO_2) addition (40 ppm) was added as potassium metabisulfate at crushing to protect the juice from oxidation. A pectinase enzyme, Lallzyme HC (Lallemand, Canada) (rate 2 g/hL) was added to the crushed and destemmed fruit (must), which was then given 1 hour of skin contact time before pressing. Grape must was pressed in a 20-kg hydro press (Marchisio, Italy) under a cover of carbon dioxide (CO_2) dry ice. A pressing regime of 3 minutes at 2 Bar followed by 14 minutes at 4 Bar was applied using an automated timer and water pressure system.

Juice was then cold settled for 24 hours at 6°C and then racked off juice lees. Juice turbidity before fermentation was measured using a 2100Qis portable turbidity meter (Hach, Colorado, USA), and a 50-mL juice sample was collected for compositional analysis (Section 2.4.10 below). A final volume of 5 L of settled juice was then set aside for winemaking for each replicate plot from the vineyard.

2.4.9 Juice compositional analysis

Juice samples taken 24 hours after the cold-soak period commenced were subjected to a range of winemaking analyses. These included, total soluble solids content (TSS), acidity (pH), acid concentration (titratable acidity; TA), primary amino acids (PAA), ammonium, free and total sulfur, sugar concentration (reducing sugars, glucose, and fructose), cations, and organic acids. Total soluble solids content (°Brix), acidity (pH) and acid concentration (titratable acidity; TA) were determined as described in Section 2.4.8 above.

Ammonium and primary amino acid analyses were carried out on the replicates of each treatment to assess the yeast assimilable nitrogen (YAN) requirements of the ferments. Ammonium concentrations were measured by an enzymatic assay monitoring the deprotonation of NADH at 340 nm using the Biosystems Y15 auto-analyser (Barcelona, Spain), in duplicate against a five-point standard curve (R^2>0.98). PAA concentrations were quantified by the NOPA (nitrogen by o-phthaldialdehyde) method with a reducing agent in basic medium generating a chromogen and measured spectrophotometrically. Sample PAA concentrations were quantified using a Biosystems Y15 auto-analyser (Barcelona, Spain), in duplicate against a five-point standard curve (R^2 > 0.98) with a method adapted from the Zoecklein et al. (2013).

Free and total SO_2 were also determined using the Biosystems Y15 auto-analyser (Barcelona, Spain). Free sulfur was quantified by reaction with 4,4'-(4-iminocyclohexa-2,5-dienylidenemethylene) dianiline chromogen (pararosaniline) and formaldehyde in acid medium. In a second reaction, free sulfur was removed by oxidation and remaining substances able to react with chromogen were measured. The difference between the results obtained from the two reactions equalled the free sulfur concentration. Total sulfur was quantified by reaction with 5-5'-ditio-2-nitrobenzoic acid (DTNB) in a basic medium. The cleavage of disulfite bonds of DTNB by sulfite generates 5-mercapto-2-nitrobenzoate that absorbs at 405 nm, with the increase in colouration being proportional to the total sulfur in the sample. These methods were adapted from the Compendium of International Methods of Wine and Must Analysis (2016) and Zoecklein et al. (2013). Results were used for winemaking quality/process control and are not reported.

Reducing sugars (glucose and fructose) were quantified by enzymatic assay based on the reduction of NADP (nicotinamide adenine dinucleotide phosphate). The reaction was monitored at 340 nm using a Biosystems Y15 auto-analyser (Barcelona, Spain). Samples were quantified in duplicate against an eight-point standard curve (R^2>0.98), and using a method adapted from the Compendium of International Methods of Wine and Must Analysis (2016) and Zoecklein et al. (2013). Results were used for winemaking quality/process control and are not reported.

The cations, potassium, magnesium, and calcium were quantified using an Agilent Capillary Electrophoresis instrument (Santa Clara, California, USA) using an aqueous solution of pyridine (10.0 mM), glycolic acid (12.0 mM) and 18-crown-6 (6 mM) (pH 3.5), which was used as a background electrolyte buffer, and all samples were diluted 5-fold in a solution containing lithium chloride as an internal standard and frozen at −80°C. Juice samples were thawed, vortexed to mix, and filtered through a 0.22-µm syringe filter prior to injection. All samples were run in duplicate and quantified on a five-point standard curve (R^2>0.98), using a method adapted from Rovio et al. (2011).

Organic acids, tartaric and malic, were quantified on a Shimadzu Prominence, High Performance Liquid Chromatography (HPLC) (Shimadzu Corporation, Kyoto, Japan) system using a phosphate buffer (25 mM, pH 2.3) on an Allure Organic Acids Restek column (5 µm, 240 x 4.6 mm) at 30°C. All samples were diluted 5-fold in phosphate buffer and filtered through a 0.22-µm syringe filter prior to injection. All samples were run in duplicate and quantified on a six-point standard curve (R^2>0.98), using methods adapted from a published protocol (Shi et al. 2011).

2.4.10 Winemaking protocol

A single juice lot (5 L) derived from each 13 kg grape parcel per vineyard plot/replicate was inoculated with Zymaflore® X5 (Laffort) yeast (rate 250 mg/L) and fermented at 15°C. A standard yeast nutrient, V Active® (Enologica Vason, Italy) addition of 600 mg/L was made to each ferment. Where juice yeast

available nitrogen (YAN) concentrations were below 250 ppm nitrogen, an additional diammonium phosphate (DAP) addition was made to raise YAN concentrations up to a minimum of 250 ppm N.

Fermentations were monitored daily by total weight loss. Towards the end of the fermentation process, total soluble solids (°Brix) were monitored using an Anton Paar DMA 35 portable density meter and when °Brix values dropped below 0, residual sugars were determined by an enzymatic assay kit. When ferments contained less than 3.0 g/L residual sugar, ferments were stopped with the addition of 50 mg/L SO_2 (in the form of potassium metabisulfite – $K_2S_2O_5$). Wine was settled for 1 week and then racked of yeast lees. Samples were taken for various chemical analysis (Sections 2.4.12 and 2.4.13 below).

2.4.11 Finished wine compositional analysis

Finished wine samples were subjected to a range of primary and secondary metabolite analyses. These included, acidity (pH), acid concentration (titratable acidity; TA), sugar concentration (reducing sugars, glucose and fructose), alcohol content (%v/v), and optical densities (OD) at 280 nm and 520 nm.

Wine pH, TA, reducing sugars and optical densities were determined using the same protocols as for juice analysis (Section 2.4.10 above). Wine alcohol was measured using an Anton Paar wine alcolyzer (Graz, Austria), and with all measurements taken in duplicate and with <0.02 %v/v variation.

All spectrophotometric assays were run on a Molecular Devices (San Jose, California, USA) Spectramax 384 Plus with a 10-mm path length cuvette reference correction. Optical density was measured directly in a UV transparent 96-well microplate at 280 and 520 nm. Samples were centrifuged or filtered before analysis and analyses were carried out in duplicate. Absorbance at 280 nm was used to quantify total polyphenols against a five-point gallic acid standard curve (R^2>0.98), based on a method adapted from Sommers and Evans (1977).

2.4.12 Analysis of methoxypyrazines and thiols

Methoxypyrazines, IBMP, IPMP (isopropyl methoxypyrazine), SBMP (sec-butyl methoxypyrazine) and thiols, 3MH, 3MHA and 4MMP, were analysed by Hill Laboratories Limited, Hamilton, New Zealand. Methoxypyrazines and thiols were extracted from wine samples using Solid Phase Micro Extraction (SPME) and further quantified using Gas Chromatography coupled with Mass Spectrometry (GC-MS).

2.4.13 Statistical analysis

Data from bunch zone temperature measurements were analysed for treatment effects using a simple one-way ANOVA (Microsoft® Excel®).

Using Genstat 22nd edition software (VSN International, Hemel Hempstead, UK), the total node count per vine was analysed using ANOVA to compare the treatments. The total node count per position was analysed using ANOVA to compare the treatments and positions. Finally, the number of nodes per cane was analysed using ANOVA to compare the treatments, cane positions (lower and upper), and the cane location (north and south).

For determination of the date of 50% budburst, for each cane the date was estimated using a logistic regression. The date of 50% budburst was then analysed using ANOVA to compare the treatments, cane positions (lower and upper), and the cane location (north and south).

Shoot length was analysed using a linear mixed model with a covariance structure to take into account the repeated measures nature of the data. While only the treatment effects were of interest, a full model was fitted including terms for the date, treatment, cane position, and cane location so that the significance test for treatment used the correct number of degrees of freedom.

To determine the date of 50% flowering, for each sampling date, the flowering % values were averaged for each cane on each vine as is the industry standard for flowering percentage assessment. For each cane, the date of 50% flowering was estimated using a logistic regression curve. The date of 50% flowering was then analysed using ANOVA to compare the treatments and cane positions (lower and upper). The dates are reported as the day in November 2022 – any day values greater than 30 are in December 2022.

For determination of the date of 50% véraison the number of nodes at véraison were summed for each cane on each vine. For each cane, the date of 50% véraison was estimated using a logistic regression curve. The date of 50% véraison was then analysed using ANOVA to compare the treatments and cane positions (lower and upper). The dates are reported as the day in 2023 (Day 1 = 1 January, Day 32 = 1 February, and Day 60 = 1 March).

Berry maturation data were analysed using a linear mixed model to compare the treatments. The model included a covariance structure to take into account the repeated measures nature of the results.

Finally, statistical analysis of the percentage fruit set, yield, settled juice composition, finished wine composition, and of methoxypyrazines and thiols was by ANOVA (Genstat 22nd edition software, VSN International, Hemel Hempstead, UK).

3 Results

3.1 Bunch zone temperatures

Across the 4-month period that treatments were applied (27 September 2022 to 7 February 2023), there was a highly significant (p<0.001) effect of treatment (PTEF) plots in elevating bunch zone temperature to a mean daily average of 18.7°C compared with 16.3°C in ambient controls. This equates to a mean difference of 2.4°C between treatments through the growing season (see Figure 3 which shows a snapshot of time through the flowering period). During the same 4-month period and, respectively, for the control and PTEF treatment plots, minimum temperatures recorded in the bunch zone were −1.7 and −1.0°C, with maximum bunch zone temperatures of 31.4 and 39.2°C.

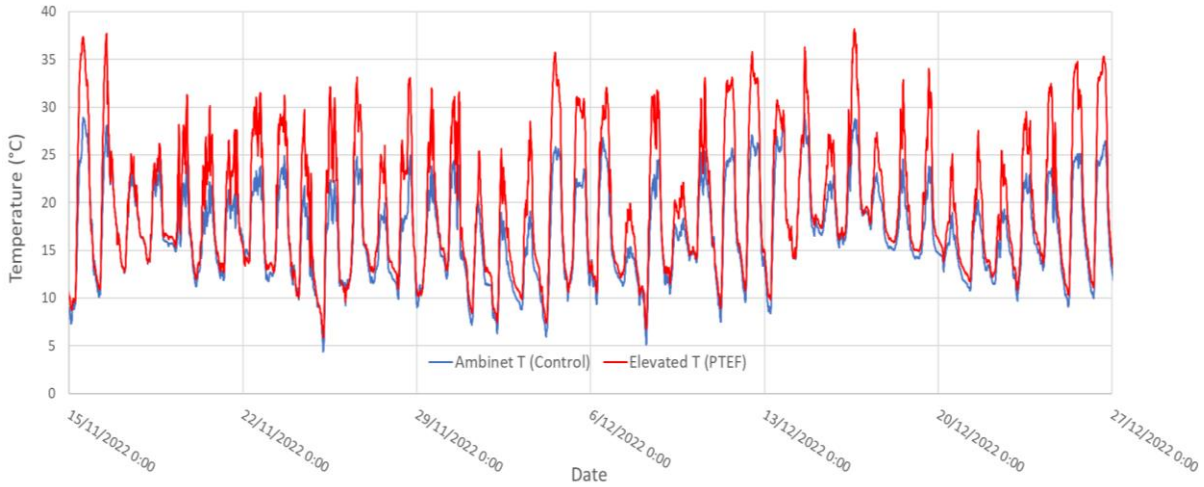

Figure 3. Mean temperature logger output (n=4) for sensors placed in the bunch zone at 1 m above ground level in control (ambient temperature (T)) and passive temperature elevation frame (PTEF) treatment (elevated T) plots. Note that at 1 m from ground level for PTEF treatment plots, this also corresponded to a sensor position in the bunch zone 100 mm above the PTEF apex from which the flue of potentially passively warmed air flowed up through the canopy. The snapshot timeframe shown corresponds to the entire flowering period across both treatments.

The mean bunch zone temperature increase of 2.4°C in PTEF plots was not evenly spread within any diurnal (day/night) period, as highlighted by the temperature differential (PTEF (elevated T) – Control (ambient T)) between treatments (Figure 4) and shown for the same flowering period.

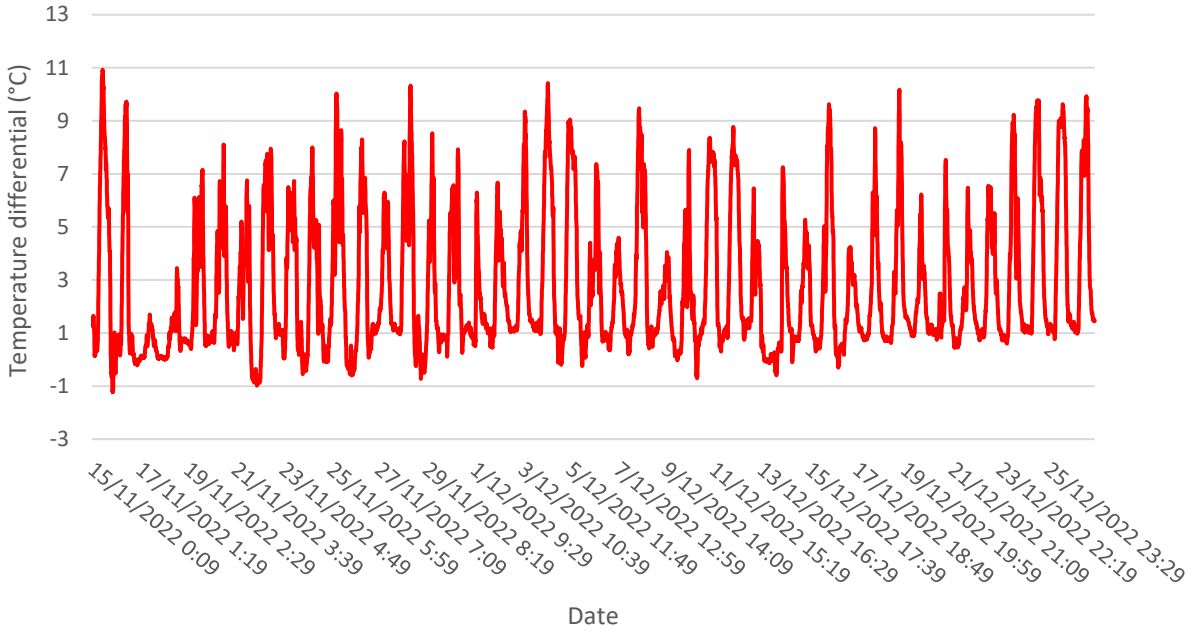

Figure 4. The temperature differential (passive temperature elevation frame (elevated T) – control (ambient T)) for bunch zone temperature between treatments and for same flowering period presented in Figure 3.

Figure 4 clearly highlights the bunch zone temperature differential between control and PTEF treatments, and which variably ranges from as little as −1.0°C to almost 11.0°C for any given diurnal period. Also indicated (and also observable in Figure 3) is that the greatest temperature differentials occur during daylight hours, with temperatures rapidly dropping off in the PTEF bunch zone to match those of control within 1–2 hours after sundown, and for the entire period prior to next sunrise.

3.2 Phenology: Budburst

There was a significant effect (p=0.014) on the date of 50% budburst, with (somewhat counterintuitively) 50% budburst occurring on average 3 days later in elevated temperature (PTEF) treatment vines compared with ambient control vines (Table 1).

Table 1. Mean day (in October 2022) of 50% budburst on canes of ambient temperature (control) vines and elevated temperature passive temperature elevation frame (PTEF) treated vines (n=32). The difference is calculated as Elevated T – Ambient T on the values using full precision and then the results rounded for presentation. SEM is the pooled standard error of the mean.

Treatment	Day of 50% budburst (October 2022)
Ambient T	7.5
Elevated T	10.7
Difference	+3.1
SEM	(0.65)

Contributing to this difference in dates of 50% budburst, was a treatment × cane position (lower or upper) interaction (p=0.052), in which lower canes had a greater delay in achieving 50% budburst under the elevated temperature treatment compared with ambient control, whilst upper canes in both treatments achieved 50% budburst within 1.3 days of each other (Table 2). This delay in date of budburst of lower canes in elevated temperature plots may be reflective of an additional average of four more nodes/buds on these canes competing for carbohydrates and other resources, rather than a direct effect of temperature elevation treatment, given that treatments had only been imposed 1 week earlier just prior to budburst.

Table 2. Mean day (in October 2022) of 50% budburst on Lower and Upper canes on ambient (control) or elevated temperature passive temperature elevation frame (PTEF) treated vines (n=16). The difference is calculated as Elevated T – Ambient T on the values using full precision and then the results rounded for presentation. SEM is the pooled standard error of the mean.

	Treatment		
Cane position	Ambient T	Elevated T	Difference
Upper	8.6	9.9	+1.3
Lower	6.5	11.5	+5.0
SEM	(0.92)		

There was no significant effect (p=0.946) of cane location (North or South orientation on the wire) on the date of 50% budburst.

3.3 Shoot length

When averaged over all dates, shoot length differed significantly with treatment (p<0.001) and there was a significant date × treatment interaction (p<0.001). Shoots from elevated temperature treatment vines were typically 18–23 cm longer than those from ambient control (Table 3), demonstrating earlier season vigour in shoot growth.

Table 3. Mean shoot length (cm) on ambient and elevated temperature passive temperature elevation frame (PTEF) treated vines over five sample dates. Values in brackets are the standard error of the mean. The Difference is calculated as Elevated T – Ambient T, and additionally expressed as a percentage difference of Ambient T (control).

	Treatment			
Date (2022)	Ambient T	Elevated T	Difference	% difference
21-Nov	42.0 (2.21)	62.4 (2.15)	+20.4	+48.7%
28-Nov	52.2 (2.62)	74.7 (2.54)	+22.5	+43.1%
6-Dec	63.8 (3.00)	85.4 (2.92)	+21.6	+33.9%
13-Dec	76.3 (3.50)	97.4 (3.39)	+21.1	+27.6%
21-Dec	92.7 (4.25)	111.0 (4.12)	+18.3	+19.8%

The significant interaction of date x treatment with the difference and percentage difference decreasing with time, may have been due to a probable combination of earlier season vigour in elevated temperature (PTEF) vines slowing, and shoot growth (length) in ambient treatment (control) vines ‘catching up’ (Table 3).

3.4 Greenseeker: canopy greenness

When averaged over three measurement occasions, the greenness of canopies (a surrogate measure of nitrogen nutritional status) was significantly greater ($p<0.001$) on a given date in elevated temperature (PTEF) treatment vines compared to ambient control (Table 4), and there was a near significant ($p=0.056$) date × treatment interaction, with the difference in greenness of the two treatments decreasing over time.

Table 4. Mean Greenseeker value (arbitrary) for 'greenness' on ambient or elevated temperature passive temperature elevation frame (PTEF) treated vines over three sampling dates. Values in brackets are the standard error of the mean. The Difference is calculated as Elevated T – Ambient T, and additionally expressed as a percentage difference of Ambient T (control).

	Treatment			
Date (2022)	Ambient T	Elevated T	Difference	% difference
18-Nov	0.6950 (0.0076)	0.7650 (0.0076)	+0.070	+10.07
6-Dec	0.7725 (0.0045)	0.8100 (0.0045)	+0.038	+4.85
13-Dec	0.7975 (0.0075)	0.8275 (0.0075)	+0.030	+3.76

The enhanced greenness of elevated temperature treated vine canopies earlier in the season compared with control vines, is in concert with the enhanced shoot growth of these same vines (Section 3.3) and reflects an earlier season demand for nutrients and resources.

3.5 Phenology: date of 50% Flowering

There was a highly significant effect ($p<0.001$) of elevated temperature (PTEF) treatment on the date of 50% flowering (23 November 2022), which was 14 days earlier than 50% flowering on canes in ambient temperature (control) vines (7 December 2022; Table 5). There was no significant effect of upper or lower cane position ($p=0.78$) on the date of 50% flowering, and no significant treatment × cane position interaction ($p=0.76$; Table 5).

Table 5. Mean day of 50% flowering (Day in November 2022; days >30 are in December 2022) on lower and upper canes of ambient temperature (control) or elevated temperature passive temperature elevation frame (PTEF) treated vines (n=8). Values in brackets are the standard error of the mean. The Difference is calculated as Elevated T – Ambient T.

	Treatment		
Cane position	Ambient T	Elevated T	Difference
Upper	37.7 (1.17)	23.0 (1.17)	-14.7
Lower	36.9 (1.17)	23.0 (1.17)	-13.9

3.6 Percentage fruit set

Bunch zone temperature treatment had a significant effect (p=0.011), increasing the percentage fruit set by 16% from 34.4% in ambient temperature (control) vines to 39.9% in elevated temperature treated vines (Figure 5). There was no significant effect of cane position (upper or lower) or treatment x cane interaction on the percentage fruit set.

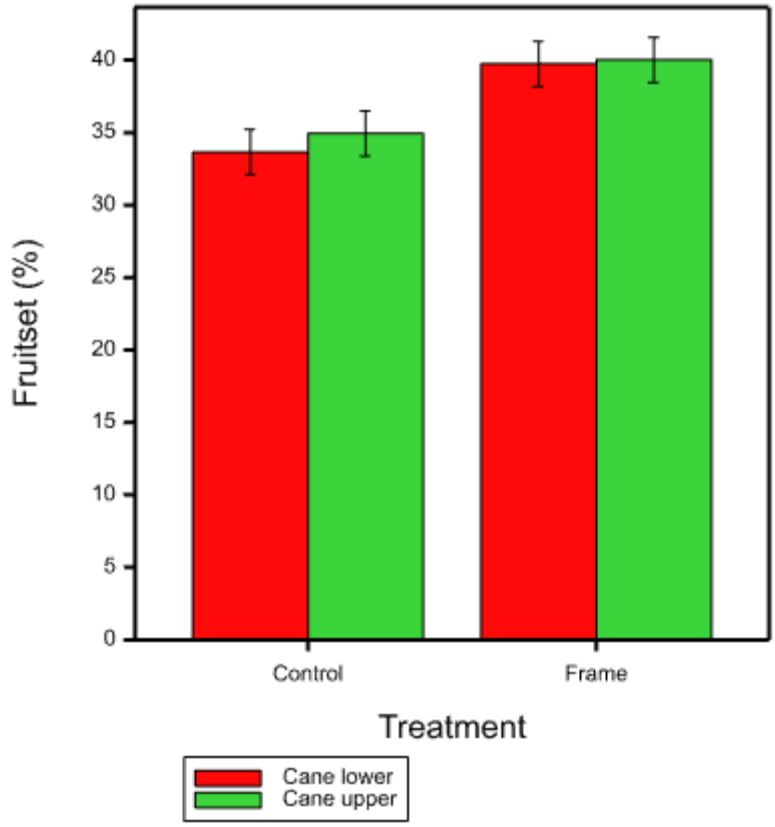

Figure 5. The percentage fruit set on lower or upper canes of ambient (control) or elevated temperature passive temperature elevation frame (PTEF) treated vines of Sauvignon blanc in a commercial vineyard during season 2022-23. Bars = 1 x SE, n = 16.

3.7 Berry maturation

There were significant treatment differences in all the berry maturation variables analysed, and these differences were generally largest at the first sample date and decreased over the sampling regime period.

Mean berry total soluble solids (TSS) accumulation (°Brix) was significantly (p<0.001) advanced in elevated temperature (PTEF) treated vines compared with ambient temperature control vines (Table 6), being 7.1 °Brix higher on the first measurement occasion (13 February 2023). This advantage decreased to 1.9 °Brix by day 42 (27 March 2023). There was a highly significant (p<0.001) effect of date on mean berry TSS, and a highly significant (p<0.001) date x treatment interaction, the

latter suggesting that the rates of TSS accumulation in the two treatments were different. Whilst the date of 50% véraison (TSS achieving 8.0 °Brix) can be interpolated for the ambient temperature treatment (control) vines as being approximately 17 February 2023 (Table 6 and Figure 6 below), berry sampling missed the timing for the elevated temperature treatment vines reaching 8.0 °Brix, but likely occurred early February approximately 2 weeks earlier.

Table 6. Mean total soluble solids (°Brix) in berries from ambient temperature (Ambient T; control) and elevated temperature (Elevated T) treated vines (n=4). Values in brackets are the standard errors of the means from a linear mixed model. The Difference is calculated as Elevated T – Ambient T, and additionally expressed as a percentage of Ambient T (control).

	Treatment			
Date	Ambient T	Elevated T	Difference	% difference
13-Feb-23	6.3 (0.41)	13.4 (0.41)	+7.1	+111.4%
20-Feb-23	9.2 (0.41)	15.7 (0.41)	+6.5	+70.4%
27-Feb-23	12.0 (0.41)	16.3 (0.41)	+4.4	+36.6%
7-Mar-23	14.5 (0.41)	18.2 (0.41)	+3.7	+25.7%
13-Mar-23	16.8 (0.41)	19.5 (0.41)	+2.7	+15.9%
20-Mar-23	18.0 (0.41)	20.7 (0.41)	+2.7	+15.0%
27-Mar-23	19.9 (0.41)	21.7 (0.41)	+1.9	+9.4%

Fruit from both treatments was harvested on the same date of 28 March 2023 for direct comparison of differences in fruit and wine quality between treatments. On harvest day, berries from elevated temperature (Elevated T; PTEF) treated vines achieved a mean TSS content of 21.73 °Brix, and the ambient temperature ‘same date’ control 19.85 °Brix. In order to also make a comparison of differences in fruit and wine quality at the same ‘target °Brix’, additional control fruit (which essentially included the remainder of the commercial block) were harvested from four immediately adjacent plots (vineyard bays) 14 days later (11 April 2023) when ambient temperature ‘target °Brix’ vines achieved a mean TSS content of 21.63 °Brix, just 0.1 °Brix lower than the elevated temperature treatment two weeks earlier (Figure 6).

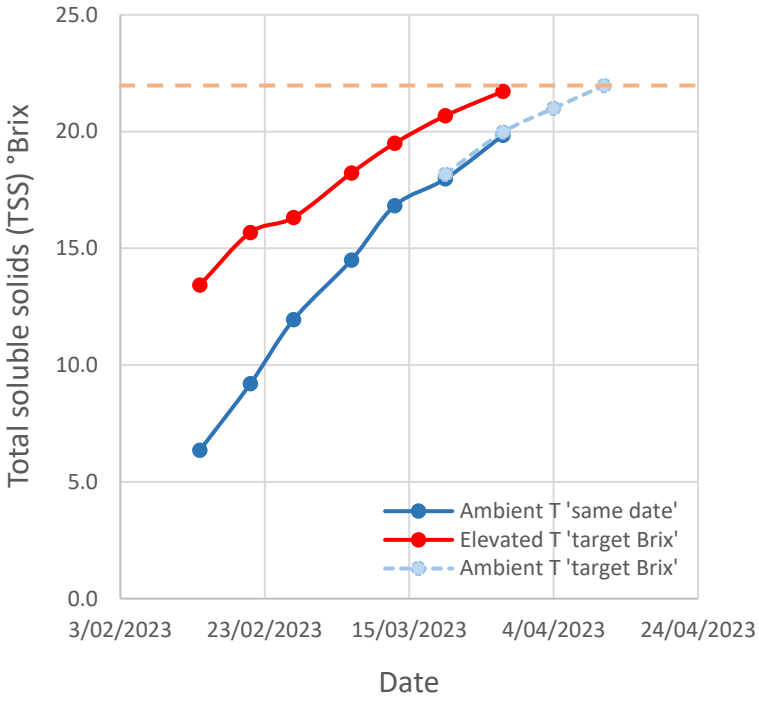

Figure 6. Total soluble solids (TSS) accumulation over time in berries during maturation from ambient temperature (Ambient T; control) and elevated temperature (Elevated T) treated vines (n=4). As denoted in the key, berries from Ambient T vines were tracked and harvested on both the 'same date' that Elevated T berries reached 'target Brix', and approximately 2 weeks later when Ambient T berries achieved equivalent 'target Brix'. The horizontal orange dashed line indicates industry standard target TSS of 21.5 °Brix for Sauvignon blanc.

In concert with TSS accumulation, berries of Elevated T treated vines had significantly higher (p<0.001) juice pH than Ambient T vines, although the effect decreased over the whole sampling period, resulting in a significant date x treatment interaction (p=0.009; Table 7).

Table 7. Mean juice pH in berries from ambient temperature (Ambient T; control) and elevated temperature (Elevated T) treated vines (n=4). Values in brackets are the standard errors of the means from a linear mixed model. The Difference is calculated as Elevated T – Ambient T, and additionally expressed as a percentage difference of Ambient T (control).

	Treatment			
Date	Ambient T	Elevated T	Difference	% difference
13-Feb-23	-	2.85 (0.029)	-	-
20-Feb-23	2.64 (0.019)	2.89 (0.019)	+0.248	+9.4%
27-Feb-23	2.75 (0.020)	3.00 (0.020)	+0.250	+9.1%
7-Mar-23	2.85 (0.022)	3.04 (0.022)	+0.193	+6.8%
13-Mar-23	2.86 (0.021)	3.06 (0.021)	+0.193	+6.7%
20-Mar-23	2.93 (0.020)	3.10 (0.020)	+0.170	+5.8%
27-Mar-23	3.00 (0.021)	3.18 (0.021)	+0.178	+5.9%

On harvest day (28 March 2023), Elevated T ‘target °Brix’ (PTEF) treated vine berries had a mean pH of 3.18, and the Ambient T ‘same date’ berries, a lower mean pH of 3.00. For the additional Ambient T ‘target °Brix’ berries harvested 14 days later (11 April 2023), berries achieved a pH of 3.08, which was lower that Elevated T berries (Figure 7).

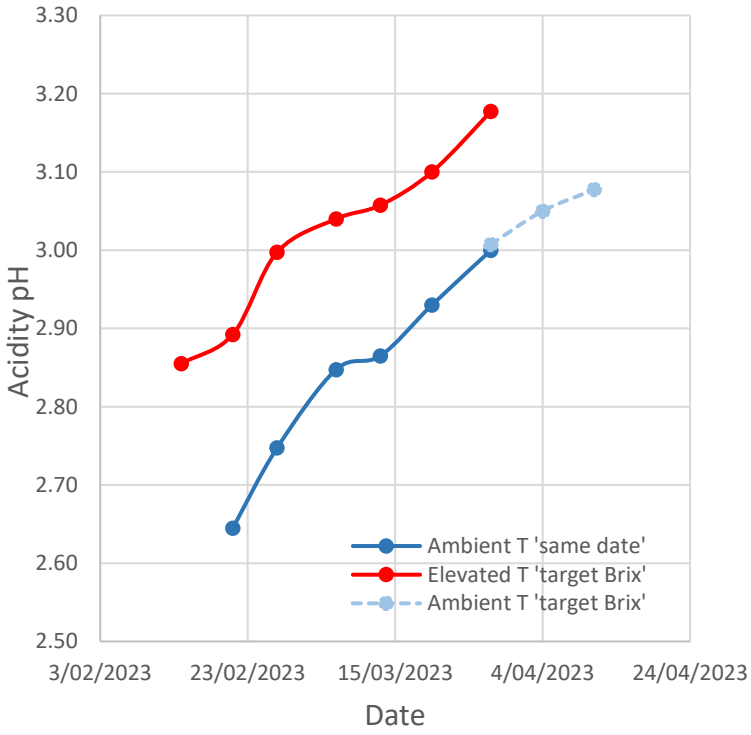

Figure 7. The change in acidity (pH) over time in berries during maturation from ambient temperature (Ambient T; control) and elevated temperature (Elevated T) treated vines (n=4). As denoted in the key, berries from Ambient T vines were tracked and harvested on both the ‘same date’ that Elevated T berries reached ‘target Brix’, and approximately 2 weeks later when Ambient T berries achieved equivalent ‘target Brix’.

Results for berry juice TA over the sampling period were converse to TSS accumulation and acidity (pH). Berries of Elevated T treated vines had significantly lower (p<0.001) juice TA than ambient temperature treated vines, although the difference decreased over the whole sampling period, resulting in a significant date x treatment interaction (p<0.001; Table 8).

Table 8. Mean titratable acidity (TA g/L) in berries from ambient temperature (Ambient T; control) and elevated temperature (Elevated T; PTEF) treated vines (n=4). Values in brackets are the standard errors of the means from a linear mixed model. The Difference is calculated as Elevated T – Ambient T, and additionally expressed as a percentage difference of Ambient T (control).

	Treatment			
Date	Ambient T	Elevated T	Difference	% difference
13-Feb-23	-	21.5 (1.03)	-	-
20-Feb-23	32.0 (0.84)	17.6 (0.84)	-14.4	-45.0%
27-Feb-23	26.6 (0.67)	16.4 (0.67)	-10.3	-38.6%
7-Mar-23	19.4 (0.60)	13.5 (0.60)	-5.9	-30.6%
13-Mar-23	16.7 (0.52)	12.4 (0.52)	-4.3	-25.7%
20-Mar-23	14.2 (0.35)	10.8 (0.35)	-3.4	-24.2%
27-Mar-23	12.5 (0.26)	9.8 (0.26)	-2.7	-21.5%

On harvest day (28 March 2023), Elevated T ‘target °Brix’ (PTEF) treated vine berries had a mean TA of 9.80 g/L, and the Ambient T ‘same date’ (control) berries a significantly higher mean TA of 12.48 g/L (Figure 8). For the additional Ambient T berries harvested at ‘target °Brix’ 14 days later (11 April 2023), berries had a 0.74 g/L lower TA of 11.74 g/L, but still 1.94 g/L higher than Elevated T ‘target °Brix’ berries, and where the ‘target °Brix’ difference was only 0.25 °Brix. Thus, when harvested at near identical target °Brix, vines with berries that had developed from budburst to véraison under elevated temperature (at which point treatments ceased), but then matured at least 2 weeks earlier under ‘ambient seasonal conditions’, had a significantly lower TA compared with all season-long ambient temperature grown berries.

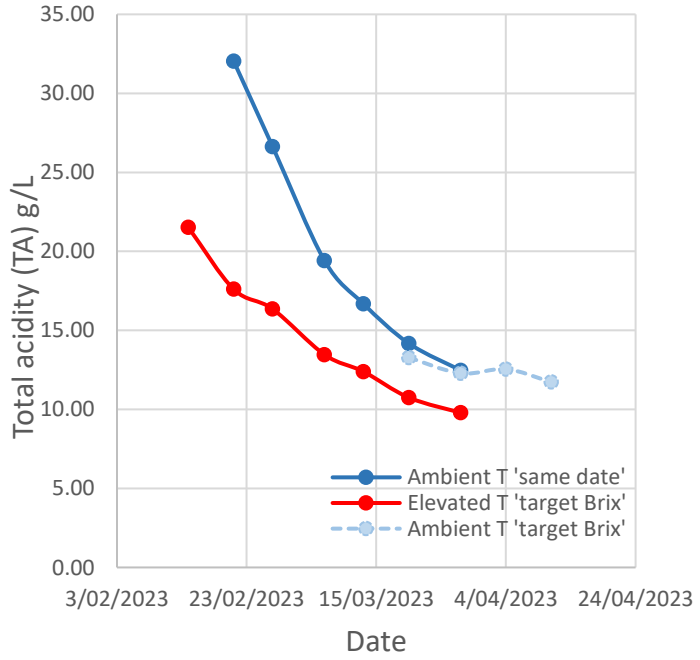

Figure 8. The change in titratable acidity (TA) over time in berries during maturation from ambient temperature (Ambient T; control) and elevated temperature (Elevated T) treated vines (n=4). As denoted in the key, berries from Ambient T vines were tracked and harvested on both the ‘same date’ that Elevated T berries reached ‘target Brix’, and approximately 2 weeks later when Ambient T berries achieved equivalent ‘target Brix’.

Mean berry weight was significantly (p<0.001) increased in elevated temperature (PTEF) treated vines compared with ambient temperature vines (Table 9), being 0.26 g higher on the first measurement occasion (13 February 2023), but with this difference decreasing to 0.05 g by day 42 (27 March 2023). There was a highly significant (p<0.001) effect of date on mean berry weight, and a highly significant (p<0.001) date x treatment interaction, the latter suggesting that the rate of berry weight accumulation in the two treatments were different.

Table 9. Mean average berry weight (g) in berries from ambient temperature (control) and elevated temperature treated vines (n=4). Values in brackets are the standard errors of the means from a linear mixed model. The Difference is calculated as Elevated T – Ambient T, and additionally expressed as a percentage difference of the Control.

	Treatment			
Date	Ambient T	Elevated T	Difference	% difference
13-Feb-23	1.09 (0.039)	1.35 (0.039)	+0.26	+23.6%
20-Feb-23	1.25 (0.039)	1.55 (0.039)	+0.29	+23.3%
27-Feb-23	1.43 (0.039)	1.70 (0.039)	+0.27	+19.1%
7-Mar-23	1.68 (0.039)	1.92 (0.039)	+0.25	+14.8%
13-Mar-23	1.78 (0.039)	1.91 (0.039)	+0.13	+7.0%
20-Mar-23	1.96 (0.039)	1.99 (0.039)	+0.02	+1.2%
27-Mar-23	1.95 (0.039)	2.00 (0.039)	+0.05	+2.8%

3.8 Yield

Several yield parameters are shown in Table 10 below for ambient and elevated temperature treated vines harvested on 29 March 2023. Although not significantly different, average bunch number per vine was slightly greater (4.8%) in elevated temperature treated vines compared with ambient control. Average bunch weight, however, was significantly (p<0.001) lower (20%) in elevated temperature (PTEF) treated vines compared with ambient control. This in turn resulted in a 15% average lower yield for vines grown at elevated temperature compared with ambient control, although this result was not significantly lower statistically (p=0.11).

Table 10. Various yield parameters at harvest on 29 March 2023 for ambient temperature (control) and elevated temperature passive temperature elevation frame (PTEF) treated vines (n=8). Additionally shown are SED (standard error of differences of means). p-values less than or equal to 0.050 are statistically significant (highlighted in bold).

	Treatment			
Yield parameter	Ambient T	Elevated T	SED	*P*-value
Average bunch number per vine	49.4	51.8	3.47	0.513
Average bunch weight (g)	109.5	87.6	3.50	**<0.001**
Average yield per vine (kg)	5.4	4.6	0.46	0.11

Despite elevated temperature grown vines having a 16% increase in fruit set (Section 3.6 and Figure 5) and a 2.8% higher average berry weight (Table 10) on the day (27 March 2023) prior to harvest (for that sub-set of bunches sampled), the observation of a significantly lower average bunch weight (Table 10) compared to ambient temperature control vines, is unexpected. One or a combination of possible explanations for this are that despite best efforts to protect vines from frost,

there were two frost events (6–7 October 2022) where temperatures as low as -1.7°C were recorded in the bunch zone beneath the frost cloth, during the period of bud-burst and where some damage may have occurred leading to variable replacement of some primary shoots with less fruitful secondary shoots. Further, since elevated temperature grown vines matured fruit significantly earlier, there was an earlier exposure to botrytis disease risk, and indeed botrytis was present in parts of the trial later in the season. Despite best efforts with a spray programme and to remove and account for diseased berries and occasional whole bunches as they were observed, some may nevertheless have been challenging to account for.

3.9 Cold-settled juice analysis

Some parameters of cold-soaked juice analysis following the processing of fruit parcels after harvest, were significantly affected by treatments (Table 11 below). Juice from fruit parcels of elevated temperature treated vines had significantly higher TSS (p=0.002), acidity (p<0.001), glucose (p=0.008), fructose (p=0.008) and the sum of glucose and fructose (p=0.006), compared with ambient temperature control juice. Conversely, titratable acidity (TA) was significantly (<0.001) lower along with malic acid (p<0.001) in juice from elevated temperature treated vines compared to ambient (Table 11). The concentrations in cold-settled juice of ammonium, primary amino acids, YAN, potassium and NTU values for turbidity, were not significantly affected by vine treatment (Table 11).

Table 11. Effect of ambient temperature (control) or elevated temperature passive temperature elevation frame (PTEF) treatment on Sauvignon blanc juice composition (after 24 hours' cold soak) harvested on 29 March 2023.

	Ambient T	Elevated T	SEM	*P*-value[1]
Total soluble solids (°Brix)	19.40	21.68	0.44	**0.002**
Acidity (pH)	3.03	3.19	0.010	**<0.001**
Titratable acidity (g/L)	12.48	9.34	0.254	**<0.001**
Ammonium (mg N/L)	78.0	78.5	15.50	0.975
Primary amino acids (mg N/L)	130.5	162.8	17.88	0.121
YAN (mg N/L)	208	241	32.6	0.354
Malic acid (g/L)	6.64	5.04	0.259	**<0.001**
Potassium (mg/L)	1732	1781	25.4	0.103
Glucose (g/L)	101.2	114.6	3.38	**0.008**
Fructose (g/L)	75.7	85.1	2.43	**0.008**
Sum Glu + Fru (g/L)	176.9	199.7	5.40	**0.006**
Free SO_2 (mg/L)	17.5	14.3	0.804	**0.007**
Total SO_2 (mg/L)	48.5	54.0	1.555	**0.012**
NTU	132	154	22.3	0.363

[1]Probability p-values are from ANOVA. p-values less than or equal to 0.050 are statistically significant (highlighted in bold).
SEM = pooled standard error of the mean from ANOVA. N = nitrogen, YAN = yeast assimilable nitrogen.

3.10 Finished wine analysis

Some parameters of finished wine analysis were significantly affected by vine treatments following completion of the winemaking process (Table 12 below). Wine from elevated temperature treated vines had significantly higher alcohol content (p=0.002), acidity (p<0.001), acetic acid (p=0.030), absorbance at OD 280 nm (p=0.013) and total phenolics (p=0.013), compared with wines made from fruit of ambient control vines. Conversely, titratable acidity (TA) was significantly (<0.001) lower along with malic acid (p<0.001) in wine from elevated temperature treated vines compared with ambient (Table 12). The concentrations in wine of total SO_2, glucose, fructose, sum of glucose and fructose, potassium, and absorbance at OD 520 nm were not significantly affected by vine treatment (Table 12).

Table 12. Effect of ambient temperature (control) or elevated temperature passive temperature elevation frame (PTEF) treatments on Sauvignon blanc wine composition for fruit harvested on 29 March 2023.

	Ambient T	Elevated T	SEM	*P*-value[1]
Fermentation duration (days)	13	13	0	n/a
Alcohol content (v/v%)	11.7	13.5	0.336	**0.002**
Acidity (pH)	3.01	3.21	0.0071	**<0.001**
Titratable acidity (g/L)	11.83	9.09	0.374	**<0.001**
Total SO_2 (mg/L)	64.0	73.2	7.44	0.260
Glucose (g/L)	0.083	0.055	0.212	0.242
Fructose (g/L)	0.47	0.23	0.299	0.462
Sum Glu + Fru (g/L)	0.55	0.29	0.319	0.441
Malic acid (g/L)	5.36	4.01	0.223	**<0.001**
Acetic acid (g/L)	0.160	0.232	0.0256	**0.030**
Potassium (mg/L)	1040	1098	104.1	0.596
OD 280 (AU)	4.49	5.02	0.151	**0.013**
OD 520 (AU)	0.069	0.087	0.0085	0.069
Total phenolics (mg GAE/L)	133.5	148.2	4.22	**0.013**

[1]Probability p-values are from ANOVA. p-values less than or equal to 0.050 are statistically significant (highlighted in bold).
SEM = pooled standard error of the mean from ANOVA. SO2 = sulfur dioxide, GAE = gallic acid equivalents,
AU = absorbance units.

3.11 Methoxypyrazine and thiol analysis

Wine made from fruit of elevated temperature grown vines contained significantly less (p=0.008) Isobutyl methoxypyrazine (IBMP), the predominant methoxypyrazine responsible for ‘bell pepper’ and ‘gooseberry’ aroma in Sauvignon blanc, than wines from ambient control vines harvested on the same date (Table 13). Conversely, concentrations of the thiol 3-mercaptohexan-1-ol (3-MH), responsible for ‘grapefruit’ aroma in Sauvignon blanc, was significantly (p=0.043) increased in wine from elevated temperature grown vines compared to ambient control. Likewise, two further thiols 3-mercaptohexyl acetate (3-MHA; attributed to ‘sweet-sweaty’ and ‘passionfruit’ aroma) and 4-mercapto-4-methylpentan-2-one (4-MMP; attributed to ‘broom’ and ‘cat’s pee’ aroma) were also present in higher

concentrations in wine from elevated temperature vines than ambient control, although not significantly (Table 13).

Concentrations of Isopropylmethoxypyrazine (IPMP) and Sec-butylmethoxypyrazine (SBMP) in at least one or both treatments, were below the analytical detection thresholds indicated (Table 13), and therefore not possible to analyse data.

Table 13. Effect of ambient temperature (control) or elevated temperature passive temperature elevation frame (PTEF) treatments on Sauvignon blanc wine composition for fruit harvested on 29 March 2023.

	Ambient T	Elevated T	SEM	*P*-value[1]
Isobutyl-methoxypyrazine (IBMP) (ng/L)	6.48	2.20	1.092	**0.008**
Isopropyl-methoxypyrazine (IPMP) (ng/L)	1.33	<1.0	n/a	n/a
3-mercaptohexyl acetate (3-MHA) (ng/L)	370	1266	444	0.090
3-mercaptohexan-1-ol (3-MH) (ng/L)	836	3285	958.6	**0.043**
4-mercapto-4-methylpentan-2-one (4-MMP) (ng/L)	63	79	31.36	0.632
Sec-butylmethoxypyrazine (SBMP) (ng/L)	<0.7	<0.7	n/a	n/a

[1]Probability *p*-values are from ANOVA. *p*-values less than or equal to 0.050 are statistically significant (highlighted in bold).
SEM = pooled standard error of the mean from ANOVA. SO_2 = sulfur dioxide, GAE = gallic acid equivalents, AU = absorbance units.

4 Discussion

In line with the aims and objectives outlined in the introduction, we have successfully scaled up and deployed replicated passive temperature elevation frames in a commercial vineyard of flagship varietal 'Marlborough Sauvignon blanc'. This was with the aim to further elevate the temperature of developing bunch zones and vine canopies beyond 2022–23 ambient temperatures, thus simulating a future Marlborough climate warming scenario. The temperature simulation was applied for 4 months from just prior to budburst until véraison. We have quantified and gained further knowledge of the impacts on time shifts in key phenological events, effect on fruit set, differences in measured vine physiology, rates of berry maturation, yield parameters, and impacts on standard juice, wine chemistry and key aroma compounds.

Data and results from temperature sensors located in developing bunch zones demonstrated that the four deployed replicate PTEF systems successfully elevated temperature by an average 2.4°C above ambient, over a 4-month period. To put that temperature elevation into context, the Intergovernmental Panel on Climate Change (IPCC) estimates that anthropogenic global warming is currently increasing at 0.2°C (likely between 0.1°C and 0.3°C) per decade due to past and ongoing emissions (IPCC 2018), which puts a 2.4°C temperature increase into 2100 and beyond.

As previously reported (Theobald et al. 2022), with the PTEF system being of passive warming design, on a diurnal basis most temperature elevation in the developing bunch zone and canopy occurred during day light hours, with limited additional night-time warming (buffering) beyond a couple of hours past sundown. Nevertheless, we observed (and within 8.1 weeks from PTEF deployment pre-budburst) a 14-day advance at 50% flowering in elevated temperature (PTEF) canopies compared with ambient control. This was likewise followed by a 2 week advance in time to 50% véraison and time to the start of total soluble solids accumulation and eventual harvest. At a target TSS of 21.5 °Brix for Sauvignon blanc, elevated temperature (PTEF) treated vines were harvested 14 days earlier than ambient control vines.

As well as impacts on the timing of key phenological stages, the average 2.4°C temperature elevation over 4 months accelerated early season shoot growth by as much as 50%, creating an increased earlier season demand for nutrients and resources, as exemplified by darker green canopies (Greenseeker) compared with ambient temperature treated vines. Temperature elevation also had a significant effect increasing fruit set by 16%, although on this occasion, and perhaps due to several factors including earlier season possible frost damage and later season disease pressure (botrytis), did not carry through to final yield increases, although this will be an area of more detailed focus going forward.

With the application of treatments completed by the onset of véraison (i.e., PTEFs removed) it is noteworthy that significant impacts on berry maturation, juice and wine composition, and wine aroma compounds continued to be observed, presumably largely driven by the advanced phenology, given that post-véraison, both treatments continued their progression under 'ambient' season conditions, albeit under different 'weather' scenarios several weeks apart.

Thus, there were significant impacts to various measured parameters during berry maturation. Most significant was the observation that even when harvested at the same target TSS content, elevated temperature grown berries had an average TA 1.94 g/L lower than ambient grown berries and higher pH. Given the importance of the balance between sugars and acidity to any wine, but particularly the importance of natural acidity to the 'crisp' Marlborough style of Sauvignon blanc, this is an important

observation. An opportunity for the future, might be to develop adaptation strategies and solutions within the vineyard which help to mitigate such impacts.

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