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The impact of temperature on 'Pinot Noir' berry and wine quality in a steeply sloping cool climate vineyard in South Australia

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Summary

Viticulture is particularly sensitive to climate change, as temperature is critical to the two key concepts of terroir and vintage. *Vitis vinifera* L. 'Pinot Noir' is known to not grow well in hot climates. A trial was run over two years in a commercial vineyard in the Adelaide Hills, South Australia, to determine the impact of higher temperatures on the 'Pinot Noir' grape and wine colour. A factorial experiment combining two sources of variation in temperature was established: three positions on a steep vineyard slope, and two thermal treatments: unheated control and heated with passive open-top transparent chambers. Elevated temperature decoupled sugars and anthocyanins in grape berries, with the heated treatment grapes producing a lower anthocyanin concentration for the same concentration of total soluble solids. Temperature effects were less defined for small batches of wines prepared from these grapes, with the wines from heated vines having higher total phenolics, and perhaps consequently lower CIELab b* values (*i.e.*, less blue pigmentation/anthocyanins). The study provides a unique insight into temperature gradients on a steeply sloping site and the effects on colour development of 'Pinot Noir' grape berries and wine.

K e y w o r d s : Pinot Noir; climate change; vineyard slope; grape color; wine color.

Introduction

The importance of climate for the production of high-quality 'Pinot Noir' grapes and wines is well established (Butler 1981, Webb *et al.* 2008, Roullier-Gall *et al.* 2014a and b, Rowley 2015). In general, 'Pinot Noir' makes uninteresting wines in hot climates, where wines lack in colour (Galet 1979, Antcliff 1976, Butler 1981, Charters *et al.* 2015). This suggests that climate change may impact wine quality in many wine regions that produce 'Pinot Noir' (Schultz and Jones 2010, Jones and Schultz 2016). However, there has been considerable consumer resistance to lightly coloured red wines, with darker red wines often assumed to be 'richer' in flavour (Parpinello *et al.* 2009). Wine critic Richard Hemming suggested that the first impressions of consumers of a wine is based on its colour (Hemming and Rosen 2015). In contrast, Valentin *et al.* (2016) found minimal support for any positive relationship between perceived wine colour and perceived quality for 'Pinot Noir' wines amongst French and New Zealand wine professionals. This was reinforced by wine critic Jamie Goode, who noted an increase in interest among wine consumers in light red wines such as lighter coloured 'Pinot Noir's over the past few years (Goode 2015). Hemming also noted a shift in the market in Australia, France, and the USA towards lighter, less extracted wines, and hence less importance being placed on colour density. In contrast, no similar trend has been noted in China (Hemming and Rosen 2015), which has been an important emerging market for Australian and other world wines. Dambergs *et al.* (2012) go as far as to state that "there is no doubt that tannin and pigment determine quality in 'Pinot Noir'".

The impact of temperature on grape colouration in 'Pinot Noir' has been examined using potted vines grown in greenhouses (Kliewer 1970, Kliewer and Torres 1972). However, these studies were limited because they were conducted on few vines grown artificially in phototron rooms, with analysis conducted on berries only, not on finished wine. Both these studies reported a decrease in colour (*i.e.* optical density at 530 µm) in grapes grown under warmer conditions.

Correlations between climate, quality (as assessed by wine grape colour and levels of glycosyl-glucose), and price paid for wine grapes have also been noted (Webb *et al.* 2008). In Australia, 'Pinot Noir' shows a linear relationship between quality and temperature, with grapes from cooler climates fetching higher prices (Webb *et al.* 2008).

A smaller scale study (Nicholas *et al.* 2011) looked at the effect of vineyard-scale climatic variability (*i.e.*, mesoclimate) on the phenolic composition of 'Pinot Noir' wines grown in several commercial vineyards in the Sonoma Valley and Los Carneros (California, USA). Temperatures during the bloom-to-*véraison* period correlated negatively with concentrations of anthocyanins, phenolics, and tannins. The authors noted a positive correlation between anthocyanins and accumulated hours from 16 °C to 22 °C. A significant increase in the skin:berry-weight ratio during growth was noted, in contrast to previous work showing a steady ratio during growth, and phenolics did not change in concentration when ripening (Nicholas *et al.* 2011).

This study aimed to investigate the impact of raised temperature on colour in 'Pinot Noir' grapes and wine, us-

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ing a passive heating system devised by Sadras and Soar (2009) for *in situ* studies on the potential impacts of climate change (Sadras *et al.* 2012, Sadras and Soar 2009). It was hypothesised that increased temperatures would decrease the colour of both the grapes and wine. Sadras and Moran (2012) reported that elevated temperatures decouple sugar and anthocyanin accumulation in berries. However, the present study was conducted in the cool Adelaide Hills region of South Australia, at a strongly sloping 'Pinot Noir' vineyard, in contrast to the previous work by Sadras and Moran (2012), Sadras and Soar (2009) that examined 'Shiraz' ('Syrah') grapes grown on a flat site in the warmer Barossa region.

Methods

Vineyard trial: A trial plot was set up on in an irrigated commercial vineyard near Lenswood, South Australia (34°53′31.9″S 138°49′34.9″E), on a north north-east facing slope at 536 m above sea level, planted with *Vitis vinifera* L. 'Pinot Noir' clone D5V12.

The vineyard soil is a sandy loam over a light sandy clay, itself overlying silt and mud stone with quartz inclusions, high in Fe and Cu, and free draining with low moisture holding capacity, with an average soil depth of 1.5 m that varies from the top to the bottom of the slope (Craig Markby 2021 pers. comm.). Daily temperature recording for the Lenswood area of the Adelaide Hills ceased in 1999 (Australian Bureau of Meteorology weather station 023801), but over the 32 year period of 1967-99, the temperatures for the October to February antipodean growing season ranged from a low of 4.2 °C to a high of 26.1 °C, and from 6.0 °C to 30.6 °C throughout the entire year (Bureau of Meteorology 2021a and b). This climate is considered very mild compared to more extreme regions of Australia. Mean monthly rainfall (1967-2021) for this Adelaide Hills region ranges from 29.5 to 76.6 mm (Bureau of Meteorology 2021c), but as is common in Australia this is supplemented in vineyards with irrigation.

The study comprised two growing seasons, October 2013-February 2014, and October 2014-February 2015. The first growing season of the study was unfavourable: cold and windy during flowering, with spring frosts, summer heatwaves, and heavy rains in February. This resulted in uneven ripening, poor berry development, and low yield (see Table). The second growing season was dry and mild, following a rainy winter, with warm weather during flowering and véraison.

The study design comprised an unreplicated factorial combining three locations on the vineyard slope, and two thermal regimes, *i.e.* untreated control versus passively heated with transparent open-top chambers of acrylic panels

Table

Harvest dates and yields per vine in kg, for both years (2014 and 2015) and both heated and control treatments

Treatment	Harvest date in 2014	Yield/ vine (kg) in 2014	Harvest date in 2015	Yield/ vine (kg) in 2015
Top, heated	27th Feb	0.56	17th Feb	1.28
Top, control	7th March	0.62	20th Feb	1.40
Middle, heated	28th Feb	0.65	24th Feb	2.22
Middle, control	10th March	0.61	25th Feb	1.85
Base, heated	7th March	0.37	26th Feb	0.62
Base, control	7th March	0.67	27th Feb	1.30

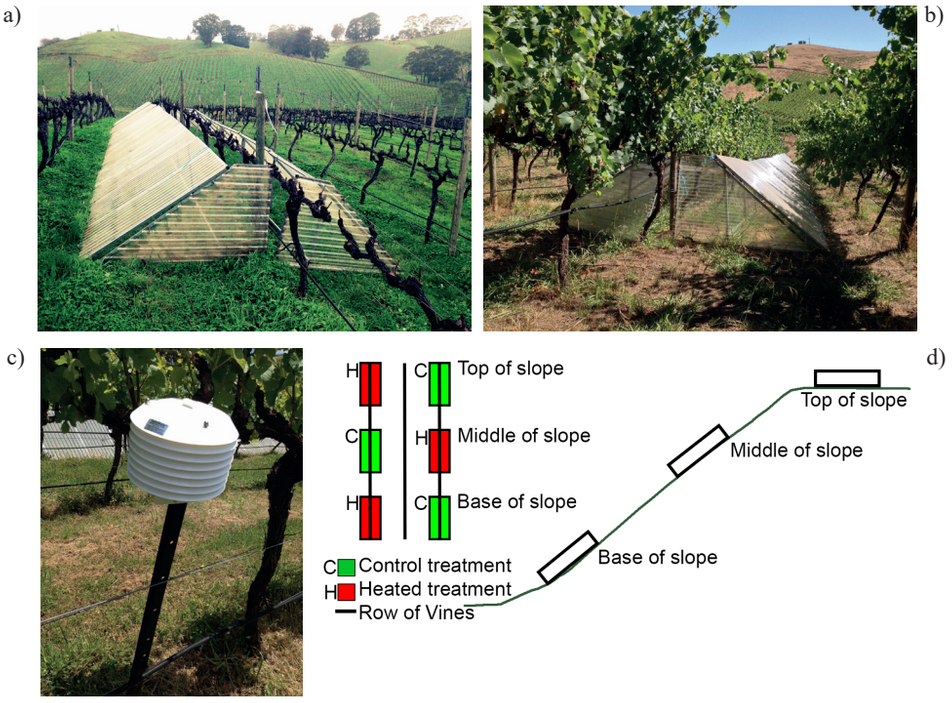

Fig. 1: **a**) Passive heating panels set up in the Lenswood vineyard, 29 Aug. 2013, showing top of slope. **b**) Passive heating panels set up in the Lenswood vineyard, 6 Feb. 2014, showing the canopy in relation to the heating panels. **c**) TinyTag sensor inside weather-proof housing, showing its location immediately beneath the canopy, 12 Nov. 2013. **d**) Diagram of vineyard experimental area, with treatments and their location on the slope indicated.

(Fig. 1a, b, and c). The chambers, described in Sadras and Soar (2009), increase day-time air temperatures with minimum impact on night temperatures (Sadras and Moran 2012, Sadras and Soar 2009). Each treatment comprised six vines, with a one-row gap between heated and control treatments. The grape clusters were located above the chambers (Fig. 1b), and experienced the air-heating effect caused by the chambers. Temperature and relative humidity were logged every 15 min using TinyTag Plus 2 TGP 4500 (Gemini Data Loggers Ltd, Chichester, West Sussex, UK) dataloggers (Fig. 1c). The standard vineyard irrigation regime was used for both controls and treatments.

Berry sampling and analysis: For the first growing season, berries were sampled initially every seven days from immediately before véraison until harvest (with a sample of 150 berries per vineyard treatment), then every ten days (with a sample of 100 berries per treatment) as the low yields became apparent. In the second season, berries were sampled every eight to nine days from immediately before véraison to harvest, with a sample of 150 berries per treatment.

For both seasons, a sub-sample of 50 berries from each treatment were analysed immediately after sampling to determine the amount of total soluble solids (TSS), pH, and titratable acidity (TA). The berries were crushed in a zip-lock plastic bag, and the juice was used for measurement of TSS, pH, and TA (titrated against tartaric acid). TSS was estimated using a standard handheld digital refractometer. TA and pH were determined with a Crison Compact Titrator (Crison Instruments SA, Barcelona, Spain). The remainder of the berries were frozen at -20 °C prior to analysis by the Iland technique (Iland *et al.* 1996 and 2004) for assay of anthocyanins and total phenolics of grape extracts, with minor modifications, using a Cintra 4040 UV/Vis spectrophotometer (GBC Scientific Equipment, Melbourne, Australia), with a 1 cm path length quartz cuvette.

For more complex spectrophotometric analyses, 50 frozen berries from each vineyard treatment were left to thaw for approximately one hour, then weighed, transferred to a 125 mL plastic beaker, and homogenised. For the first year of the study, an Ultra-Turrax T25 homogeniser (IKA Works GmbH & Co, Staufen, Germany) was employed for 90 seconds. For the second year, homogenisation varied slightly, with an immersion blender used for 30 s. For both methods, homogenisation of the flesh and skins of the berries was complete. Each homogenate was mixed thoroughly, then approximately 1 g of homogenate was placed in a 15 mL centrifuge tube for extraction steps. Three extracts of each sampling were made, with the average of the three extracts (*i.e.* technical replicates) used for each data point. A mix of 50:50 (v:v) MilliQ water (acidified to pH 2.0 with concentrated hydrochloric acid):ethanol was prepared, and 10 mL was added to each centrifuge tube. The mixture was then extracted for two hours, with the tubes shaken vigorously every 5 min, then centrifuged at 3,500 rpm for 10 min. The volume of the supernatant ('the extract') was measured to determine the 'total extract volume'. One mL of extract was diluted with 10 mL of 1.0 M HCl in another centrifuge tube and mixed thoroughly. After three hours, the absorbance of the extract diluted in HCl was read at 700, 520, and 280 nm (Iland *et al.* 1996 and 2004), using the Cintra spectrophotometer as above. Readings were also taken at 420 and 620 nm (Glories 1984, Ivanova *et al.* 2012). Each extract was read three times and the mean recorded.

An additional aliquot from the extract was used to analyse pigment colour and density by the CIELab method (Liang *et al.* 2011, Ohno 2000), using the Cintra spectrophotometer, with a narrow (1 mm path length) quartz cuvette. Each aliquot was read twice and the mean recorded. The CIELab parameters, originally devised for the colour printing industry, provide an analysis of colour and density expressed as a three-dimensional 'colourspace'. The three CIELab parameters, L*, a*, and b*—were calculated for all grape and wine analyses. L* defines 'lightness', with zero as absolute black and 100 as absolute white; in terms of 'Pinot Noir' grape ripening, the parameter L* is an inverse measure of the darkness or ripeness of the grapes. Parameter a* defines colour in terms of green (negative values) to red (positive values); in the context of grape ripening, it corresponds to the conversion of loss of chlorophyll and production of red pigments. Parameter b* assigns blue (negative values) to yellow (positive values) components, so b* is the inverse measure of anthocyanin production (Liang *et al.* 2011, Cesa *et al.* 2017).

Winemaking: Low grape yield prevented winemaking in the first season. In the second season, grapes from all treatments were harvested between 24 and 25 °Brix, with the harvest date determined by the TSS. Winemaking was conducted as per Dambergs *et al.* (2012) and Liccioli (pers. comm. 2014). The harvested grapes were destemmed manually, and mouldy, under- or over-ripe berries were discarded. Then the yield of healthy grapes was split into three 1.3 kg replicate fermentations per vineyard treatment, and 50 ppm potassium metabisulfite was added. The berries for each replicate ferment were crushed manually in a plastic bag, then placed into a 1.5 L Bodum French Press coffee plunger. Each batch was inoculated with the yeast *Saccharomyces cerevisiae* EC1118 at a rate of 0.5 $g \cdot L^{-1}$, then the ferments were plunged daily and maintained in a room at 18 °C.

When less than 1 $g \cdot L^{-1}$ residual sugar remained, each of the three replicate ferments was pressed using the coffee pot plunger with a 4 kg weight left in place for 5 min to ensure even pressing, then the liquid from each ferment was decanted into an argon-filled glass bottle. The pressed skins were stirred and re-pressed, and the remaining liquid added to the bottle. Each bottle was topped up with argon gas, then sealed. The wine was left 48 hours to settle, then decanted off the lees into a fresh glass bottle containing argon gas. A further 50 ppm of potassium metabisulfite was added, and glass marbles added to bring the level of the wine into the neck of the bottle. Malolactic fermentation was not undertaken. The wines were cold stabilised, then bottled in 200 mL brown glass bottles.

Wine analyses: The pigment colour of each of the three wine replicates were analysed by the CIELab method (Liang *et al.* 2011, Ohno 2000), as above. Each replicate wine was sampled once, each sample was read three times, and the mean recorded.

Somers Analysis was undertaken with the Cintra spectrophotometer to determine total phenolics, total an-

thocyanins, and colour density of the experimental wines (Mercurio *et al.* 2007, Somers 1971, Somers and Evans 1974 and 1977). The protocol was as per Mercurio *et al.* (2007), but only total phenolics, total anthocyanins, and colour density were measured. Each of the three replicate wines was sampled once, each sample was read twice with means recorded (*i.e.* three valid wine replicates per treatment).

Statistical analyses: Statistical analyses were undertaken using Microsoft Excel, SAS StatView (SAS, Cary, NC), and GNU R (R Core Team 2019). A two-phase model was fitted as per Sadras and Moran (2012, p. 116), which explains:

"Phase 1: A= a + b TSS if TSS ≤ TSSx – Eqn 1a

Phase 2: A= a′ + b′ TSS if TSS > TSSx – Eqn 1b

where a and a′ are intercepts and b and b′ are slopes of linear regressions and TSSx is a threshold that marks the shift from Phase 1 to Phase 2".

The break point (or statistical 'decoupling') between these two linear phases was determined using the GNU R package 'segmented' (Muggeo 2003 and 2008). Departures from linearity were determined based on the significance (p) of a quadratic term. An analysis of residuals was used to test the effects of the heated treatments and the position on the slope, and the significance of the difference between the two residuals was determined using ANOVA.

Significance was determined via ANOVA using a two-factor cross-factored unreplicated model (Doncaster and Davey 2007), and the significant difference limit was defined as probability $p < 0.05$. The two growing seasons were used as binary replicates; not a large number, but all that could be accommodated for the study period. However, the data in this study represents trends (regressions) taken over a period of several months. These regressions contained a large number of valid replicates with statistically significant differences, facilitating analysis as separate factors, *i.e.* heated *vs.* unheated, and position on the slope.

Graphs showing means and standard errors were produced using a modified version of the 'PlotMeans.R' script devised by Doncaster (2017). Vapour pressure deficit (VPD) was calculated from field measurements of temperature and relative humidity, using the 'RHtoVPD' function in the GNU R package 'plantecophys' (Duursma 2015), assuming an air pressure of 101.3 kPa for the elevation of 536 m above sea level.

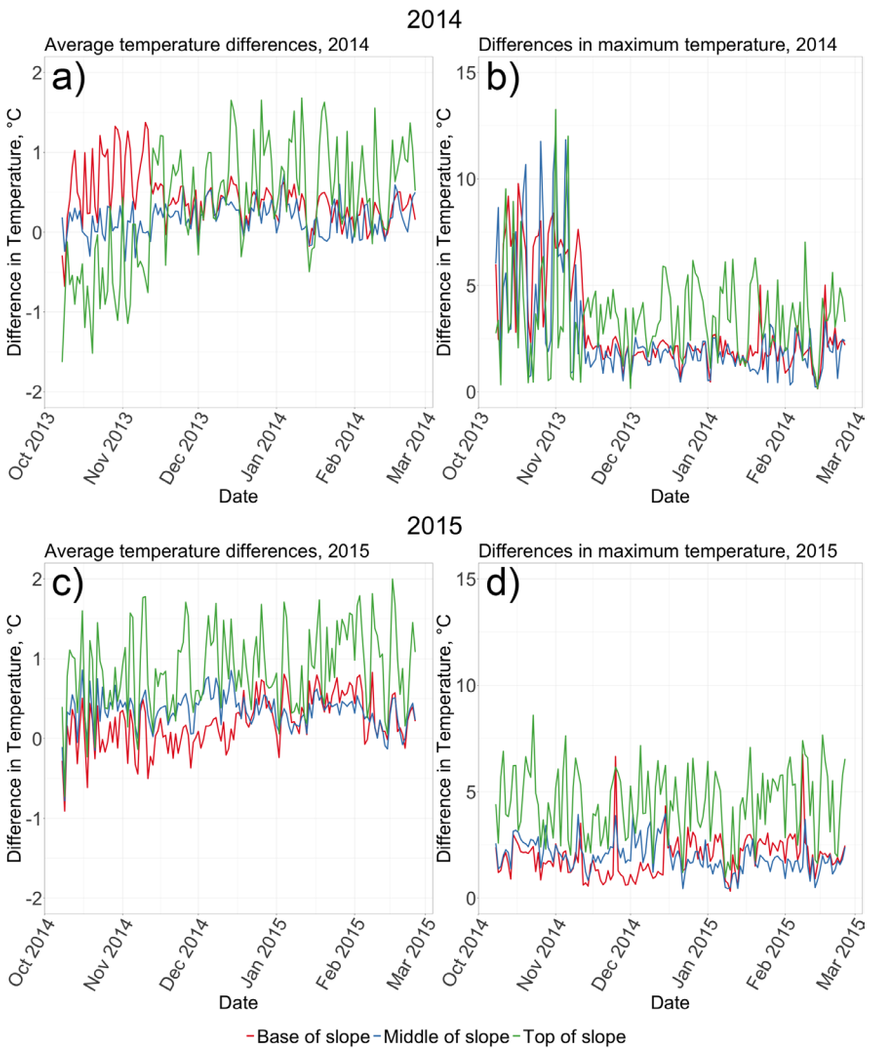

Fig. 2: Average temperature differences (**a** and **c**) and differences in maximum temperature (**b** and **d**) between heated and control treatments respectively. X-axis shows dates of average readings over two growing seasons (first season: 8 Oct 2013 to 25 Feb 2014; second season: 8 Oct 2014 to 25 Feb 2015; *i.e.* Southern hemisphere growing seasons, **a** and **b**; **c** and **d**). Note higher temperature difference values for heated vines (right) versus unheated (left).

Results and Discussion

Passive heating system effects: Location on the slope and thermal regimes interacted, whereby differences in seasonal average temperature between heated and control treatment were 1.6 °C at the top of the slope and 0.2 to 0.4 °C at the middle and bottom of the slope over the entire study period (differences during the two growing seasons are shown in Fig. 2a and c). Differences in seasonal maximum temperature between heated and control was 9.8 °C at the top of the slope, 18.9 °C in the middle and 13.3 °C at the bottom over the entire study period (differences during the two growing seasons are shown in Fig. 2b and d). Such increases are consistent with projections for climate change in Australia (Hughes 2003, Hallett *et al.* 2018).

The heated treatment compared with the unheated control at the top of the slope had a VPD of -0.127 kPa, the middle a VPD of -0.154 kPa, and the base a VPD of +0.0122 kPa.

Note that there were lower yields in 2014, when compared with 2015, due to vintage effects (Table). As discussed in the Methods section ('Vineyard trial'), the weather differed

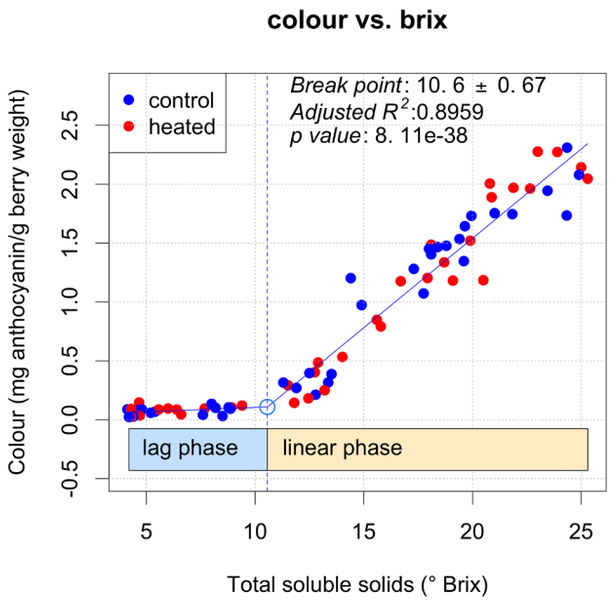

Fig. 3: Scattergraph of bilinear model of total soluble solids (TSS) versus colour. The blue solid line is the piecewise regression, and the blue dotted line shows a bilinear model with the break point at 10.56 ± 0.6705 °Brix.

between the two years of the study, with the first year being particularly challenging. This table also shows the harvest dates, which differed both by treatment and by position on the slope. As expected, the heated treatments ripened earlier than the controls (with the exception of the base of the slope in 2014). However, ripening dates also differed depending on the position on the slope, as discussed later in this section (under the subheading 'Wine').

Berry traits: The relationships between grape traits and TSS were analysed for the data pooled across the two seasons (Figs 3, 4 and 5). Fig. 3 shows the relationships between TSS and anthocyanins of the grape extracts. Similar to that described by Sadras and Moran (2012), an initial time lag phase was followed by an approximately linear phase during which TSS and anthocyanins increased roughly in parallel. A piecewise regression returned a break point (a decoupling) between the lag phase and the linear phase at 10.6 ± 0.7 °Brix. Following the model of Sadras and Moran (2012), the data were restricted to the point after the break point, a linear regression fitted, and the residuals for both the control and heated treatment were calculated.

In agreement with Sadras and Moran (2012), the heated treatment had a lower concentration of anthocyanins for the same level of TSS compared to the unheated control, as shown by the negative mean residual for the heated treatment and the positive mean residual for the unheated control (Fig. 3). This suggested that the warmer temperatures had decoupled the accumulation of sugar and anthocyanin ($p < 2.2 \times 10^{-16}$, see suppl. Tab. S1). The geometry of the slope also introduced a source of variability in temperature control, as noted above, presumably from heated air rising up the slope (the passive heating panels were originally

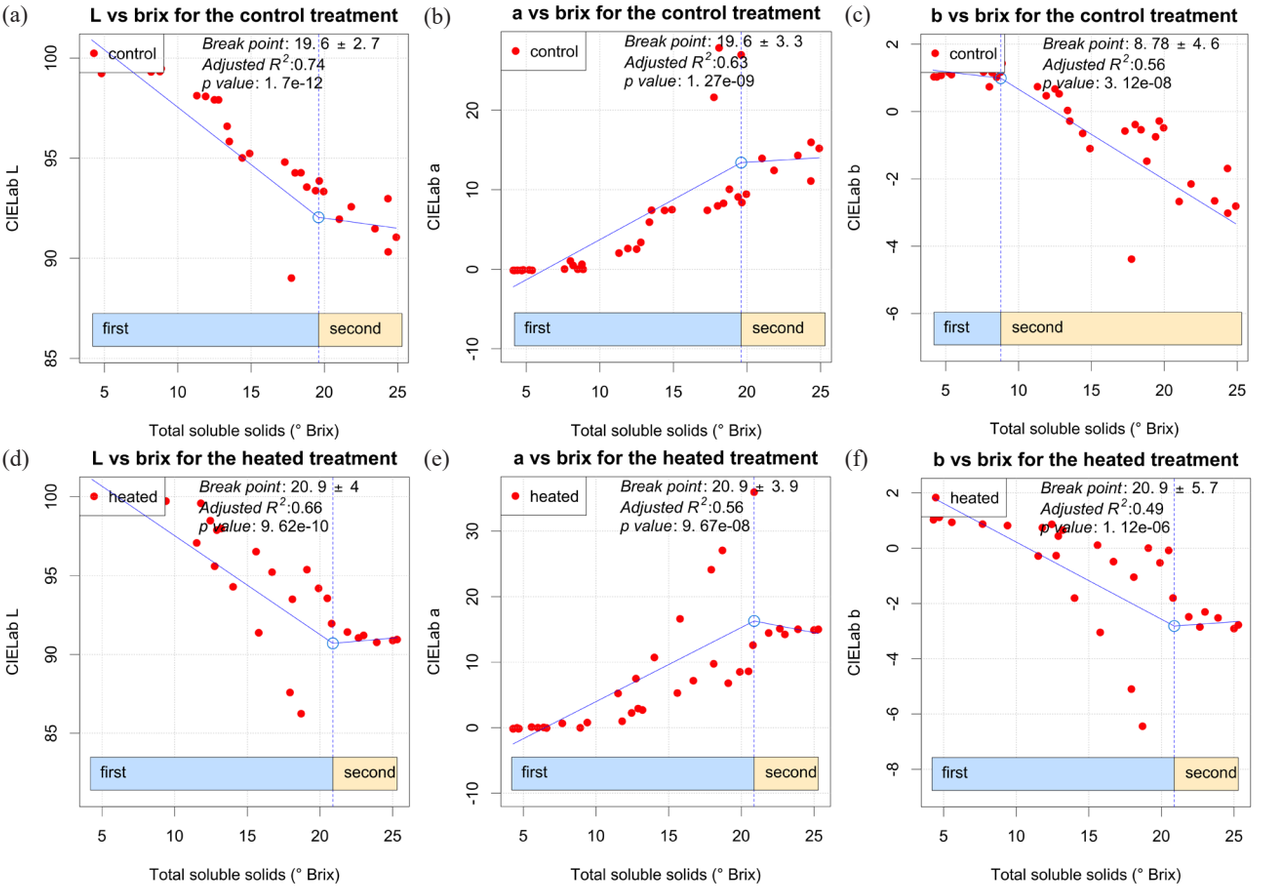

Fig. 4: Scattergraphs with bilinear model for total soluble solids versus CIELab parameters (**a**) L*, (**b**) a*, (**c**) b*, for the control treatment, and CIELab parameters (**d**) L*, (**e**) a*, (**f**) b*, for the heated treatment. The blue solid line is the piecewise regression, the blue dotted line is the break point.

designed for a flat site). This is discussed below. In Fig. 4 the heated and control treatments have been separated, and bilinear models are also seen in Fig. 4, and in Fig. 5a (TA), but not in 5b (pH) or 5 c (total phenolics). The break point varied between traits, so the validity of any linear models is doubtful.

Differences in grape development between the heated and control treatments were clearly visible, with véraison occurring earlier in the heated treatments than the controls. Véraison was noted to occur in the heated treatments on 8th January and in the unheated control on 22nd January, suggesting that véraison occurred approximately two weeks earlier in the heated treatments than in the unheated controls (although the grapes were not sampled daily, so the exact dates of véraison may be slightly earlier than suggested; suppl. Tab. S4). The heated treatments were also quicker to ripen, and reached the target sugar levels earlier than the controls (Table, see also the discussion on harvest dates in the 'Wine' subsection below). This is potentially important to 'Pinot Noir' wine regions in Australia and globally, because such elevated temperatures are predicted to be more common under most projected climate change scenarios.

It seems likely that the wine industry will have to grapple increasingly with the dual issues of higher TSS and inferior colour in grapes and wine produced in existing 'Pinot Noir' wine regions, if the link between TSS and colour becomes decoupled in commercial vineyards in the manner suggested by this study. This may require changes in viticultural and oenological techniques (Van Leeuwen *et al.* 2013), or it may necessitate expansion into regions previously considered to be too cold for red wine production (as has been seen in regions such as the UK (Georgeson and Maslin 2017) and Hokkaido (Hirota *et al.* 2017 [abstract only], Nemoto *et al.* 2016)). Alternatively, consumer preference may adapt to favour the new styles of wine produced under such conditions (van Leeuwen *et al.* 2013).

Wine: Ferments proceeded smoothly, with sugars declining rapidly and temperatures remaining steady. The lightness (CIELab parameter L*) of the wines, *i.e.* the inverse of colour density, showed significant differences ($p < 0.05$) between locations on the slope, with the middle of the slope producing wines that were somewhat lighter than either the top or the base; but no significant differences were observed between the heated and control treatments (suppl. Tab. S2). Under our experimental conditions, wine lightness (L*, Fig. 6) was not impacted by temperature.

CIELab parameter a* (increasing value indicates green-to-red, *i.e.* grape ripening) differed ($p < 0.05$) between the heated and control treatments, with the heated wines being slightly more positive (redder) than the control wines, but no significant differences occurred between locations on the slope (suppl. Tab. S2).

CIELab parameter b* (increasing value blue-to-yellow, i.e. inverse of grape anthocyanin development) varied with both location on the slope and thermal regime (Fig. 6 and suppl. Tab. S2). In particular, parameter b* (Liang *et al.* 2011, Cesa *et al.* 2017) was higher (*i.e.* less blue) at the top of the slope, and increased going up the slope (albeit with noticeable overlap between the base and middle of the slope). It was also higher (less blue) in the unheated control than in

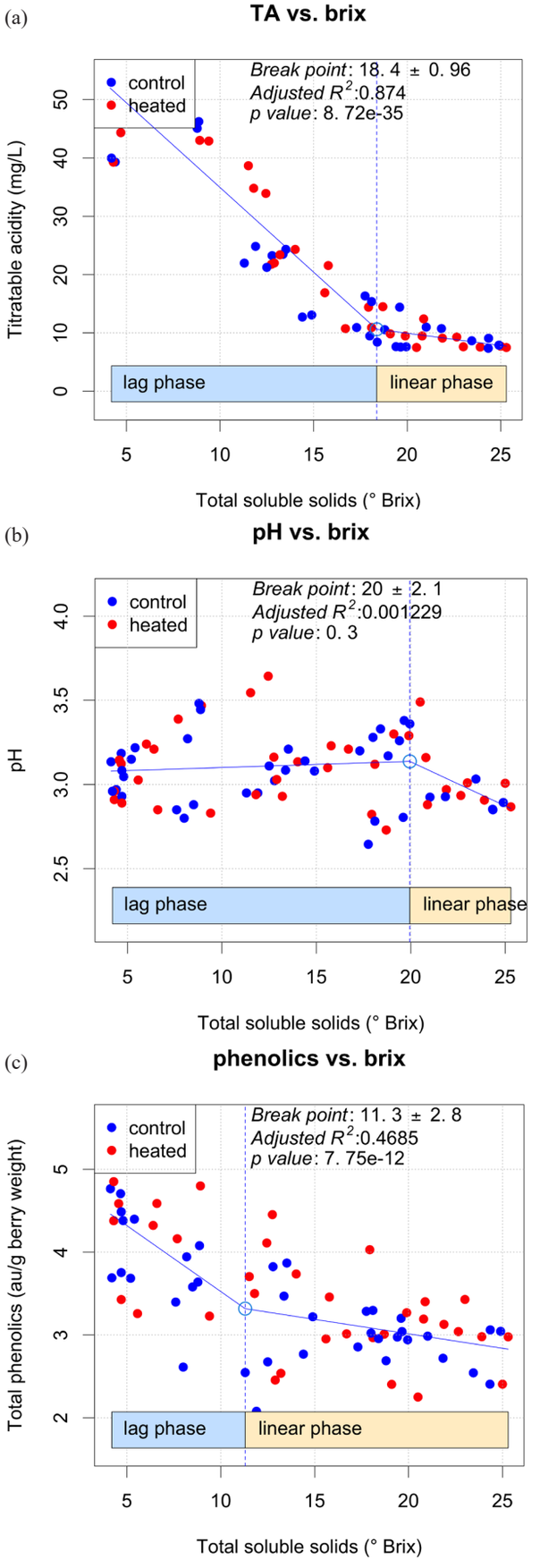

Fig. 5: Scattergraphs with bilinear models for total soluble solids vs (**a**) Titratable acidity, (**b**) pH, and (**c**) total phenolics. The blue solid line is the piecewise regression, and the blue dotted line is the break point.

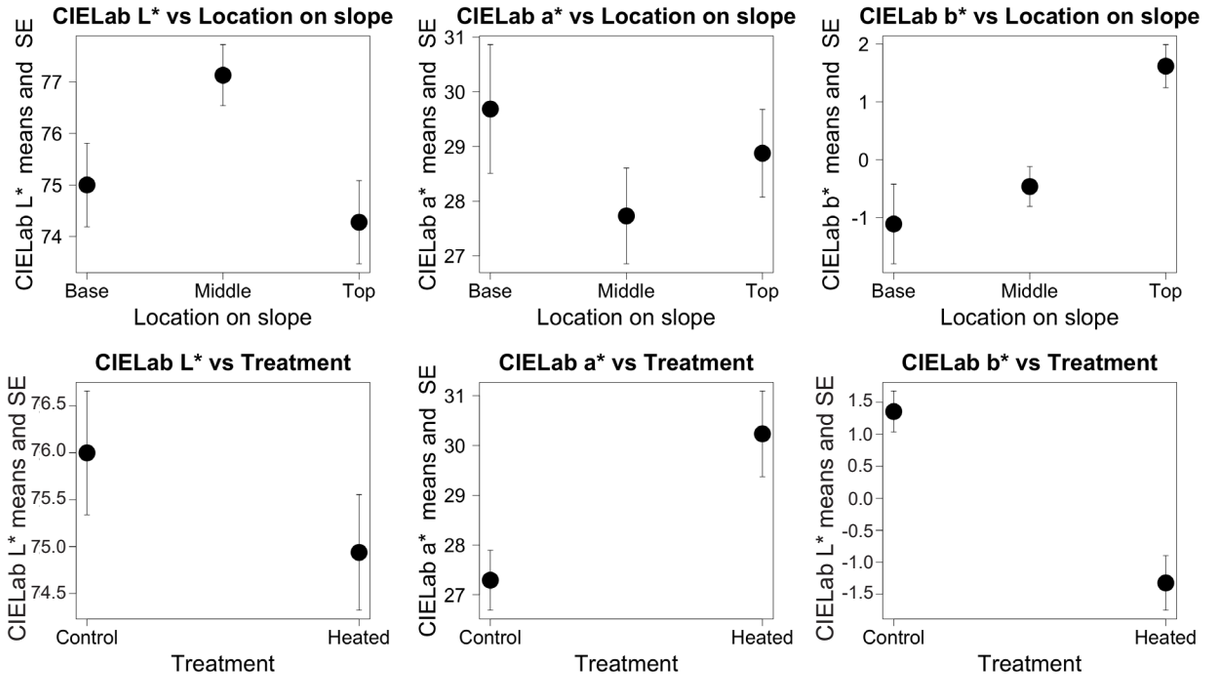

Fig. 6: Top row: Effects of the location on the slope on wine versus CIELab colour parameters; Lower row: Effects of passive heating treatments and control treatments versus colour parameters. Significant differences were observed with heating for CIELab parameters a* and b*, and with slope position for b*. Three readings were averaged for each sample from three replicate ferments (n = 3). Error bars show ± 1 standard error of the mean.

the heated treatment. It also seemed to be more impacted by warmer temperatures than parameter a* (Liang *et al.* 2011, Cesa *et al.* 2017). Parameter L* (lightness), in contrast, seemed to be most impacted by the location on the slope. It can be speculated that physical factors associated with slope influencing fruit and wine may include temperature (*e.g.* Fig. 2 clearly shows that the temperature increased going up the slopes), but also UV levels, and soil properties such as depth. Although these latter parameters were not measured as part of this study, they may be of interest for future studies, as small-scale variables in terroir at an intra-vineyard level.

Both thermal regime and location on the slope affected the Somer's data (Fig. 7 and suppl. Tab. S3). The heated treatments showed higher levels of total anthocyanins and total phenolics than the controls. The base of the slope showed the highest levels of anthocyanins and total phenolics, followed by the top, and with the middle showing the lowest levels. Colour density was higher in both the top and base of the slope than the middle. Whilst differences in temperature between the top, middle, and base of the slope were subtle, they were noticeable.

These differences are only noticeable (Fig. 7) if the relevant heated and control treatments are separated by their location on the slope. As with the CIELab data, this indicates that site (especially the related, minor differences in temperature) may be highly important in determining wine colour and phenolic contents. These vineyard slope effects have not been previously reported. In particular, the wines from the heated treatment were slightly redder (higher a*, $p = 2.7\times10^{-4}$) and slightly bluer (lower b*, $p = 2.2\times10^{-9}$) than wines from the unheated control, *i.e.* heated treatment wines were more coloured, though lighter in density. They also had slightly higher anthocyanin levels ($p = 0.026$, although the range overlaps considerably with that of the unheated control) and higher total phenolic levels ($p = 2.7\times10^{-13}$) than wines from the unheated control. Whether these differences could be detected visually and by taste is not known, but may be an important consideration for further study.

The importance of phenolic compounds - both in terms of colour compounds, and of tannins - has long been noted (Dambergs *et al.* 2012). Colour is recognised as an important factor in determining consumer acceptance of a wine (Dambergs *et al.* 2012, Parpinello *et al.* 2009). Previous wisdom suggests that cooler climates would favour colour development, particularly for 'Pinot Noir' (Kliewer 1970, Kliewer and Torres 1972, Yamane *et al.* 2006, Mori *et al.* 2007, Sadras and Moran 2012). Our study of heating 'Pinot Noir' vines in a cool environment noted the same decoupling of anthocyanins and sugars in 'Pinot Noir' grapes as seen in 'Syrah' and 'Cabernet Franc' in hotter environments (Sadras and Moran 2012). A similar effect was noted in Bonada *et al.* (2015), where flavonoids and colour were reduced in berries of Barossa 'Shiraz' grapes grown under high temperatures.

The results are less clear for wines than for berries. As noted in Bindon *et al.* (2008) and Bonada *et al.* (2015), wine composition differences are only partly reflected by differences in berry composition. Wines produced by the heated treatment were redder (higher a* values) and bluer (lower b* values), *i.e.* more purple, with increased levels of total phenolics (and perhaps of total anthocyanins), than those produced from the unheated control (Fig. 6 and Fig. 7). This may be explained in part by the higher levels of total phenolics observed in the heated treatment, and may indicate the type of change in wine colour that might be expected under projected climate change scenarios (Hughes

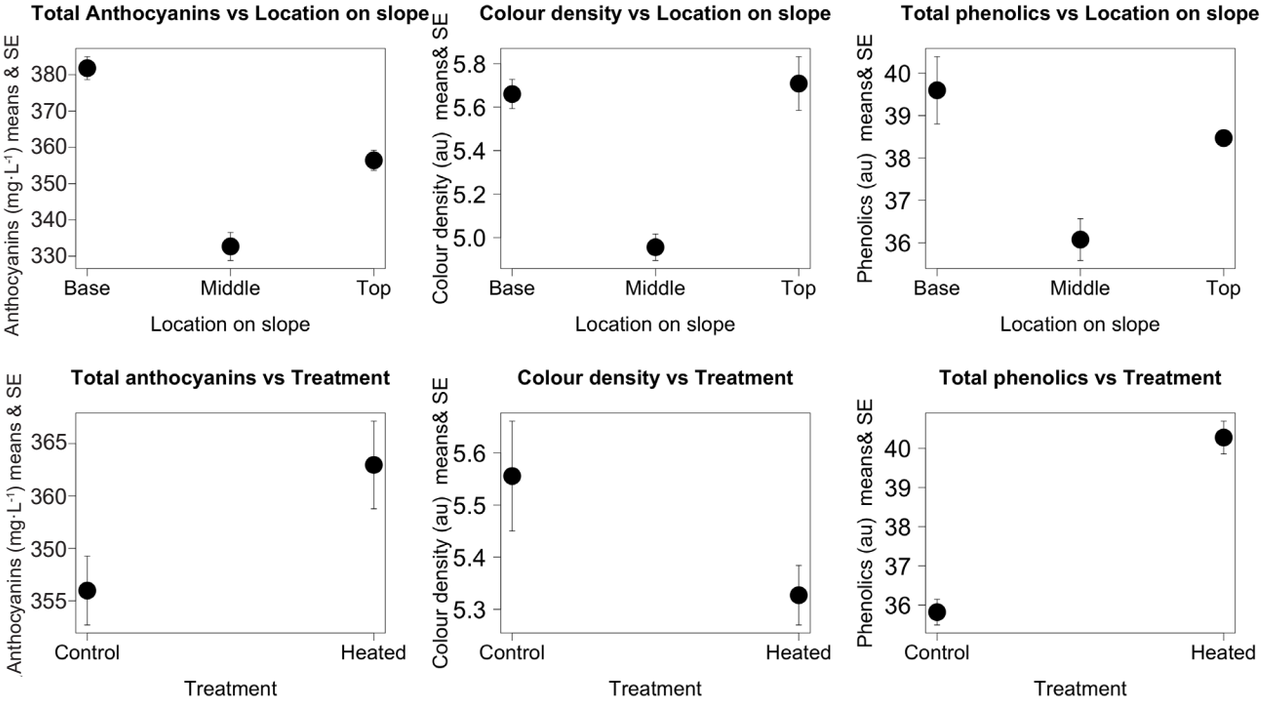

Fig. 7: Top row: Effects of location on the slope versus total anthocyanins, colour density, and total phenolics of wines; Lower row: Effects of heated and control treatments versus total anthocyanins, colour density, and total phenolics. Significant differences were found between the wines produced by passive heating and by slope position. Two readings were averaged for each sample from three replicate ferments (n = 3). Error bars show ± 1 standard error of the mean.

2003, Hallett *et al.* 2018). This is somewhat similar to the findings of Bonada *et al*. (2015), where wines produced from grapes from their treatments (artificially heated and water deficit) were redder (higher a*) than their control treatments. But in contrast to the results here, they found the wines from the treatments to be darker (lower L*) and more yellow (higher b*).

It is possible that colour differences could reflect tannin levels. The reason for the increase in total phenolics is less obvious, with most previous research suggesting that total phenolics may be more influenced by radiation than by temperature (Nicholas *et al.* 2011, Song *et al.* 2015). In contrast, Nicholas *et al.* (2011) reported that vineyard sites experiencing cooler temperatures during the previous autumn produced wine with significantly higher total phenolics, perhaps showing that the dynamics of soil *versus* air temperatures are complex. Boulton (2001) noted that early studies on co-pigmentation found tannin additions shifted the colour of malvidin 3-monoglucoside towards blue, rather than its usual red colouration, which would also appear to be the case in the present study. The authors attributed this phenomenon to monomeric cofactors and dimers, rather than the tannins *per se*; however, these would be included in any measure of total phenolics, and hence the higher levels of total phenolics in the heated treatment may explain the lower values for the CIELab b* parameter (*i.e.* more bluish tinge). The importance of site is supported by this study. The previously comparable study using passive heating (Sadras and Soar 2009) was undertaken on a flat site, so that the entrapment of warm air by the panels was efficient. In this study - the first of its kind on a steeply sloped site - it was found that the warming was unsurprisingly transported up the slope by air convection, perhaps drawing cooler air into the bottom or middle sections. Importantly, this points to a natural effect of warming found for sloping sites that has not been widely studied in recent scientific literature (but see Gladstones (2011) and Gladstones (1992) for discussion of the topic). Such sites are usually chosen for their resistance to frost and direction towards sunlight (*i.e.* north-facing in the southern hemisphere).

Differences in ripening time based upon location on the slope have been noticed by the vineyard management (Craig Markby 2013 pers. comm.), and were confirmed during the course of this study. These differences were particularly noticeable in the better 2015 growing season, with the control vines at the top of the slope harvest seven days ahead of the control vines at the base of the slope, and two days ahead of the control vines in the middle of the slope, with a similar pattern seen in the heated treatment vines (Table). This echoes experience in other wine regions, where differences in vineyard site, and within a particular vineyard, have long been considered to impact wine quality and composition (van Leeuwen *et al.* 2004, Van Leeuwen and Seguin 2006, Hong 2011, Nicholas *et al.* 2011, de Andrade *et al.* 2013, Roullier-Gall *et al.* 2014a and b).

A final point would be to question how these changes in colour and phenolics are likely to be perceived by consumers. It has been presumed that any factor which increases colour density may make the wine more acceptable to consumers (Parpinello *et al.* 2009, Dambergs *et al.* 2012). However, there seems to be a trend for increasing interest in lighter reds among some wine consumers, including lighter

coloured 'Pinot Noir's (Goode 2015). Van Leeuwen *et al.* (2013) have also suggested that consumer preferences may shift as wine styles change in response to climate change.

Conclusions

Differences between the heated and control treatments were clearly noticeable in terms of grape pigmentation, but to a lesser extent for resulting wine colour. The location on the slope appeared to contribute to the effect, highlighting more complex topographic interactions. Elevated temperatures decoupled the accumulation of sugars and anthocyanins, as reported in hotter environments with diverse varieties. This study suggests that climate change will likely impact the production of 'Pinot Noir' wine in Australia.

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References

Antcliff, A.; 1976: Some Wine Grapes for Australia. Clayton, Commonwealth Sci. Indust. Res. Org.

Bindon, K.; Dry, P.; Loveys, B.; 2008: Influence of partial rootzone drying on the composition and accumulation of anthocyanins in grape berries (*Vitis vinifera* cv. Cabernet Sauvignon). Aust. J. Grape Wine Res. **14**, 91-103. DOI: https://doi.org/10.1111/j.1755-0238.2008.00009.x

Bonada, M.; Jeffery, D. W.; Petrie, P. R.; Moran, M. A.; Sadras, V. O.; 2015: Impact of elevated temperature and water deficit on the chemical and sensory profiles of Barossa Shiraz grapes and wines. Aust. J. Grape Wine Res. **21**, 240-253. DOI: https://doi.org/10.1111/ajgw.12142

Boulton, R.; 2001: The Copigmentation of Anthocyanins and Its Role in the Color of Red Wine: A Critical Review. Am. J. Enol. Vitic. **52**, 67-87.

Bureau of Meteorology; 2021a: Lenswood: Monthly mean maximum temperature. Melbourne, VIC, Australia. (http://www.bom.gov.au/jsp/ncc/cdio/weatherData/av?p_nccObsCode=36&p_display_type=dataFile&p_startYear=&p_c=&p_stn_num=023801).

Bureau of Meteorology; 2021b: Lenswood: Monthly mean minimum temperature. Melbourne, VIC, Australia (http://www.bom.gov.au/jsp/ncc/cdio/weatherData/av?p_nccObsCode=38&p_display_type=dataFile&p_startYear=&p_c=&p_stn_num=023801)

Bureau of Meteorology; 2021c: Lenswood: Monthly rainfall. Melbourne, VIC, Australia. (http://www.bom.gov.au/jsp/ncc/cdio/weatherData/av?p_nccObsCode=139&p_display_type=dataFile&p_startYear=&p_c=&p_stn_num=023801)

Butler, R.; 1981: Pinot Noir: The Effect of Stem Inclusion and Sulphur Dioxide Addition on Wine Composition and Quality. Roseworthy, University of Adelaide.

Cesa, S.; Carradori, S.; Bellagamba, G.; Locatelli, M.; Casadei, M. A.; Masci, A.; Paolicelli, P.; 2017: Evaluation of processing effects on anthocyanin content and colour modifications of blueberry (*Vaccinium* spp.) extracts: Comparison between HPLC-DAD and CIELAB analyses. Food Chem. **232**, 114-123. DOI: https://doi.org/10.1016/j.foodchem.2017.03.153

Charters, S.; Robinson, J.; Harding, J.; 2015: Quality in Wine. In: J. Robinson, J. Harding (Eds): The Oxford Companion to Wine. Oxford University Press.

Dambergs, R. G.; Sparrow, A.; Carew, A. L.; Scrimgeour, N.; Wilkes, E.; Godden, P.; Herderich, M.; Johnson, D.; 2012: Quality in a cool climate - maceration techniques in Pinot Noir production. Wine Vitic. J. **27**, Art. N3.

De Andrade, R. H. S.; Do Nascimento, L. S.; Pereira, G. E.; Hallwass, F.; Paim, A. P. S.; 2013: Anthocyanic composition of Brazilian red wines and use of HPLC-UV–Vis associated to chemometrics to distinguish wines from different regions. Microchem. J. **110**, 256-262. DOI: https://doi.org/10.1016/j.microc.2013.04.003

Doncaster, C. P.; 2017: Analysis of Variance and Covariance in R. (https://web.archive.org/web/20171109012356/http://www.southampton.ac.uk:80/~cpd/anovas/datasets/ANOVA%20in%20R.htm)

Doncaster, C. P.; Davey, A. J. H.; 2007: Analysis of Variance and Covariance. Cambridge University Press, Cambridge, UK.

Duursma, R. A.; 2015: Plantecophy - an R package for analysing and modelling leaf gas exchange data. PLoS ONE **10**, e0143346. DOI: https://doi.org/10.1371/journal.pone.0143346

Galet, P.; 1979: A Practical Ampelography. Comstock Publishing Associates, Ithaka, USA.

Georgeson, L.; Maslin, M.; 2017: Distribution of climate suitability for viticulture in the United Kingdom in 2100. ECRC Research Report 177. UCL Environmental Change Research Centre, London, UK (https://discovery.ucl.ac.uk/id/eprint/10115230/).

Gladstones, J. S.; 1992: Viticulture and Environment. Winetitles.

Gladstones, J. S.; 2011: Wine, Terroir and Climate Change. Wakefield Press, Kent Town, Australia.

Glories, Y.; 1984: La couleur des vins rouges: 2ème partie mesure, origine et interpretation. Conn. Vigne Vin, **18**, 253-271.

Goode, J.; 2015: The Rise of the Lighter-Coloured Red Wine. Jamie Goode's Wine Blog. (https://www.wineanorak.com/wineblog/uncategorized/the-rise-of-the-lighter-coloured-red-wine)

Hallett, C. S.; Hobday, A. J.; Tweedley, J. R.; Thompson, P. A.; Mcmahon, K.; Valesini, F. J.; 2018: Observed and predicted impacts of climate change on the estuaries of south-western Australia, a Mediterranean climate region. Reg. Environ. Change, **18**, 1357-1373. DOI: https://doi.org/10.1007/s10113-017-1264-8

Hemming, R.; Rosen, M.; 2015: Can colour influence taste? (http://www.decanter.com/features/can-colour-influence-taste-245901/)

Hirota, T.; Yamazaki, T.; Yasui, Y.; Fukuwara, J.; Niwa, K.; Nemoto, M.; Hamasaki, T.; Shimoda, S.; Kanno, H.; Nishio, Z.; 2017: Climate change favors viticulture and wine production in Hokkaido, Japan. An example of Pinot Noir cultivation since 1998 (Abstract). Clim. Bios. **17**, 34-45. DOI: https://doi.org/10.2480/cib.J-17-034

Hong, Y. S.; 2011: NMR-based metabolomics in wine science. *Magn Reson Chem,* 49 Suppl 1**,** S13-21. DOI: https://doi.org/10.1002/mrc.2832

Hughes, L.; 2003: Climate change and Australia: trends, projections and impacts. *Austral Ecology,* 28**,** 423-443. DOI: https://doi.org/10.1046/j.1442-9993.2003.01300.x

Iland, P. G.; Bruer, N.; Edwards, G.; Weeks, S.; Wilkes, E.; 2004: Chemical Analysis of Grapes and Wine: Techniques and Concepts Adelaide, Australia, Patrick Iland Wine Promotions Pty Ltd.

Iland, P. G.; Cynkar, W.; Francis, I. L.; Williams, P.; Coombe, B.; 1996: Optimisation of methods for the determination of total and red-free glycosyl glucose in black grape berries of *Vitis vinifera*. Aust. J. Grape Wine Res. **2**, 171-178.

Ivanova, V.; Vojnoski, B.; Stefova, M.; 2012: Effect of winemaking treatment and wine aging on phenolic content in Vranec wines. J. Food Sci. Technol. **49**, 161-172. DOI: https://doi.org/10.1007/s13197-011-0279-2

Jones, G. V.; Schultz, H. R.; 2016: Climate change: Climate change and emerging cool climate wine regions. Wine Vitic. J. **31**, 51-53.

Kliewer, W.; 1970: Effect of day temperature and light intensity on colouration of *Vitis vinifera* L. Grapes. J. Am. Soc. Hortic. Sci. **95**, 693-697.

Kliewer, W.; Torres, R.; 1972: Effect of controlled day and night temperatures on grape colouration. Am. J. Enol. Vitic. **23**, 71-77.

Liang, Z.; Sang, M.; Fan, P.; Wu, B.; Wang, L.; Yang, S.; Li, S.; 2011: CIELAB coordinates in response to berry skin anthocyanins and their composition in Vitis. J. Food Sci. **76**, C490-C497. DOI: https://doi.org/10.1111/j.1750-3841.2011.02095.x

Mercurio, M. D.; Dambergs, R. G.; Herderich, M. J.; Smith, P. A.; 2007: High throughput analysis of red wine and grape phenolics: Adaptation and validation of methyl cellulose precipitable tannin assay and modified somers color assay to a rapid 96 well plate format. J. Agric. Food Chem. **55**, 4651-4657. DOI: https://doi.org/10.1021/jf063674n

Mori, K.; Goto-Yamamoto, N.; Kitayama, M.; Hashizume, K.; 2007: Loss of anthocyanins in red-wine grape under high temperature. J..Exp. Bot. **58**, 1935-1945. DOI: https://doi.org/10.1093/jxb/erm055

Muggeo, V. M.; 2003: Estimating regression models with unknown break-points. Stat. Med. 22, 3055-3071. DOI: https://doi.org/10.1002/sim.1545

Muggeo, V. M. R.; 2008: segmented: an R Package to Fit Regression Models with Broken-Line Relationships. R News **8**, 20-25.

Nemoto, M.; Hirota, T.; Sato, T.; 2016: Prediction of climatic suitability for wine grape production under the climatic change in Hokkaido. J. Agric. Meteorol. **72**, 167-172. DOI: https://doi.org/10.2480/agrmet.D-15-00027

Nicholas, K. A.; Matthews, M. A.; Lobell, D. B.; Willits, N. H.; Field, C. B.; 2011: Effect of vineyard-scale climate variability on Pinot noir phenolic composition. Agric. For. Meteorol. **151**, 1556-1567. DOI: http://dx.doi.org/10.1016/j.agrformet.2011.06.010

Ohno, Y.; 2000: CIE fundamentals for color measurements. NIP & Digital Fabrication Conference, 540-545. Society for Imaging Science and Technology.

Parpinello, G.; Versari, A.; Chinnici, F.; Galassi, S.; 2009: Relationship among sensory descriptors, consumer preference and color parameters of Italian Novello red wines. Food Res. Int. **42**, 1389-1395. DOI: https://doi.org/10.1016/j.foodres.2009.07.005

R Core Team; 2019: R: A Language and Environment for Statistical Computing. Vienna, Austria, R Foundation for Statistical Computing (https://www.R-project.org/)

Roullier-Gall, C.; Boutegrabet, L.; Gougeon, R. D.; Schmitt-Kopplin, P.; 2014a: A grape and wine chemodiversity comparison of different appellations in Burgundy: Vintage vs terroir effects. Food Chem. **152**, 100-107. DOI: https://doi.org/10.1016/j.foodchem.2013.11.056

Roullier-Gall, C.; Lucio, M.; Noret, L.; Schmitt-Kopplin, P.; Gougeon, R. D.; 2014b: How Subtle Is the "Terroir" Effect? Chemistry-Related Signatures of Two "Climats de Bourgogne" PLoS ONE **9**, e97615. DOI: https://doi.org/10.1371/journal.pone.0097615

Rowley, M.; 2015: Pinot Noir: A snapshot of Australian Pinot Noir production and purchases. Wine Vitic. J. **30**, 67.

Sadras, V. O.; Bubner, R.; Moran, M. A.; 2012: A large-scale, open-top system to increase temperature in realistic vineyard conditions, 11-25. In: V. O. Sadras; M. A. Moran; P. R. Petrie (Eds): A Window into Hotter and Drier Futures: phenological shifts and adaptive practices, SARDI, Adelaide, Australia.

Sadras, V. O.; Moran, M. A.; 2012: Elevated temperature decouples anthocyanins and sugars in berries of Shiraz and Cabernet Franc. Aust. J. Grape Wine Res. **18**, 115-122. DOI: https://doi.org/10.1111/j.1755-0238.2012.00180.x

Sadras, V. O.; Soar, C. J.; 2009: Shiraz vines maintain yield in response to a 2–4 °C increase in maximum temperature using an open-top heating system at key phenostages. Eur. J. Agron. **31**, 250-258. DOI: http://dx.doi.org/10.1016/j.eja.2009.09.004

Schultz, H. R.; Jones, G. V.; 2010: Climate induced historic and future changes in viticulture. J. Wine Res. **212**, 137-145. DOI: https://doi.org/10.1080/09571264.2010.530098

Somers, T. C.; 1971: The polymeric nature of wine pigments. Phytochemistry **10**, 2175-2186. DOI: http://dx.doi.org/10.1016/S0031-9422(00)97215-7

Somers, T. C.; Evans, M. E.; 1974: Wine Quality - Correlations with Color Density and Anthocyanin Equilibria in a Group of Young Red Wines. J. Sci. Food Agric. **25**, 1369-1379. DOI: https://doi.org/10.1002/jsfa.2740251105

Somers, T. C.; Evans, M. E.; 1977: Spectral evaluation of young red wines: Anthocyanin equilibria, total phenolics, free and molecular SO2, "chemical age". J. Sci. Food Agric. **28**, 279-287. DOI: https://doi.org/10.1002/jsfa.2740280311

Song, J.; Smart, R.; Wang, H.; Dambergs, B.; Sparrow, A.; Qian, M. C.; 2015: Effect of grape bunch sunlight exposure and UV radiation on phenolics and volatile composition of *Vitis vinifera* L. cv. Pinot noir wine. Food Chem, **173**, 424-431. DOI: https://doi.org/10.1016/j.foodchem.2014.09.150

Valentin, D.; Parr, W. V.; Peyron, D.; Grose, C.; Ballester, J.; 2016: Colour as a driver of Pinot noir wine quality judgments: An investigation involving French and New Zealand wine professionals. Food Qual. Pref. **48**, 251-261. DOI: https://doi.org/10.1016/j.foodqual.2015.10.003

Van Leeuwen, C.; Friant, P.; Choné, X.; Tregoat, O.; Koundouras, S.; Dubourdieu, D.; 2004: Influence of Climate, Soil, and Cultivar on Terroir. Am. J. Enol. Vitic. **55**, 207-217.

Van Leeuwen, C.; Schultz, H. R.; De Cortazar-Atauri, I. G.; Duchêne, E.; Ollat, N.; Pieri, P.; Bois, B.; Goutouly, J. P.; Quénol, H.; Touzard, J. M.; 2013: Why climate change will not dramatically decrease viticultural suitability in main wine-producing areas by 2050. Proc. Natl. Acad. Sci. **110**, E3051-E3052. DOI: https://doi.org/10.1073/pnas.1307927110

Van Leeuwen, C.; Seguin, G.; 2006: The concept of terroir in viticulture. J. Wine Res. **17**, 1-10. DOI: https://doi.org/10.1080/09571260600633135

Webb, L.; Whetton, P.; Barlow, E.; 2008: Modelling the relationship between climate, winegrape price and winegrape quality in Australia. Clim. Res. **36**, 89-98. DOI: https://doi.org/10.3354/cr00739

Yamane, T.; Jeong, S. T.; Goto-Yamamoto, N.; Koshita, Y.; Kobayashi, S.; 2006: Effects of temperature on anthocyanin biosynthesis in grape berry skins. Am. J. Enol. Vitic. **57**, 54-59.

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